Impacts of Construction Activity on Bioretention Performance

Robert A. Brown[1] and William F. Hunt III, P.E., M.ASCE[2]

Abstract: Bioretention cells are incorporated as part of low impact development (LID) because of their ability to release influent runoff as exfiltration to the soil or evapotranspiration to the atmosphere. However, little care is taken as to the techniques used to excavate bioretention cells, and there is little concern as to the soil-moisture condition during excavation. Certain excavation techniques and soil-moisture conditions create higher levels of compaction which consequently reduce infiltration capacity. Two excavation techniques, the conventional "scoop" method which purposefully smears the underlying soil surface and the "rake" method which uses the teeth of an excavator's bucket to scarify the underlying soil surface, were tested. Field tests were conducted on three soil types (sand, loamy sand, and clay) under a variety of antecedent soil-moisture conditions. Multiple hydraulic conductivity, surface infiltration, and soil compaction measurements were taken for each excavated condition. In all cases, the rake method of excavation tended to yield more permeable, less compacted soils than the scoop method. The difference of infiltration and hydraulic conductivity between the two excavation techniques was statistically significant ($p<0.05$) when tests were conducted in wet soil conditions. Also, the infiltration rate at the clay site was significantly lower ($p<0.05$), and the hydraulic conductivity at the sandy site was significantly lower ($p<0.05$) when the scoop methodology was used. Based on results of the experiment and because essentially no extra cost is associated with the rake method of excavation, it is recommended over the conventional scoop method. Another recommendation is to excavate under relatively dry soil conditions. The use of the rake method under dry soil conditions is expected to increase long-term exfiltration from bioretention cells.

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Introduction

Approximately one third of the estuaries and lakes/reservoirs in the United States have been assessed as part of the National Water Quality Inventory, and 32% of these estuaries and 47% of these lakes/reservoirs were identified as impaired. The main cause of impairment was nutrients and one of the top three sources of nutrients was urban storm water runoff (U.S. EPA 2007). Regionally, two of the most productive estuaries in the United States are the Pamlico and Albemarle Sounds in North Carolina [North Carolina Division of Water Quality (NCDWQ) 1994] and the Chesapeake Bay (Chesapeake Bay Program 2008). Stringent storm water regulations have been put in place for cities and counties in the Neuse and Tar-Pamlico River basins and 20 coastal counties in North Carolina (NCDWQ 2007) and in the Chesapeake Bay watershed (Chesapeake Bay Program 2008).

To reduce the negative effects caused by urbanization and to meet the new storm water rules, strategies, such as low impact development (LID), that employ infiltration are increasingly adopted. The goal of LID is to plan and construct a site so that the hydrology and water quality mimic that of the initial undeveloped site (Davis, 2008). Bioretention is a very common LID practice which meets several design goals: hydrologic, water quality, and aesthetic.

Bioretention combines a natural and engineered system to manage storm water from developed areas. They are designed to at least treat the water quality volume of runoff. Bioretention removes runoff pollutants through adsorption, biological decomposition, filtration, and sedimentation (Davis et al. 2001). Bioretention cells also function to remove pollutant loads through runoff volume reductions due to exfiltration and evapotranspiration (Hunt et al. 2006; Li et al. 2009; Jones and Hunt 2009).

While a recent flurry of research has been conducted on bioretention cells, limited data on how construction activity impacts their performance are available. Some data are available on innovative construction techniques to improve exfiltration in storm water best management practices (BMPs). One study by Tyner et al. (2009) examined ways to improve exfiltration in permeable pavement systems in regions with clay soil. They found that exfiltration could be significantly improved when the subgrade was treated with boreholes, subsoil ripping, or trenching. Disturbing the compacted bottom layer created a significant increase in exfiltration compared to the undisturbed control plot (Tyner et al. 2009). If construction processes are optimized to promote higher exfiltration rates from the bottom layer and sides of bioretention cells, outflow volume will decrease which will consequently de-

[1]Ph.D. Candidate, Dept. of Biological and Agricultural Engineering, North Carolina State Univ., Box 7625, Raleigh, NC 27695 (corresponding author). E-mail: rabrown4@ncsu.edu

[2]Associate Professor and Extension Specialist, Dept. of Biological and Agricultural Engineering, North Carolina State Univ., Box 7625, Raleigh, NC 27695. E-mail: bill_hunt@ncsu.edu

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crease pollutant loads released to the storm drain network. More exfiltration also contributes to meeting another LID goal of maintaining predevelopment groundwater recharge to help restore stream base flow and groundwater components of the hydrologic cycle (Davis et al. 2009). However, with more exfiltration, the potential for transporting additional pollutant loads to the surrounding soil or the groundwater increases.

