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

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Abstract. Measuring infiltration and leaching at the plot scale is difficult, especially for high hydraulic conductivity soils. Infiltration rate has been indirectly calculated at the plot scale by comparing surface runoff to rainfall. Direct measurement of infiltration and leaching beyond the point scale is typically limited to locations where land forming has been performed, e.g. infiltration ponds and fields with basin irrigation. The standard method for field measurement of infiltration is a 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 m by 1 m and 3 m by 3 m areas in this research). Water tanks (0.8 m$^3$ and 4.9 m$^3$) and gravity flow were used to supply water and tracers to the plots. A constant head was maintained within the plot automatically using float valves for lower flow rates and manually with a gate valve for higher flow rates. Observation wells were installed 0.5 m outside the plot to monitor for water table rise and tracers that leached into the groundwater. The procedure was tested on soils ranging from silt loam to coarse gravel with measured infiltration rates ranging from 5 to 70 cm/hr. Guidelines are provided for tank size and refilling frequency for field experiments. In addition,
numerical simulations were performed to estimate time of response in wells for various soil and experimental design conditions.

**Keywords.** Berm, Gravel, High conductivity soils, Infiltration, Leaching, Plot scale.
Introduction

Physical properties of porous media 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 scale up to the plot or field scale. Sisson and Wierenga (1981) considered the effect of double ring infiltrometer diameter (up to 127 cm) on steady-state infiltration, and found increasing variability with smaller ring sizes. Lai and Ren (2007) also found that larger double ring infiltrometers (>80 cm) were necessary in order to reduce variability in infiltration results. Massman (2003) found 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 and/or leaching of tracers at a larger scale, however, is difficult, especially for high hydraulic conductivity soils where large volumes of water are required. The standard method for field measurement of infiltration is a double ring infiltrometer (ASTM D3385-09), with the inner ring typically limited to a diameter of 30 cm. Infiltration rate has been indirectly calculated at the plot scale by comparing surface runoff to simulated rainfall (Fiedler et al., 2002) or run-on (Sarkar et al., 2008). Direct measurement of infiltration on a plot or field scale is typically limited to locations where land forming has been performed, e.g. infiltration ponds (Massman, 2003) and 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 high hydraulic conductivity soils. A secondary objective was to use a conservative tracer to investigate solute transport.

Materials and Methodology

Field Site for Application and Testing

Both 1 m by 1 m and 3 m by 3 m berms were tested at an alluvial floodplain site located adjacent to Pumpkin Hollow Creek in the Ozark ecoregion of northeastern Oklahoma (latitude: 36.02°, longitude: -94.81°). As a small tributary of the Illinois River, Pumpkin Hollow Creek was a first order ephemeral stream in its upper reaches. At the field site, the floodplain was 120 to 130 m across, with a watershed area of 15 km². The land use at the site was pasture for cattle. Ozark floodplains generally consist of coarse chert gravel overlain by a mantle (1 to 300 cm) of gravelly loam or silt loam (Heeren et al., 2011). The Pumpkin Hollow field site was a combination of Razort gravelly loam and Elsah very gravelly loam, although infiltration experiments were limited to the Razort gravelly loam soils. Topsoil thickness ranged from 0 to 3 cm, and bulk densities of the cohesive material were in the range of 1.4 to 1.6 g/cm³.

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 1). 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 did not separate from the elbows.

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 could be inundated without overflowing the berm. The vinyl hose was placed in a shallow trench (3 to 5 cm) cut through the surface thatch layer to minimize lateral flow at the surface. 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.

Figure 1. Berm infiltration method, including vinyl berms to contain water-tracer solution and observation wells for collecting groundwater samples: design (left) and implementation at the Pumpkin Hollow floodplain site in eastern Oklahoma (right).

High-density polyethylene tanks, 4.9 and 0.76 m³, were used for the 3 m by 3 m and the 1 m by 1 m plots, respectively, to mix water and a potassium chloride tracer. 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 one minute intervals. An additional water level data logger was used to monitor atmospheric pressure. Logger data were processed with HoboWare Pro software, which adjusted for changes in atmospheric pressure and water density. Tank water depth over time was used to calculate flow rate with a volumetric rating curve.

