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Application of Time Domain Reflectometers in Urban Settings

Time domain reflectometers (TDRs) are in-situ monitoring probes that record soil moisture content when calibrated to a particular soil. Typically TDRs are used in agricultural settings, but this technology may also be applied to urban soils. The Urban Watershed Management Branch located at the Edison Environmental Center (EEC) has been exploring the use of TDRs as a way to monitor stormwater infiltration practices. TDRs are installed in pilot- and full-scale bioretention units (e.g., rain gardens). The TDRs are capable of measuring soil moisture and sensing the wetting front as the stormwater infiltrates through the planting media and into the native soil.

Recently, a new permeable pavement parking lot was constructed at the EEC. This parking lot was designed for long-term monitoring and included the installation of TDRs, both in the crushed concrete storage layer and in the underlying soil. Early indications suggest that while this novel application of TDRs in crushed concrete may not provide calibrated moisture content, wetting fronts correspond to those of the TDRs in soils. Extensive bench-scale testing was performed in crushed concrete prior to the permanent installation below the paved surfaces as a proof of concept test.

Application of this technology may be suitable to urban areas that are interested in modifying tree pit design, controlling stormwater through rain gardens and porous pavements, or using manufactured or engineered soils, and seek or require supporting data that water is infiltrating and available to plants.

Keywords
tormwater, low impact development, time domain reflectometers, monitoring, urban fill soil

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Introduction

Time domain reflectometers (TDRs) are sensors that measure the volumetric water content of soils and porous media. The sensors consist of stainless steel rods connected to a circuit board in an epoxy housing. An electromagnetic pulse is propagated along the rods. The time, or period, required for the signal to travel down the rods and back varies with the volumetric water content of the surrounding media and temperature. A calibration curve is needed for the specific media. TDRs were developed mostly for agricultural applications; however, the technology has also been applied to forestry and ecological research. This study demonstrates the use of TDRs for quantifying drainage properties in low impact development (LID) stormwater controls, specifically permeable pavement and rain garden systems. TDRs were successfully used to monitor the responses of urban fill, engineered bioretention media, and the aggregate storage layer under permeable pavement to multiple rain events of varying depth, intensity, and duration.

The hydrologic performance of permeable pavement and rain garden systems has previously been quantified for underdrain systems, but there have been few studies of systems that drain to the underlying soils. We know of no published studies outlining the use of TDR technology to document drainage properties in media other than soil. In this study TDRs were installed at multiple locations and depths in underlying urban fill soils, engineered bioretention media, and recycled concrete aggregate (RCA) in a permeable pavement parking lot and associated series of rain gardens at EPA's Edison Environmental Center in New Jersey. Bench- and pilot-scale tests were performed before permanent installation to test the sensors' ability to detect the wetting front during both saturated and unsaturated flow conditions.

Bench- and Pilot-Scale Tests

Bench- and pilot-scale tests were conducted in the winter and spring of 2009 to determine the ability of horizontally deployed TDRs to quantify wetting and draining curves under saturated (Figure 1) and unsaturated (Figure 2) conditions.

Figure 1. The response of TDRs in 5/8" diameter gravel with protective PVC housing (left) and without housing (right) were studied at the bench scale under saturated conditions.

Figure 2. The response of TDRs in 1" diameter recycled concrete aggregate with protective PVC housing (left and center) and without housing (right) were studied at the pilot scale under unsaturated flow conditions.

TDRs (Campbell Scientific, Model CS616) were installed in varying aggregate sizes both with and without PVC housing. The PVC pipes were filled with aggregate with the intention of protecting the sensors from compaction during parking lot construction. Multiple PVC housing designs were tested, including 3" and 6" diameter pipe size, ends capped and open, and drainage holes and slots (vertical and horizontal).

Installation and Monitoring at the Full-Scale

During the summer of 2009, 24 TDRs were installed under the permeable pavement parking lot at six locations (12 in the RCA layer and 12 in the underlying fill). EPA installed 48 TDRs in six rain garden cells (24 in the engineered bioretention media and 24 in the underlying soil) across 12 locations. An insertion device was used to ensure the rods were parallel and level during installation in undisturbed soil faces (Figure 3a).