The potential for groundwater contamination from over infiltration has been a well noted concern (Pitt et al. 1999, 2002; Clark and Pitt 2007; Shuster et al. 2007). However, Pitt et al. (1999) and Clark and Pitt (2007) both found that for storm water, when pretreated by sedimentation which occurs in bioretention, the potential for groundwater contamination is low for metals, pesticides, and most organics. Because many states, such as North Carolina (NCDWQ 2007) require 0.6 m (2 ft) of separation between the bottom of the infiltrating practice and the seasonally high water table, the likelihood groundwater contamination is further reduced. The pollutants studied have been shown not to migrate beyond this 0.6 m (2 ft) soil depth (Kwiatkowski et al. 2007; Dierkes and Geiger 1999). Provided infiltration BMPs are sited properly, they are not expected to negatively impact groundwater (Kwiatkowski et al. 2007).

A goal of LID is to promote infiltration, thereby reducing runoff. During development, soil compaction occurs that consequently decreases infiltration rates. Compaction has an important influence on soil hydraulic properties, including soil-water retention, soil water diffusivity, and saturated and unsaturated hydraulic conductivities, which govern infiltration rates (Horton et al. 1994). Pitt et al. (2002) found that soils in urban areas usually undergo major modifications that result in increased runoff, such as compaction during construction. Additional changes that affect natural infiltration are the removal of surface soils and exposure of subsurface soils during earth moving practices. Earth moving equipment compacts the soil which decreases subsoil permeability (Gregory et al. 2006). Rainfall on exposed subsoil has also been shown to cause surface sealing in clay and sandy soils, which will decrease infiltration rates (Gimenez et al. 1992; Radcliffe et al. 1991). In order to avoid surface sealing, construction should be sequenced to avoid rainfall on the exposed cut.

Gregory et al. (2006) examined the effects of compaction on infiltration rates at urban construction sites in North Central Florida by using a double-ring infiltrometer. Infiltration was measured in noncompacted and compacted soils from three land types—natural forest, planted forest, and pasture. The infiltration rates had wide variability, but overall, construction activity reduced infiltration rates 70 to 99% at all sites. A cone penetrometer was used to measure soil compaction, and it showed the maximum compaction levels occurred between 20 and 30 cm (8 to 12 in.) below the soil surface. For the sandy soils in North Central Florida, this study showed that even the lowest levels of compaction resulted in significantly lower infiltration rates. In addition to significantly decreasing infiltration rates, soil compaction resulting from vehicular traffic in urban development construction significantly increased soil bulk density.

Pitt et al. (2008) showed similar results to Gregory et al. (2006): typical soil compaction considerably reduced infiltration rates. Tests on both clay and sandy soils showed that infiltration rates were significantly reduced in compacted soils, and clay soils were less able to withstand low levels of compaction compared to sandy soils. Both Gregory et al. (2006) and Pitt et al. (2008) related specific levels of compaction to infiltration rates, and they showed that using a soil cone penetrometer is a relatively reliable way to determine areas affected by compaction and therefore be expected to have decreased infiltration rates.

Fig. 1. Photos demonstrating rake method (left) versus scoop method (right) for excavation

In Pitt et al. (2008), 153 double-ring infiltration tests were run to examine the effects of infiltration in sandy versus clay, wet versus dry, and compacted versus noncompacted soils. The set point for separating wet and dry soils was a soil-moisture content of 20%. A soil was considered compacted if the cone index exceeded 2,070 kPa (300 psi) in the top 7.6 cm (3 in.). Compaction had the greatest effect on sandy soil infiltration rates but there was little effect on infiltration rate resulting from an increase in soil-water content. In clay soils, compaction and soil-moisture content both negatively affected infiltration rates. Pitt et al. (2008) found that saturated and compacted clay soils resulted in little effective infiltration, while dry, noncompact, clay soils had relatively high infiltration rates. For dry, noncompact, clay soils, the mean field infiltration rate was 24.5 cm/h ($n=18$), where the mean infiltration rate for the other three conditions of clay soils was 0.5 cm/h ($n=60$) (Pitt et al. 2008). Akram and Kemper (1979) tested the impact of compaction on varying water contents in soils. Their research showed that as water content in the soil approached field capacity, the effect of compaction resulted in maximum bulk densities and minimum infiltration rates; therefore, construction activity should be avoided in saturated soils.

The objective of this project was to examine how the construction of bioretention cells impacted the in situ soil's ability to exfiltrate storm water, thus impacting groundwater recharge. This was accomplished by testing two different excavation techniques in two major soil types (sandy and clayey) and in two soil-moisture conditions (wet and dry). The infiltration rate, saturated hydraulic conductivity, bulk density, and level of compaction for each of the eight conditions were measured. The results from these data will be used to make recommendations for excavation techniques and conditions to promote the highest levels of exfiltration from bioretention cells.