A combination of 5.1 cm diameter Polyvinyl chloride (PVC) pipe with a manual gate valve and vinyl garden hoses with float valves were used to deliver gravity fed water from the tanks to the plots. For low flow rates, one to two garden hoses with float valves were sufficient. When higher flow rates were required to achieve the desired constant head, flow was dominated by the larger PVC pipe and the garden hoses with float valves were relatively ineffective. For these cases a fine-adjustment gate valve was required to manually control the flow rate to achieve a relatively constant head in the plots. When a tank was nearly empty, flow was temporarily stopped while water and tracer was added to the tank. Chloride was used as a conservative tracer with injection concentrations 20 to 30 times background levels. Depth in each plot area was monitored with a water level data logger. Heads were limited by the diameter of the berm and varied spatially according to the topography within the plot.

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 four to twelve 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 then calculated. Water table elevation data had an accuracy of 1 cm.
Low flow sampling with a peristaltic pump was used to collect water samples from the top of the water table, which ranged from 50 to 150 cm below ground surface. Both well and plot water samples were collected and tested for chloride concentration with ion chromatography which had a minimum detection limit of 0.16 mg/L.

**Finite Element Modeling**

Porous media flow from hypothetical 1 m by 1 m infiltration plots were simulated using HYDRUS-3D (Šimůnek et al., 2006) for three different soil types: sand, loam, and silt. This method was not expected to be used on soils finer than silt. HYDRUS is a finite element model for simulating two- and three-dimensional movement of water, heat, and multiple solutes in variably saturated media (Šimůnek et al., 2006; Akay et al., 2008). The HYDRUS code numerically solves the Richards equation for saturated-unsaturated water flow (Šimůnek et al., 2006).

The finite element grid consisted of triangular prism elements spaced equally every 25 cm in the horizontal, lateral, and vertical directions. The simulation domain consisted of a 1 m by 1 m constant head infiltration plot centered within a 10 m by 10 m area with a 3-m deep soil profile (Figure 2). All cells on the surface of the simulation domain outside the infiltration plot were no-flux boundaries. A constant head boundary condition was used to simulate the infiltration plot with constant heads ranging from 2.54 to 15.24 cm. The initial water table depth was varied between simulations, which included depths of 1.0, 2.0, and 2.5 m below ground surface. Below the water table, a no flux boundary condition was specified for the shell and bottom of the simulation domain to simulate the presence of a regional groundwater system. Above the water table, the shell boundary condition was a possible seepage face (Figure 2). At the water table depth, observation nodes were added to the simulation domain located at various distances (0 to 450 cm) away from the edge of the infiltration plot.

![Figure 2. Simulation domain for HYDRUS-3D modeling of hypothetical infiltration experiments with a 1 m by 1 m infiltration plot.](image-url)
The van Genuchten-Mualem model (van Genuchten, 1980) was used to describe the water retention, \(\theta(h)\), and conductivity, \(K(h)\), functions for the assumed homogeneous soil matrix:

\[
\theta(h) = \begin{cases} 
\theta_r + \frac{\theta_s - \theta_r}{\left(1 + |zh|^{\alpha}\right)^n} & h < 0 \\
\theta_s & h \geq 0
\end{cases}
\]

(1)

\[
K(h) = K_s S_e^{\frac{1}{m}} \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2, \quad m = 1 - 1/n, \quad n > 1
\]

(2)

where \(S_e = (\theta - \theta_r)/(\theta_s - \theta_r)\) is the effective saturation; \(\alpha\) (L\(^{-1}\)), \(n\), and \(l\) are empirical parameters; \(\theta_s\) is the saturated water content (L\(^3\)L\(^{-3}\)); \(\theta_r\) is the residual water content (L\(^3\)L\(^{-3}\)); and \(K_s\) (LT\(^{-1}\)) is the saturated hydraulic conductivity. Hydraulic parameters for the sand, loam, and silt soils were acquired from the soil catalog in HYDRUS, derived from Carsel and Parrish (1988), in order to represent average values for these different textural classes (Table 1). It should be noted that these equations are designed for the soil matrix; macropores were not directly simulated. It should be noted that these equations are designed for the soil matrix; macropores were not directly simulated.

Table 1. Soil properties for the sand, loam, and silt soils simulated by HYDRUS-3D for the hypothetical 1 m by 1 m infiltration experiments. Soil properties were from the soil catalog for the textural classes in HYDRUS (Šimůnek et al., 2006).

