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Technical Note

Berm Method for Quantification of Infiltration at the Plot Scale in High Conductivity Soils

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Abstract

Measuring infiltration at the plot scale is difficult, especially for high hydraulic conductivity soils. At the plot scale, the infiltration rate is usually calculated by comparing surface runoff to rainfall. Direct measurement of infiltration beyond the point scale is typically limited to locations where land forming (e.g., infiltration pond) has been performed or fields with basin irrigation systems. The standard method for field measurement of point-scale infiltration is the double ring infiltrometer, which is limited in size (typically 30 cm diameter). In this research, a new method is proposed that uses a temporary berm constructed of a water-filled 15-cm diameter vinyl hose with the edges sealed to the soil using bentonite. The berm is capable of confining infiltration plot areas of various sizes (e.g., 1 × 1 and 3 × 3 m areas in this research). Water tanks with 0.8 and 4.9 m³ capacity were used to supply water to the plots by gravity flow. A constant head could be maintained within the plot using either an automatic float valve for lower infiltration rates or a manually operated gate valve for higher infiltration rates. Observation wells were installed outside the plots to monitor for water table rise and tracers that leached into the groundwater. Guidelines are provided for tank size and refilling frequency for conducting field experiments. The procedure was tested on soils ranging from silt loam to coarse gravel using 12 1 × 1 and 3 × 3 m plots at three alluvial floodplain sites. Measured infiltration rates ranged over two orders of magnitude (0.8–74 cm/h) and were typically greater than the estimated permeability of the limiting layer reported in soil surveys, suggesting the need for larger scale field measurements of infiltration rates.

Keywords: berm, gravel, high conductivity soils, infiltration, plot scale

Introduction

Physical properties of a porous media like soil tend to be highly variable in space until a representative elementary volume (REV) is reached (Brown et al. 2000). It is unknown how well point measurements of infiltration can be extrapolated to the plot or field scale. Sisson and Wierenga (1981) studied the effect of increasing the double ring infiltrometer diameter (up to 127 cm) on steady-state infiltration and reported increasing variability with smaller ring sizes. Lai and Ren (2007) also found that larger double ring infiltrometers (>80 cm) were necessary to reduce variability in measured infiltration rates. Massman (2003) observed that hydraulic conductivities measured with flood tests in infiltration basins were up to two orders of magnitude higher or lower than hydraulic conductivities determined from air conductivity or estimated from grain size parameters.

Measuring infiltration rates at a larger scale, however, is difficult, especially for high hydraulic conductivity soils in which large volumes of water are required. The standard method for field measurement of infiltration is a double ring infiltrometer (ASTM D3385 2009; Marshall and Stirk 1950; Angulo-Jaramillo et al. 2000), with the inner ring typically limited to a diameter of 30 cm. Approaches using rainfall-simulator infiltrometers have been proposed (Adams et al. 1957; Parr and Bertrand 1960), but typically these systems measure infiltration rates over a small area (approximately 15 cm). Haws et al. (2004) measured infiltration rates using

nested infiltrometers at different spatial scales, including 20 × 20, 60 × 60, and 100 × 100 cm² infiltrometers. Their conclusion was the need for infiltration tests at even greater spatial scales. Infiltration rate can also be indirectly calculated at the plot scale by comparing surface runoff to simulated rainfall (Fiedler et al. 2002) or inflow-outflow (Sarkar et al. 2008). Direct measurement of infiltration on a plot or field scale is typically limited to locations where an infiltration pond is constructed (Massman 2003) or in fields with basin irrigation. The objective of this research was to develop a straightforward method for directly quantifying infiltration rates at the plot scale in hydraulically conductive soils (i.e., gravelly silts, loams, and sands) potentially influenced by significant preferential flow.