Construction Description

An expert excavator who understood the importance of using consistency in the excavation techniques for the purposes of research was contracted for this project to construct the bioretention cells. The excavation techniques were a "rake" versus a "scoop" approach. Examples of the two methods can be seen in Fig. 1. The "rake" approach used the teeth of the backhoe bucket to scarify and till the surface, where the "scoop" technique had more smearing and compaction associated with it. The "scoop" technique is consistent with sewer and utility line placement where the surface is smoothed and compacted to minimize shifting and settling. Due to the maximum compaction levels from construction activ-

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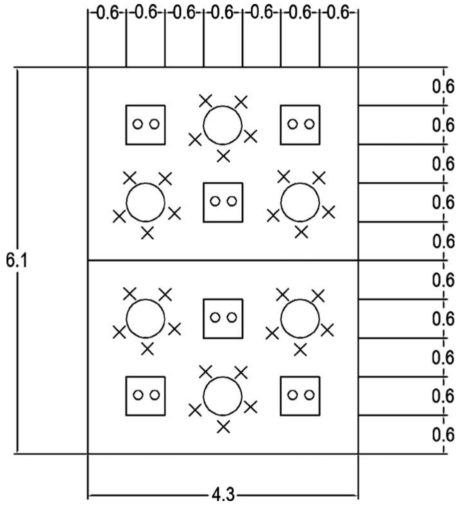

Fig. 2. Overhead schematic of the soil testing layout. Its dimensions are 4.3 m by 6.1 m (14 ft by 20 ft) with 0.6 m (2 ft) spacing between each soil test site. The plot was split in half to test for the two excavation techniques. The large circles represent infiltration test sites and the Xs represent soil compaction test sites. The small circles in the rectangular boxes indicate sites where soil cores were taken. All units are in meters.

Fig. 3. Layout of soil cores (circles) and double-ring infiltrometers (rectangles) in the field for the site that employed the scoop method. The soil texture from the rake method can be seen in the top of the photo.

ity occurring between 20 to 30 cm (8 to 12 in.) below the surface of the impacted soil layer (Gregory et al. 2006), emphasis was placed on using consistency in technique for excavating the final 30 cm (12 in.) of soil to the desired bottom depth of the bioretention cell.

The second phase studied was excavating in different soil-moisture conditions—wet soil versus dry soil. In order to test the difference of these conditions, excavation in dry soil took place after at least a week of dry, warm weather. To test for excavation in wet soil, the top layer of soil was excavated, leaving approximately 30 cm (12 in.) of soil between the surface and the proposed bottom layer of the bioretention cell. An earthen berm was built around the testing area, and it was manually irrigated overnight to saturate the soil. By removing the top layer of soil, the soil at the proposed bottom layer of the bioretention cell became saturated quicker so final excavation could proceed on the following day. This replicated finishing excavation the day after rainfall. One cell was designated as the "wet" cell and the other was designated as the "dry" cell, and each of these was divided into two roughly equal sized sections to test the different excavation techniques. The soil cores and infiltration tests were each taken at three locations in each subplot, as noted in Fig. 2. Fig. 3 displays the layout of sampling equipment in the field.

Bioretention cells were constructed in an area of clay soil, representative of the Piedmont region of North Carolina (NCSU Lake Wheeler Field Research Facility in Raleigh), and in an area of sandy soil, representative of the upper coastal plain of North Carolina (Nash County Agricultural Center in Nashville). The two cells constructed in Raleigh each received rooftop runoff from 255 m^2 (2,740 ft^2). The watershed at the Nashville site is rather large [0.7 ha (1.8 acre)] but more permeable, so only one cell was constructed. The cell was separated into two parts by an internal berm to test the effects by excavating in wet versus dry soil. North Carolina design standards recommend a fill media depth of 0.6–1.2 m (2–4 ft) and 0.76 m (30 in) is recommended for nitrogen treatment (NCDWQ 2007). Using this as guidance, a typical fill media depth of 0.6–0.9 m (2–3 ft) was used for this study to ensure the excavation depth was consistent with typical bioretention cell construction.

Monitoring Methods

Prior to construction, three soil permeability tests were run at the site of each proposed bioretention cell and at the proposed final excavation depth, 0.9 m (3 ft). Soil permeability was tested using a compact closed head permeameter, commonly referred to as an Amoozemeter. This device is used to determine permeability in an unsaturated soil. The procedure for determining soil permeability followed Amoozegar (2006). Soil cores were also taken with a soil auger to determine soil texture at the site.

After excavation was complete, field testing took place. The order of testing was as follows: (1) soil samples were collected and weighed on-site to test for gravimetric moisture content of the soil at the time of construction; (2) double-ring infiltrometers and soil cores were placed at test sites to avoid foot traffic; (3) soil was tested for compaction; and (4) infiltration tests were run and soil cores were taken. Once these tests were completed, the cells were backfilled with gravel and bioretention fill media and there was no further testing at the site. For each combination of excavation technique, soil type, and antecedent moisture condition, there were two soil samples collected for measuring gravimetric soil-moisture content; six soil cores to test for hydraulic conductivity and bulk density; three infiltration tests; and 15 soil compaction measurements.