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Residual Water Content, (\theta_r) (cm(^3) cm(^{-3}))</th>
<th>Saturated Water Content, (\theta_s) (cm(^3) cm(^{-3}))</th>
<th>(\alpha) (cm(^{-1}))</th>
<th>(n)</th>
<th>Saturated Hydraulic Conductivity, (K_s) (cm min(^{-1}))</th>
<th>Pore-Connectivity Parameter, (l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.045</td>
<td>0.430</td>
<td>0.145</td>
<td>2.68</td>
<td>0.495</td>
<td>0.5</td>
</tr>
<tr>
<td>Loam</td>
<td>0.078</td>
<td>0.430</td>
<td>0.036</td>
<td>1.56</td>
<td>0.017</td>
<td>0.5</td>
</tr>
<tr>
<td>Silt</td>
<td>0.034</td>
<td>0.460</td>
<td>0.016</td>
<td>1.37</td>
<td>0.004</td>
<td>0.5</td>
</tr>
</tbody>
</table>

HYDRUS simulations were conducted to determine the time at which a detectable water table rise, defined as 1 cm, was observed in the observation nodes. This information was used to correlate the response time in observation wells installed next to the infiltration plot relative to the soil type, head in the infiltration plot, distance the observation well was installed from the infiltration plot edge, and the water table depth.

**Results and Discussion**

Based on the two 1 m by 1 m plots and two 3 m by 3 m plots, infiltration rates ranged from 5 to 70 cm/hr, indicating considerable heterogeneity in the infiltration rates of the Pumpkin Hollow floodplain due to the occurrence of gravel outcrops. Measured infiltration rates were greater than the estimated permeability of the limiting layer reported by the U.S. Natural Resources Conservation Service (NRCS) for Cherokee County, Oklahoma (NRCS, 2012), which ranged from 1.5 to 5 cm/hr for the Razort gravelly loam soil. 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 which may be infrequent but have a disproportionate impact on infiltration.

This method was successful in quantifying high infiltration rate soils (i.e., gravels) even for large 3 m by 3 m plots, and lower infiltration rates could be easily measured. Larger plot sizes may require excessively large tanks, and thus continuous pumping and dosing to inject tracers directly into the pump hose may provide a better alternative for 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, one of the 3 m by 3 m plots had a quasi-steady state infiltration rate of 6.3 cm/hr, which required an average flow rate of 9.5 L/min. According to Figure 3, the tank would need to be refilled every 8 hr for a 4.9 m³ tank. Actual times to empty the tank after quasi-steady state was reached were 6.5, 6.0, and 8.0 hr, which is consistent with the fact that refills were performed before the tank was completely empty.

![Figure 3. Relationship between expected infiltration flow rate and time to empty water tank for different size water tanks.](image)

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 for 85 to 92 percent of the time (Figure 4). Float valves were reliable and effective, allowing the system to run automatically for several hours at a time. Manual gate valves required attentive monitoring in order to be effective.
Figure 4. Measured plot water depth over time for a 1 m by 1 m plot with flow controlled primarily by an automatic float valve (a) and for a 3 m by 3 m plot with flow controlled primarily by a manual gate valve (b). Water depths were within 1.5 cm of the mean depth 92% (left) and 89% (right) of the time, meeting the prescribed requirements for constant head infiltration.

Observed response times based on chloride detection in groundwater wells (located 0.5 m from the edge of the berm) ranged from 18 minutes (coarse gravel outcrop) to more than 32 hours. All plots had at least some wells where chloride was never detected above background levels (duration of experiments ranged from 3 to 32 hours), again indicating significant heterogeneity within the floodplain soils.

Modeled response times using HYDRUS-3D were more dependent on water table depth than distance from the plot edge. In sand and coarser soils (Figure 5), response times were predicted to be less than 200 minutes (approximately 3 hrs), even with a deep water table (250 cm) and observation wells installed as much as 4 m from the edge of the infiltration plot. For silt and finer soils, experiments would need to be conducted for multiple days when sampling from a groundwater table 200 cm below ground surface (Figure 5), unless significant macroporosity is present.

Conclusion

This research successfully demonstrated an innovative method for quantifying infiltration rates and leaching in highly conductive gravelly soils at the plot scale, maintaining a constant head at least 85% of the time during experiments. Guidelines have been provided for future infiltration experiments. The berm infiltration method allows investigations of various plot sizes and was demonstrated to be capable of measuring infiltration rates ranging from 5 to 70 cm/hr. Larger plot sizes may require continuous pumping and tracer injection directly into the pump hose instead of using tanks for mixing. Numerical modeling indicated that experimental times in homogeneous soils were more dependent on water table depth than well distance from the plot edge, especially for coarser soils. Experimental durations may be less than 200 minutes in sand and coarser soils to multiple days for silt and finer soils.
Figure 5. HYDRUS-3D predicted response times in observation wells installed next to infiltration plots as a function of soil type, head in the infiltration plot (h), distance the observation well was installed from the infiltration plot edge, and the depth to water table.

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