Methods and Materials

Field Sites for Testing

Four infiltration tests were conducted using 1 × 1 and 3 × 3 m plots at each of three alluvial floodplain sites in the Ozark ecoregion of northeastern Oklahoma and northwestern Arkansas (Table 1). Plots included those without (control) and with gravel outcrops (outcrop). The Ozark ecoregion of Missouri, Arkansas, and Oklahoma is approximately 62,000 km² (Figure 1) and is characterized by gravel bed streams and cherty soils in the riparian floodplains (Fuchs et al. 2009; Heeren 2012). The erosion of carbonate bedrock (primarily limestone) by slightly acidic water has left a large residuum

Table 1. Infiltration Experiments at Three Alluvial Floodplain Sites in the Ozark Ecoregion

Site	Date	Plot size (m)	Treatment	Duration (h)	Infiltration rate (cm/h)
Clear Creek	4/12/11	1 × 1	Control	41	5.6
Clear Creek	4/12/11	3 × 3	Control	41	3.3
Clear Creek	7/27/11	1 × 1	Outcrop	48	1.3
Clear Creek	7/27/11	3 × 3	Outcrop	45	0.8
Pumpkin Hollow	5/4/11	1 × 1	Outcrop	32	5.3
Pumpkin Hollow	5/5/11	3 × 3	Outcrop	2.8	18
Pumpkin Hollow	6/1/11	1 × 1	Outcrop	4.3	74
Pumpkin Hollow	6/2/11	3 × 3	Control	24	6.3
Barren Fork	6/30/11	1 × 1	Outcrop ^a	22	11
Barren Fork	6/30/11	3 × 3	Outcrop ^a	22	13
Barren Fork	7/13/11	1 × 1	Control	46	6.9
Barren Fork	7/13/11	3 × 3	Control	48	3.8

a. Gravel under 0.3 to 1 m of silt loam.

Figure 1. Selected alluvial floodplain sites in the Ozark ecoregion.

of chert gravel in Ozark soils, with floodplains generally consisting of coarse chert gravel overlain by a mantle (1–300 cm) of gravelly loam or silt loam. Bulk densities of the cohesive soil range between 1.4 and 1.6 g/cm³ [Natural Resources Conservation Service (NRCS) 2012]. The alluvium is spatially heterogeneous, resulting in preferential flow pathways that are hypothesized to be ancient buried gravel bars (Heeren et al. 2010, 2011). Similar hydrogeologic conditions exist near gravel bed streams in their associated alluvial floodplains worldwide.

The Barren Fork Creek site (Figure 1, latitude: 35.90°N, longitude: 94.85°W) was immediately downstream of the Eldon Bridge USGS gauge station 07197000. With a watershed size of 845 km², the Barren Fork Creek site was a fourth-order stream with a historical median discharge of 3.6 m³ s⁻¹. The study area at the Barren Fork Creek was located on the outside of a meander bend that was being actively eroded by the stream (Midgley et al. 2012). The soils were classified as Razort gravelly loam underlain with alluvial gravel deposits. Thickness of the loam ranged from 0.5–1.0 m. Soil hydraulic studies on these soil types have shown that subtle morphological features can lead to considerable differences in soil water flow rates (Sauer and Logsdon 2002). Fuchs et al. (2009) described some of the soil and hydraulic characteristics of the Barren Fork Creek floodplain site, including estimates

of hydraulic conductivity for the gravel subsoil between 140 and 230 md⁻¹ based on falling head trench tests. Heeren et al. (2010) performed a tracer injection into a preferential flow pathway (PFP), identified as a buried gravel bar, at the Barren Fork Creek site. Local transient storage and physical non-equilibrium were observed as evidenced by the elongated tails of breakthrough curves in some observation wells because of physical heterogeneity in the aquifer materials.

The Pumpkin Hollow floodplain site was also located in the Ozark ecoregion of northeastern Oklahoma (latitude: 36.02°N, longitude: 94.81°W). A small tributary of the Illinois River, Pumpkin Hollow Creek was a first-order ephemeral stream in its upper reaches. The entire floodplain was 120–130 m across at the research site, with an estimated watershed area of 15 km². The land use at the site was pasture for cattle grazing. The Pumpkin Hollow field site was a combination of Razort gravelly loam and Elsah very gravelly loam. However, the infiltration experiments were limited to the Razort gravelly loam soils. Topsoil thickness ranged from 0–3 cm, and bulk densities of the cohesive material were in the range of 1.3–1.5 g/cm³.