All of the soil tests were conducted prior to backfilling the bioretention cell with gravel and sandy fill media, so the reported infiltration rates are not the final infiltration rates. The final infiltration rates are lower than the reported values because of the impact of backfilling. Despite the reduced infiltration rates, the impact is not expected to be severe enough to negate the effects of excavation technique or antecedent moisture condition found in this study. Amerson et al. (1991) examined how compaction, fines, and contact area of gravel affected infiltration. Their main conclusion was that the fines associated with gravel were a greater problem than compaction by falling gravel or the contact

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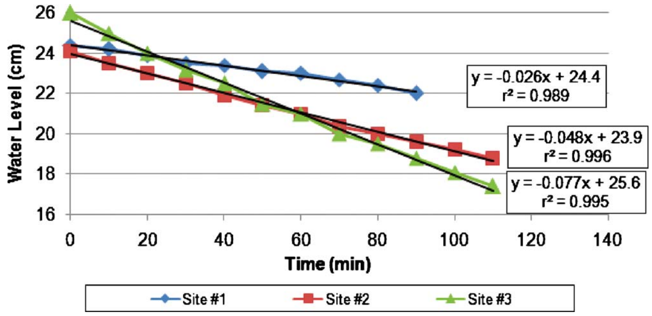

Fig. 4. Typical graph of double-ring infiltrometer inner ring depths versus time. Linear regression lines were applied to the data to determine the surface infiltration rate. Data presented are specific to the dry, scoop test plot at the Nashville site.

area effect. Since North Carolina bioretention guidelines require washed gravel, the negative impact on infiltration from backfilling should be minimized. Small and large gravel, with median particle sizes of 1 cm (0.4 in.) and 3 cm (1.2 in.), respectively, were dropped from 1.2 m (4 ft). The results showed that there was no statistical difference between measured infiltration rates from the "controlled" undisturbed soil and sites where small and large gravel were dropped (Amerson et al. 1991).

Infiltration rates were measured using double-ring infiltrometers. These rings had diameters of 30 and 61 cm (12 and 24 in.), and they were pushed 10 to 20 cm (4 to 8 in.) into the ground with care not to disturb the surface integrity. The procedure used followed a falling head test, similar to that performed by Bean et al. (2007). The double ring prevents divergent flow of water in layered soil from the middle ring by forcing water to travel in the vertical direction only (ASTM 2003). Tests were run for at least 90 min or until all of the water infiltrated, but steady state typically occurred within the first ten minutes or less. For cases when the initial infiltration was more rapid than the steady state rate, the initial couple data points were removed before calculating the least-squares line. The infiltration rates were determined by fitting the least-squares line to a plot of inner ring water depth versus time. An example of typical infiltration data are displayed in Fig. 4, as well as the linear regression line with corresponding equation and coefficient of determination (r^2). Of 24 infiltration tests, 14 had r^2 values greater than 0.98. For the four tests that had r^2 values less than 0.95, the water level drawdown was 5 mm or less in 90 to 120 min. Accuracy in reading a scale to the nearest millimeter on 10-min intervals accounts for the lower r^2 values. The drawback of the infiltrometer is that it only tests the infiltration at the surface layer, so soil cores were also taken to test for hydraulic conductivity in the laboratory. Similar to the study of Gregory et al. (2006), five cone index measurements were taken near each infiltration test site. A Spectrum Field Scout SC-900 hand cone penetrometer was used to measure compaction. This instrument did not work as well in clay soils because the range of the device was usually exceeded [greater than 6,200 kPa (900 psi)] at shallow depths.

The procedure to determine soil-moisture conditions followed ASTM D2216 (ASTM 2005), and the procedure from Klute (1986) was followed to determine saturated hydraulic conductivity. A constant head permeability test was performed on the 7.6 cm (3 in.) diameter soil cores to determine the saturated hydraulic conductivity. Afterwards, the cores were oven-dried at 110°C and weighed to determine the mass of the dry solids. Bulk density was calculated by dividing the mass of the dry solids by the known volume of the soil core. Following the tests, the soil from each set of two soil cores were mixed and particle size analysis tests were run on the mixed soil using the hydrometer method (Gee and Bauder 1986).

The pooled data set of infiltration and saturated hydraulic conductivity were not normally distributed. A Box-Cox transformation was applied to the infiltration and saturated hydraulic conductivity data, with shift parameters of 0.22 and 0.44, respectively (Box and Cox 1964). Box-Cox transformation was used because it provided the most consistent variances, and Levene's test (homogeneity of variance test) showed Box-Cox to be the best method of transformation. Once the transformed data set was normally distributed, three-factor ANOVA was run using the statistical analysis package SAS version 9.1.3. The pooled data were then separately analyzed in two categories, using two-factor ANOVA. In the first category, the data were separated by antecedent moisture condition (dry versus wet), and in the other category the data were separated by major soil type (sandy versus clayey). The impacts of the remaining two factors (excavation technique and soil type/antecedent moisture condition) were examined on infiltration and saturated hydraulic conductivity. Also, the first order interactions of the remaining two factors were analyzed to determine whether there was an effect or a constant difference across the factors.

Results

Nashville (Sandy Soil Site)

Bioretention cell construction at the Nash County Agricultural Center, in Nashville, took place from August 2–3, 2008. The weather conditions for the two days during construction were mostly sunny with high temperatures above 36°C (97°F). In Nashville, N.C., the antecedent weather conditions for the two weeks prior to construction were hot and dry. The high temperature for the previous week ranged from 34–37°C (93–98°F). The weather data were collected at a rain gauge and ambient air temperature logger, located 1 km (0.6 mi) from the construction site, which was part of another ongoing monitoring project by NCSU. In the 9 days prior to excavation, the rain gauge only recorded 0.18 cm (0.07 in.) of rainfall on July 31. No overland runoff was observed, nor expected, from this one event. Due to the lack of rainfall, it was assumed that initial construction did indeed take place under dry soil conditions.