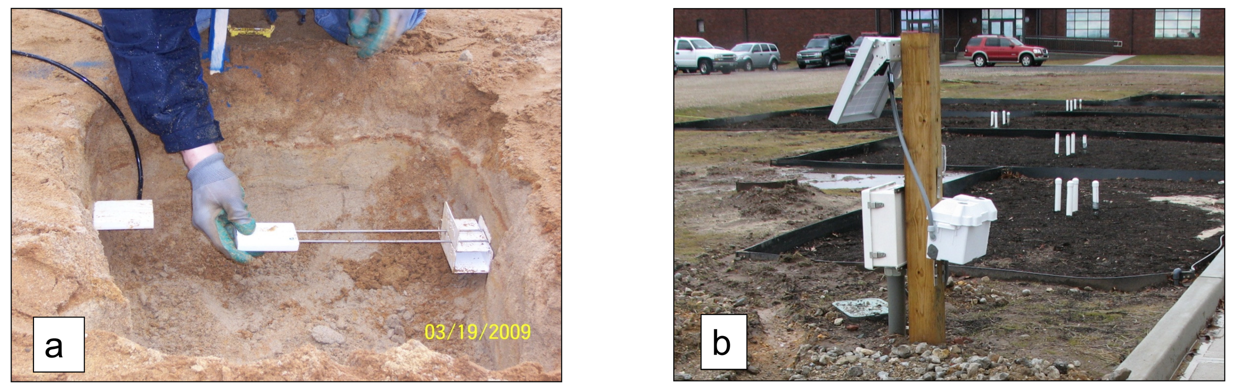

Figure 3. A manufacturer-provided tool guides a TDR horizontally into underlying soil (a). Pairs of TDRs were installed to both assess the precision of the sensors and back-up readings in the event of an individual sensor failure. Sensors were wired to dataloggers powered by a deep-cycle battery that is recharged by a solar panel (b).

Thermistors were installed with each set of TDRs to enable temperature correction of the data. TDRs and thermistors were connected to dataloggers (Figure 3b) programmed to record at 10-minute intervals. Using known soil moisture values (determined gravimetrically), calibration curves were generated in the laboratory using the underlying soil and a sandy soil similar to the bioretention media. A calibration could not be performed for the RCA because it was not possible to gravimetrically measure a range of moisture content values. Therefore, temperature-corrected period data, rather than volumetric water content, is used as the response metric for the TDRs installed in the RCA layer.

TDR responses to seven storms during October 2009 were analyzed for four parameters: 1) maximum response amplitude; 2) time to maximum response (from onset of rain); 3) response time lag; and, 4) percentage return to antecedent moisture within 24 hr after rain. Rain volume and intensity were measured on-site.

Bench- and Pilot-Scale Results

TDRs detected the passage of the wetting front under both saturated and unsaturated flow conditions in RCA (Figures 4 and 5). TDRs within the PVC housing successfully measured drainage properties under saturated conditions (Figure 4). Configuration of the PVC pipe was significant; sensors housed within a 6" diameter pipe with holes and end caps produced a response most similar to the control (unhoused) sensor. However, the sensors housed in PVC pipes did not produce a similar response to the unhoused sensors under unsaturated flow conditions (Figure 5). Accordingly, sensors were not housed in PVC when installed in the full-scale parking lot.

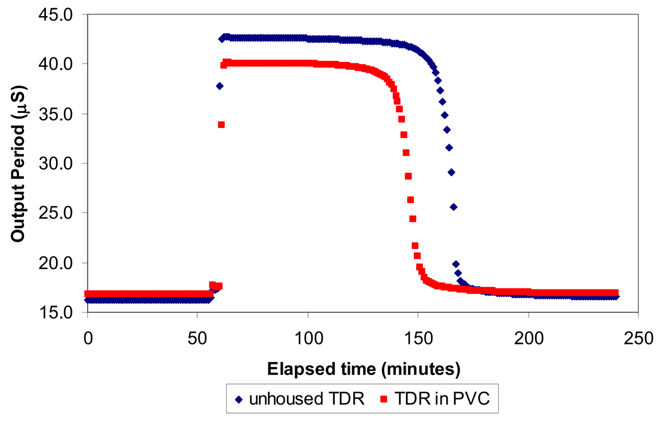

Figure 4. Representative hydrograph from 2/23/09 test of TDRs in 1" diameter recycled concrete aggregate under saturated flow conditions.

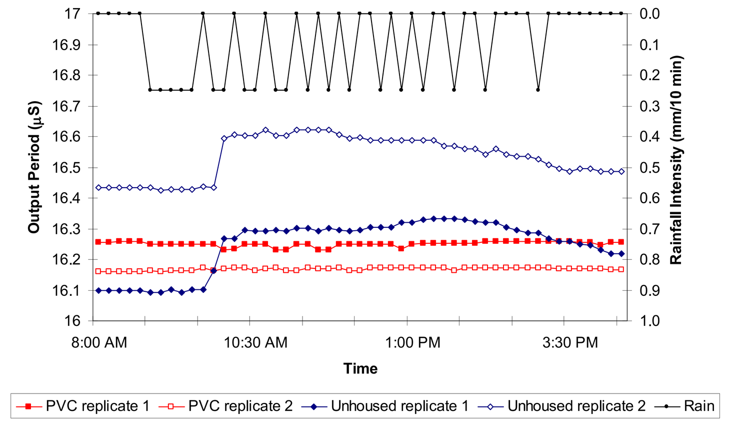

Figure 5. Representative hydrograph from 3/9/09 test of TDRs in 1" diameter recycled concrete aggregate under unsaturated flow conditions.

Full-Scale Results

The TDRs installed in urban fill soil, engineered bioretention media, and RCA have all successfully documented the passage of the wetting front produced by both direct precipitation and stormwater runoff from impervious surfaces. Figure 6 shows the correspondence between rain events and the responses in both the RCA layer and the underlying soil.