The Clear Creek alluvial floodplain site was located just west of Fayetteville, AR in the Arkansas River Basin and flows into the Illinois River (Figure 1, latitude: 36.13°N, longitude: 94.24°W). The total drainage area was 199 km² for the entire watershed. Land use in the basin was 36% pasture, 34% forest, 27% urban, and 3% other. Soils were loamy and silty, deep, moderately well drained to well drained (U.S. EPA 2009), and generally contained less chert or gravel than the Barren Fork Creek or Pumpkin Hollow floodplain sites. A fourth-order stream with a flow of approximately 0.5 m³ s⁻¹ at the study site had an upstream contribution area of 101 km². The study site had Razort gravelly loam soils with pasture as the dominating land use feature.

Berm Installation, Hydraulics, and Sampling

The berm was constructed of four sections of 15 cm vinyl hose attached to four 90° elbows constructed from 15 cm steel pipe (Figure 2). Each elbow had an air vent, and one elbow had a gate valve with a garden hose fitting for water. The vinyl hoses were secured to the elbows with stainless steel hose clamps and sealed with silicone sealant. The berms were then partially filled with water to add weight, but excess pressure was avoided to ensure the vinyl hose did not separate from the elbows. A circular plot would have provided the smallest ratio of boundary length to plot area and may help reduce errors in measured infiltration rates. The berm infiltrometer method being proposed is not limited to square configurations. Actually, any configuration shape can be used as long as the shapes can be fabricated and transported to the field sites. This research used a square plot area because of the ease associated with assembling and disassembling the berms in the field. Also, it is possible to use larger-sized circular or rectangular infiltrometers. The advantages of the berm infiltrometer are that it causes less soil disturbance and is easier to assemble and disassemble in the field, such that even larger berm infiltrometers can be easily constructed (i.e., 10 × 10 m plots). Although a rainfall simulator may represent natural events more closely, the berm infiltrometer method provides more consistent control of hydrologic conditions (i.e., constant head infiltration).

The experimental plots were located on relatively level areas in an attempt to maintain uniform water depths. Larger plots required shallower slopes to ensure that the entire plot

Figure 2. (a) Profile view; (b) field installation of the berm infiltration method (image courtesy of Peter Q. Storm).

could be inundated without overflowing the berm. The limiting value of the slope depends on the diameter of the vinyl hose used in creating the plot. Microtopographic variations may impact the ability to completely inundate the plot area and create head differences associated with these variations. Water level loggers could be used to monitor head differences at various locations in the plot. The vinyl hose was placed in a shallow trench (3–5 cm) cut through the surface thatch layer to result in good contact between the soil surface and the vinyl hose and minimize lateral flow at the soil surface through the thatch layer. A thick bead of liquid bentonite was also placed on the inside and outside of the berm to create a seal between the berm and the soil.

High-density polyethylene tanks with capacities of 4.9 and 0.76 m³ were used to supply water to the 3 × 3 and the 1 × 1 m plots, respectively. The tanks were instrumented with automated water level data loggers with an accuracy of 0.5 cm (HoboWare U20, Onset Computer Corp., Cape Cod, MA) to monitor water depth (pressure) and temperature at 1-min intervals. An additional water level data logger was used to monitor the atmospheric pressure. Logger data were processed with HoboWare Pro software, which adjusted for changes in atmospheric pressure and water density. Measured tank water depth over time was used to calculate the flow rate using a volumetric rating curve.

A combination of 5.1-cm diameter PVC pipe with a manual gate valve and vinyl garden hoses with float valves were used to deliver water from the tank to the plot by gravity flow. For lower infiltration rates, one or two garden hoses fitted with float valves were sufficient to maintain a constant head in the plots. However, under higher infiltration rates, the garden hoses were not adequate to maintain a constant head. In such cases, the larger PVC pipe fitted with a fine-adjustable manual gate valve was used to control the required flow rate to the plots. When the tank was nearly empty, flow was temporarily stopped while water was added to the tank. Depth in each plot area was monitored with a water level data logger. The infiltration head varied spatially according to the surface microtopography of the plot. The maximum possible ponding depth was limited by the diameter of the vinyl hose berm.

Suction cup lysimeters were not used because of the difficulty of installation in gravelly soils, risk of creating preferential flow paths in vadose zone, and low likelihood of intercepting macropores. Because there are not currently any effective techniques for taking measurements from underneath a given plot in these gravelly soils, observation

wells were installed every 0.5–2 m around the perimeter of the plots to collect groundwater samples (Figure 2). A Geoprobe Systems drilling machine (6200 TMP, Kejr, Inc., Salina, KS), which has been found to be effective in coarse gravel soils (Heeren et al. 2011; Miller et al. 2011), was used to install the observation wells around each plot. Boreholes were sealed with liquid bentonite to avoid water leaking down the hole. Observation wells were instrumented with water level data loggers. Reference water table elevations, obtained with a water level indicator and laser level data for each well, were also calculated. Water table elevation data had an accuracy of 1 cm.