Initial soil cores were taken at depths of 1.2 m (4 ft) deep, and they showed soils with high sand content. The results from six initial soil permeability tests, 90 cm (3 ft) below the surface in the proposed area for the bioretention cell was a mean permeability of 16.6 cm/h, with a standard deviation of 12.9. The reason for the high standard deviation was due to two of the sites having low permeability values (1.0 and 2.1 cm/h) because they had higher clay content. During excavation, it was discovered that the region with higher clay content was more prevalent than anticipated. The soil texture, as classified by the USDA was loamy sand for the dry test plot and sand for the wet test plot. These two plots were separated by 1.5 m (5 ft). The average soil particle distribution from the test soil cores for the dry and wet test plots were 84.0% sand, 1.8% silt, and 14.2% clay; 91.5% sand, 4.0% silt, and 4.6% clay, respectively.

Gravimetric soil-moisture content was measured in the loamy-sand layer and sandy layer immediately above it in the dry test plot. The average gravimetric soil-moisture content was 3.2% for

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Table 1. Results from Soil Tests for Hydraulic Conductivity (K_{Sat}), Surface Infiltration, and Dry Bulk Density for Nashville Site

		K_{Sat} (cm/h)			Infiltration (cm/h) (n=3)		Bulk density (kg/cm^3)		
Site	Type	Average	Standard deviation	n[a]	Average	Standard deviation	Average	Standard deviation	n
"Dry"/(loamy sand)	Scoop	3.98	3.58	4	3.0	1.5	1.74	0.068	4
	Rake	7.31	6.08	6	6.7	5.0	1.70	0.018	6
"Wet"/(sand)	Scoop	7.93	6.77	5	43.6	16.8	1.67	0.035	5
	Rake	21.6	7.45	6	61.9	26.5	1.61	0.035	6

[a]It was later discovered that results from two of the soil cores from the "dry-scoop" test site and one of the cores from the "wet-scoop" test site were invalid due to cracks in the cores created during collection.

the sand layer and 11.4% for the loamy-sand layer, with standard deviations of 0.7 and 1.5%, respectively. The average gravimetric soil-moisture content of the samples in the wet cell was 9.4% with standard deviation of 0.7%. According to Pitt et al. (2008), both of these sites would have been classified as dry.

The results from the field and laboratory soil tests are displayed in Table 1. For both soil types tested, infiltration and saturated hydraulic conductivity were greater when the rake method was used. This is assumed to be due to higher levels of soil compaction associated with more scoop method bucket contact which consequently had higher soil bulk density. With higher levels of compaction and larger bulk densities, water movement through the soil slows down (Horton et al. 1994).

The rake versus the scoop construction methodologies were able to be tested in two situations: (1) a dry loamy-sand soil and (2) a wet sandy soil. Hydraulic conductivity was greater by 84 and 172% for the dry and wet situations, respectively, when a rake methodology was used. Similarly, when using the rake method, the average surface infiltration rate was greater by 123 and 42% in the dry and wet situation, respectively. The cause for this improvement is partially explained by a lower bulk densities associated with the rake methodology (Table 2).

The negative relationship of hydraulic conductivity versus dry bulk density is shown in Fig. 5. Larger bulk densities associated with the soil samples from the scoop method have lower hydraulic conductivities. Plotting the residuals of hydraulic conductivity versus the residuals of bulk density and taking into account the effects of excavation technique and soil-moisture condition, there was a statistically significant negative association of hydraulic conductivity to bulk density (p-value=0.017).

Scarifying the soil by using the teeth of the bucket improved exfiltration by helping to prevent a restrictive layer from forming. A graph of the average compaction levels found in the wet cell is displayed in Fig. 6, and it is apparent from this plot that the scoop method has higher levels of compaction. The average of the five compaction levels associated with each infiltration test is displayed in Table 3. Of the 12 infiltration tests, the four test sites that would be considered compacted by Pitt et al. (2008) were among the four lowest infiltration rates.

Table 2. Changes in Performance by Using Rake Method over Scoop Method

		Average difference		
Site	Method for improvement	K_{Sat} (%)	Infiltration (%)	Bulk density (%)
"Dry"/(loamy sand)	Excavation technique-rake	84	123	−2.4
"Wet"/(sand)	Excavation technique-rake	172	42	−3.8

Raleigh (Clay Soil Site)

Bioretention cell construction at Lake Wheeler Field Labs, in Raleigh, took place from October 10–12, 2008. The weather conditions for the three days during construction were cloudy with high temperatures exceeding 21°C (70°F). In Raleigh, N.C., the antecedent weather conditions for nine days prior to construction were warm and dry. The high temperature for the previous week ranged from 20–27°C (68–81°F). The first day of construction, there were light afternoon showers, with total rainfall amounts of 0.8 mm (0.03 in.), as reported from a nearby rain