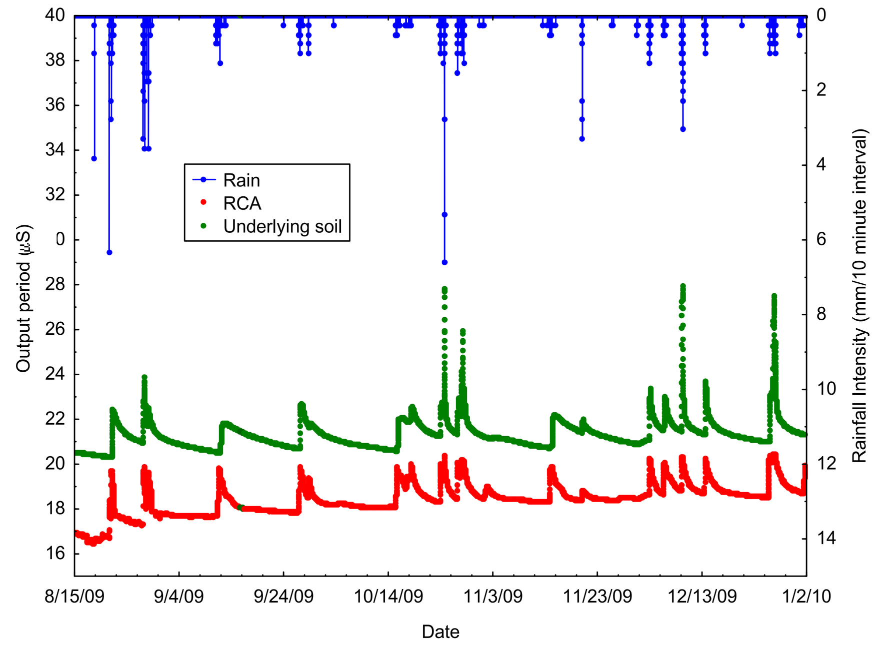

Figure 6. Responses of RCA and underlying soil TDRs (as temperature-corrected signal period) to rain events during a three-month period in the parking lot.

Responses cluster according to media type in multivariate space when the four parameters generated from the TDR data were analyzed using principal components analysis using Statistica Version 9 (Figure 7).

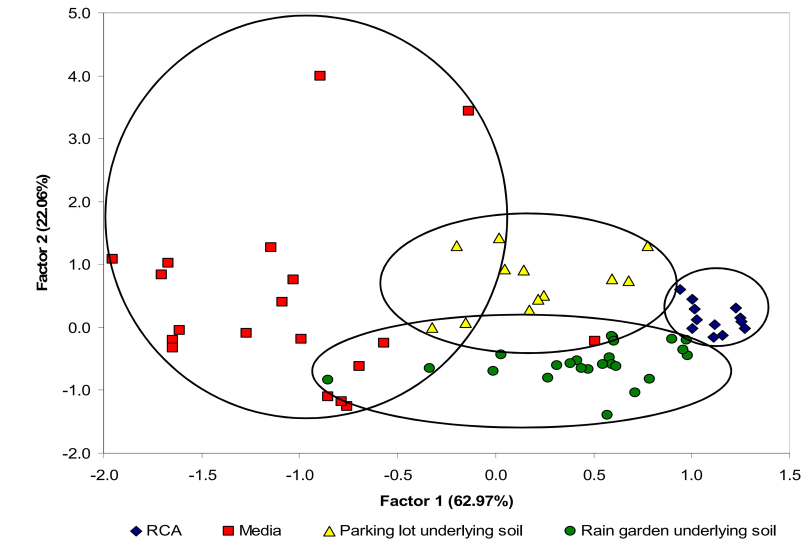

Figure 7. Results of principal components analysis of the four parameters generated from the TDR data in the parking lot and the rain gardens.

Media types separated mainly along the Factor 1 axis, indicating media types differed in time lags, time to maximum response, and percentage return to antecedent moisture condition. The underlying soil separated on Factor 2 axis, reflecting variations in maximum amplitude response to rain events between the rain garden and parking lot locations.

Conclusions and Future Directions

Initial results indicate that TDRs are capable of quantifying the magnitude and timing of the wetting front in aggregate, urban fill soil, and engineered media. Data will continue to be collected with the current embedded configuration of TDRs and thermistors in the parking lots and rain gardens to assess performance of these stormwater LID controls over the next decade. This long-term study will assess both instrumented measurements and more traditional water quantity and quality constituents. The service lifetime of these devices is therefore a potential outcome of this monitoring effort. Additional bench- and pilot-scale tests may be performed on the TDRs and thermistors to further quantify and assess the applicability of this technology in non-soil or atypical media applications.

For Further Information

Rowe, A.A., Borst, M., O'Connor, T.P., Stander, E.K. (in press). Conference proceedings of ASCE/EWRI 2010 International Low Impact Development Conference, San Francisco, CA.

Parking lot opening news release:
http://yosemite.epa.gov/OPA/ADMPRESS.NSF/0/61B216A56EA5E4AC8525765D0056A5A7

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