Results and Discussion

This plot infiltration method using the berm setup was found to be suitable for use in soils with high infiltration rates, even for large 3 × 3 m plots, and in soils with lower infiltration rates. Larger plot sizes may require excessively large tanks; thus, continuous pumping and dosing to inject tracers directly into the pump hose may provide a better alternative to ensure adequate mixing. Figure 3 shows the relationship between flow rate and the time to empty the tank, which can be used to aid the design of infiltration experiments. For example,

Figure 3. Relationship between expected infiltration flow rate and time to empty water tank for different size water tanks.

Figure 4. Example of measured plot water depth over time for (a) 1×1 m plot with flow controlled primarily by an automatic float valve; (b) 3×3 m plot with flow controlled primarily by a manual gate valve for the Pumpkin Hollow site.

one of the 3×3 m plots at the Pumpkin Hollow field site had a quasi-steady state infiltration rate of 6.3 cm/h , which required an average flow rate of 9.5 L/min . According to Figure 3, the tank would need to be refilled at least every 8 h for a 4.9 m^3 tank. Actual times to empty the tank after reaching a quasisteady state in the field experiments were 6.5, 6.0, and 8.0 h, which is consistent with the fact that refills were performed before the tank was completely empty.

A constant head assumption was considered valid if the water depth in the infiltration plot was within 1.5 cm of the mean depth. All experiments met this requirement. An example of measured plot water depth over time for a 1×1 m plot with flow controlled primarily by an automatic float valve and for a 3×3 m plot with flow controlled primarily by a manual gate valve for the Pumpkin Hollow site is shown in Figure 4. Water depths were within 1.5 cm of the mean depth 92 and 89% of the time for this example (Figure 4). Float valves were found to be reliable and effective, allowing the system to run automatically for several hours at a time. Manual gate valves required attentive monitoring during the experiments.

Soils were heterogeneous, even within a small area of a given floodplain. Not surprisingly, infiltration rates also varied greatly, ranging two orders of magnitude (Figure 5, Table 1). The heterogeneity also resulted in experimental durations that ranged between 2.8–48 h to ensure steady-state infiltration and measureable responses in the observation wells. Pumpkin Hollow generally had the highest infiltration rates, whereas Clear Creek had the lowest infiltration rates. Though not strong, there was a positive correlation between infiltration rate and the presence of gravel outcrops (Figure 5). The geometric mean infiltration rate for gravel outcrops (7.2 cm/h) was higher than the infiltration rate for control plots (5.0 cm/h). In fact, the two lowest infiltration rates were on gravel outcrops at the Clear Creek site. In that particular location, though there was significant gravel, higher clay content limited the water flow.

Measured infiltration rates were greater than the estimated permeability of the limiting layer reported by the U.S. NRCS for Cherokee County, Oklahoma (NRCS 2012), which ranged from 1.5–5 cm/h for the Razort gravelly loam soil (Figure 5). This difference indicates the need for larger scale field measurements of infiltration rate. For example, soil survey measurements may represent a typical soil pedon but miss gravel outcrops or large macropores that may be infrequent but have a disproportionate impact on infiltration.

Figure 5. Infiltration rates from plot scale experiments for both control and gravel outcrop locations with the expected range of infiltration rates based on the permeability of the limiting layer (NRCS 2012) shown in gray.

Conclusions

This research demonstrated an innovative method for quantifying infiltration rates in highly conductive gravelly soils at the plot scale, maintaining a constant head at least 85% of the time during experiments. The berm infiltration method allowed investigations of various plot sizes and was capable of measuring infiltration rates over a range of two orders of magnitude (0.8 – 74 cm/h). Larger plot sizes may require continuous pumping and tracer injection directly into the pump hose instead of using tanks for mixing. Measured infiltration rates were greater than the estimated permeability of the limiting layer reported in soil surveys, suggesting the need for larger scale field measurements of infiltration rates.

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