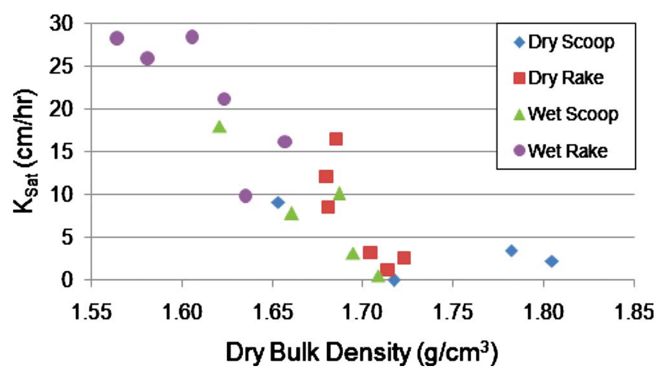

Fig. 5. Saturated hydraulic conductivity versus dry bulk density for the Nashville site.

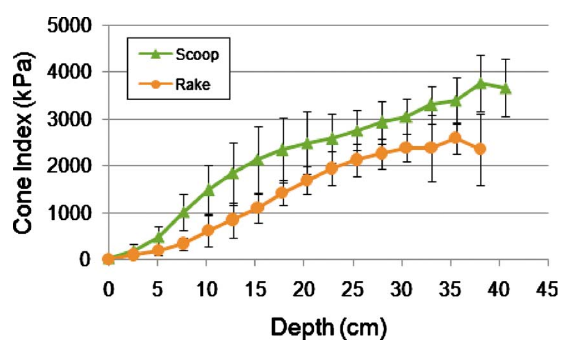

Fig. 6. Average compaction levels in the "wet" cell test plot for the scoop versus rake excavation methods at the Nashville site with error bars that represent standard deviation.

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Table 3. Average Soil Cone Index for Individual Infiltration Test Sites with Corresponding Infiltration Rates

Test plot	Test number / Depth (cm)	Average soil cone index (kPa) 2.5	7.6	15.2	22.9	30.5	40.6	Infiltration (cm/h)	High compaction[a]
Wet rake	1	130	320	1,100	2,150	2,530		83.5	
	2	90	320	850	1,690	2,300		32.4	
	3	100	420	1,400	2,010	2,390	2,600	69.9	
Wet scoop	1	150	830	1,540	2,110	3,150	4,350	38.6	
	2	200	870	2,280	2,610	2,980	3,720	62.3	
	3	270	1,380	2,610	3,040	3,050	2,910	29.8	
Dry rake	1	560	2,660	4,650	4,260	4,360		3.4	X
	2	10	230	1,250	2,990	3,280		12.5	
	3	550	3,740	5,840	6,600			4.2	X
Dry scoop	1	1,030	3,470	5,000	4,130	4,130	5,080	1.5	X
	2	340	2,080	3,280	3,690	2,870	2,720	2.9	X
	3	360	1,940	3,410	3,350	3,370	2,820	4.6	

[a]High compaction if soil cone index >2,070 kPa in top 7.6 cm (Pitt et al. 2008).

Table 4. Results from Soil Tests for Hydraulic Conductivity (K_{Sat}), Infiltration, and Dry Bulk Density for Raleigh Site

		K_{Sat} (cm/h)			Infiltration (cm/h) (n=3)		Bulk density (kg/cm^3)		
Site	Type	Average	Standard deviation	n^a	Average	Standard deviation	Average	Standard deviation	n
"Dry"/(clay)	Scoop	1.81	2.13	4	0.4	0.5	1.48	0.090	6
	Rake	2.29	2.88	6	0.8	0.5	1.63	0.075	6
"Wet"/(clay)	Scoop	0.62	0.77	5	0.2	0.1	1.37	0.103	6
	Rake	4.37	5.65	6	1.2	0.3	1.17	0.054	6

[a]It was later discovered that results from two of the soil cores from the "dry-scoop" test site and one of the cores from the "wet-scoop" test site were invalid due to cracks in the cores created during collection.

gauge monitored by the North Carolina State Climate Office—0.8 km (0.5 mi) from the construction site. The only rain event that occurred during the 2 weeks prior to construction was 1.12 cm (0.44 in.) event during the morning of October 1—9 days prior to construction. To avoid having light rain affect the soil-moisture condition of the dry cell, a plastic sheet was placed over the site of construction and the surrounding area. No overland runoff was observed nor expected from this one event. Due to the lack of rainfall, it was assumed that initial construction did indeed take place under dry soil conditions.

Soils with high clay content were found when taking initial soil cores at this site. The results from six initial soil permeability tests showed soils with very low permeability. Three tests were run at each of the future bioretention cells location and at an approximate depth of the bottom of the cell. The dry cell had an average predisturbance permeability of 0.88 cm/day with a standard deviation of 0.11 cm/day, while the wet cell had an average predisturbance permeability of 0.69 cm/day with a standard deviation of 0.72 cm/day. The magnitude of the predisturbed permeability was much less than the saturated conductivity values found after excavation. A possible explanation for the variation could be due to smearing that may have occurred while augering boreholes to test for predisturbed permeability. The variation could also be as a result of continuous macropores present in the soil cores that were taken after excavation (Bouma 1982).

The average gravimetric soil-moisture content for the dry cell was 21.8% with standard deviations of 7.6%. The average gravimetric soil-moisture content for the wet cell was 28.7% with standard deviation of 1.8%. According to Pitt et al. (2008), both of these sites would have been classified as saturated. Despite the extended dry period, the clay subsoil did not drain as fast as the sandy soil so the soil maintained higher water content.

The results from the field and laboratory soil tests are displayed in Table 4. Similar to the results from the Nashville site, infiltration and saturated hydraulic conductivity were greater when the rake method was used. This is also assumed to be due to higher levels of soil compaction associated with more scoop method bucket contact. In Table 4, the average saturated hydraulic conductivities are three to four times greater than the average infiltration rates. The discrepancy between these two measurements could be explained by the presence of macropores. When measuring saturated hydraulic conductivity in soil horizons that have continuous macropores, the impact on the range of hydraulic conductivity was up to a factor of 200 for the one soil type tested (Bouma, 1982). Infiltration tests are performed in the field, so if macropores exist, they will draw the water down fast initially, but would slow down and approach steady state once the macropores

Table 5. Changes in Performance by Varying Excavation Technique and Antecedent Moisture Condition

		Average difference		
Site	Method for improvement	K_{Sat} (%)	Infiltration (%)	Bulk density (%)
"Scoop"/(clay)	Soil-moisture condition—dry	192	79	8.0
"Wet"/(clay)	Excavation technique—rake	605	400	−14.5

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Table 6. Average Soil Cone Index for Individual Infiltration Test Sites with Corresponding Infiltration Rates

Test plot	Test number	Average soil cone index (kPa)				
	Depth (cm)	2.5	7.6	12.7	Infiltration (cm/h)	High compaction[a]
Wet rake	1	491	4,191	5,090	1.0	**X**
	2	469	3,417	4,148	1.1	**X**
	3	323	2,645	4,930	1.5	**X**
Wet scoop	1	927	3,074	4,302	0.3	**X**
	2	1,579	4,211	4,886	0.2	**X**
	3	1,227	4,602	5,619	0.2	**X**
Dry rake	1	298	3,150	4,891	1.2	**X**
	2	1,931	4,827	6,206	0.2	**X**
	3	429	3,010	5,684	0.9	**X**
Dry scoop	1	201	2,758	3,587	1.0	**X**
	2	333	3,916	4,316	0.3	**X**
	3	1,345	4,392	4,897	0.0	**X**

[a]High compaction if soil cone index >2070 kPa in top 7.6 cm (Pitt et al. 2008).

are full of water. Bouma (1982) observed a steady infiltration rate occurred after 5 min which was consistent with the measured infiltration data. Based on these results, the field measured infiltration rate would be more representative of the conditions that will control exfiltration through the bottom of the bioretention cell.

The four combinations of soil type/soil condition for the excavation technique methodologies at this site were: (1) rake method for a dry sandy-loam soil with clay subsoil; (2) scoop method for a dry clay soil; and (3) and (4) rake and scoop methods for a wet clay soil. When the rake methodology was used under wet soil conditions, hydraulic conductivity and infiltration rate were 605 and 400% greater, respectively, compared to when the scoop methodology was used. When excavation took place using the scoop methodology, hydraulic conductivity and infiltration rate were 192 and 79% greater, respectively, when excavation took place under dry conditions compared to wet conditions.

When using the rake method in the dry cell, despite higher infiltration and hydraulic conductivity, the bulk density was larger. It is assumed that this was due to lower clay content in the soil at the test site. The average soil composition for the rake and scoop method for the dry cell were 75.5% sand, 16.4% silt, and 8.0% clay; and 35.8% sand, 12.4% silt, and 51.9% clay, respectively. As classified by the USDA, the texture of the rake method was sandy loam, and the texture of the scoop method was clay. Also, the soil texture of the wet cell was clay for both excavation techniques with an average soil composition of 24.7% sand, 9.6% silt, and 65.8% clay. The average of the five compaction levels associated with each infiltration test is displayed in Table 6. All the test sites would be considered compacted by Pitt et al. (2008).

Combined Results

The data sets were pooled to test the impacts that excavation technique, antecedent moisture condition, soil type, and interactions among the three had on infiltration and saturated hydraulic conductivity. p-values for the combinations based on soil condition are presented in Table 7. Analyzing the data based on soil condition showed there is a significant impact of excavation technique on infiltration and saturated hydraulic conductivity for the wet condition (p-values=0.034 and 0.005, respectively), but there is no significant impact for the dry condition. The interaction of excavation technique and soil type is greater than 0.05 for all cases so there is a constant difference across these factors, meaning that the same type of impact is observed in both clay and sandy soils for the rake method and for the scoop method of excavation.

p-values for the combinations based on soil type are presented in Table 8. Analyzing the data based on soil type showed there is a significant impact of excavation technique on saturated hydraulic conductivity in sandy soil (p-value=0.024) and infiltration rate in clay soil (p-value=0.046), but there is no significant impact on infiltration rate in sandy soil or saturated hydraulic conductivity in clay soil. There was no effect on soil condition in the clay site but there was a significant impact on infiltration and saturated hydraulic conductivity at the sandy site. This is due to the dry cell having higher clay content. According to the USDA classification system, the soil texture of the wet and dry cells were sand and loamy sand, respectively. Finally, the interaction of excavation technique and soil condition is greater than 0.05 for all cases. This

Table 7. Effects of Soil Condition on Infiltration and Saturated Hydraulic Conductivity (p-Values)

Factor (soil condition—dry versus wet)	Excavation technique (rake versus scoop)	Excavation technique and soil type
Infiltration (dry)	0.156	0.925
K_{Sat} (dry)	0.508	0.573
Infiltration (wet)	**0.034**	0.476
K_{Sat} (wet)	**0.005**	0.623

Note: Bold denotes statistically significant relationship.

Table 8. Effects of Soil Type on Infiltration and Saturated Hydraulic Conductivity (p-Values)

Factor (soil type—clay versus sand)	Excavation technique (rake versus scoop)	Soil condition (dry versus wet)	Excavation technique and soil condition
Infiltration (clay)	**0.046**	0.521	0.600
K_{Sat} (clay)	0.173	0.952	0.202
Infiltration (sand)	0.150	**$<$0.0001**	0.844
K_{Sat} (sand)	**0.024**	**0.030**	0.222

Note: Bold denotes statistically significant relationship.

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means that the same type of impact is observed in both wet and dry soil for the rake method and for the scoop method of excavation.

The hydrological significance of excavating bioretention cells under ideal conditions is the media will be able to drawdown and fully empty in a shorter time period. The impact on performance will have the greatest effect for bioretention cells that include an internal water storage zone or for those constructed without underdrains because faster drawdown will allow for more available storage volume in the media to fully capture more events or larger portions of events. Prior to backfilling the cell with gravel and sand, the impact of using the rake method for excavation in dry loamy sand (Table 2) and in wet clay (Table 5) can allow for the infiltration rate to be two and four times greater, respectively, than when the scoop method is used. This could potentially lead to complete drawdown occurring up to two to four times faster if ideal excavation techniques and conditions are used. Li et al. (2009) and Passeport et al. (2009) showed that an internal water storage zone is capable of completely capturing events without generating outflow. For consecutive events over a short period of time, performance is reduced because the water storage zone is not completely drained (Li et al. 2009). Through use of innovative construction techniques, the water storage zone could drain faster and fully capture or capture more of the following event. Another case is for bioretention constructed without underdrains like that in Emerson and Traver (2008). The bioinfiltration traffic island was constructed by mixing the in situ soil with sand. If innovative construction techniques are used, runoff can drain from the sandy media faster and allow for availability of more storage volume in the media and create a larger driving pressure head.

Conclusions

Based on the data collected, it was determined that excavating the final 30 cm (12 in.) using the teeth on the bucket to rake the surface, instead of using the bucket to scoop and make the surface smooth, improved the soil properties that govern infiltration. The rake method scarified the bottom layer in the bioretention cell and created more pore spaces which is evidenced by a lower bulk density. This helped promote the underlying soil's ability to exfiltrate water from bioretention cells to the underlying soils. The potential for exfiltration was reduced when using the scoop method because it compacted the soils to a greater extent, as evidenced by higher bulk densities. With higher exfiltration rates, the volume of water entering the storm drain network is expected to decrease, thus reducing pollutant load.

In particular, when excavating in wet conditions, the hydraulic conductivity and infiltration rate associated with the scoop method were significantly less than that of the rake method (p-values $=0.005$ and 0.034, respectively). Under dry conditions, there was no statistical significance associated with excavation technique, but the trend showed improved infiltration and hydraulic conductivity when using the rake method. The hydraulic conductivity associated with the scoop method of excavation were significantly less at the sandy soil sites (p-value $=0.024$), and the infiltration rate associated with the scoop method of excavation was significantly less at the clay soil sites (p-value $=0.046$). Based on the results of this study and because there is no extra cost associated with the rake method, it is recommended to use the rake excavation technique in preference to the "conventional" scoop method for future bioretention or other infiltration BMP projects to decrease outflow volume and pollutant loads. The same recommendation of scarifying the soil surface with the teeth of the bucket can also be applied to the side walls of the excavated pit to promote exfiltration from the sides of bioretention cells.

For pure sand environments, because of extremely high infiltration rates and hydraulic conductivities, excavation may take place under wet or dry soil conditions. For clay to loamy sand, however, excavation during a dry soil condition is recommended. The infiltration rates were less impacted in dry soil compared to wet soil. In general, excavation should be avoided during or immediately following a rainfall event, or if a rainfall event will occur before the cell's media can be replaced. The authors encourage readers to verify that the "rake" method complies with local code.

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