Effect of Amendment Type and Incorporation Depth on Runoff from Compacted Sandy Soils

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Abstract: Increased runoff rates and volumes from urbanizing watersheds are generally attributed to increased imperviousness within the watershed. While pervious surfaces in urban areas are often credited with having little runoff contribution, soil compaction can reduce infiltration capacity, leading to increased runoff. The objective of the research reported in this paper was to evaluate the hydrologic response of potential treatments for mitigating urban soil compaction. In the lysimeter study of the research reported in this paper, two Florida soils [(1) Arredondo fine sand, and (2) Orangeburg fine sandy loam] were compacted and potential mitigating treatments were applied to evaluate runoff reduction. Treatments combined two incorporation depths [(1) 10 cm, and (2) 20 cm] with three amendment cases [(1) no amendment, (2) compost, and (3) fly ash] and were applied to both soils. A set of compacted lysimeters for each soil were designated as controls and remained compacted (no treatment) throughout the research reported in this paper for comparison with amendment type and depth treatments. Runoff volumes were collected from 19 natural and simulated events over a 5-month period. Natural rainfall events ranged in depth from 4–59 mm over 3–23 h (average intensity, 1–7 mm/h), while simulated events ranged from 50–114 mm depths over 32–61 min (average intensity, 91–124 mm/h). Bulk densities, cone index profiles, and infiltration rates were also measured on each of the 42 lysimeters. Due to greater infiltration rates and lower bulk densities, tillage with or without compost at either incorporation depth produced significantly less runoff than compacted soils (mean runoff coefficients, $p<0.005$ and 0.03–0.14 compared to 0.19 and 0.46, respectively; mean effective curve numbers, 62–71 and 40–49, compared to 87 and 75, respectively). Fly ash treatments did not significantly reduce runoff production compared to controls and increased runoff production on Arredondo soil. Based on a standard method, runoff production from control lysimeters was similar to dirt roads, while tillage treatments with or without compost produced runoff similar to vegetated open space in fair condition. These results suggest that 10-cm tillage alone may be an effective practice to substantially reduce runoff generated from shallow (20–25 cm) compacted urban soils. Future research should focus on investigating shallower tillage depths and long term runoff reductions of tillage on urban soils, as well as potential effect of tillage and amendments, on landscape plant health and performance. **DOI: 10.1061/(ASCE)IR.1943-4774.0000840.**

Introduction

Urbanization increases total impervious area (TIA) in the landscape, by including streets, sidewalks, parking lots, driveways, and buildings. Runoff from impervious surfaces increases peak flow rates, time to peak, and runoff volumes compared to undeveloped land uses, resulting in overland erosion and stream bank instability [National Research Council (NRC) 2008]. Urban runoff also transports pollutants, such as sediments, nutrients, heavy metals, and pathogens into surface waters (Barrett et al. 1998; Davis et al. 2001; Lee and Bang 2000).

Increased TIA physically, biologically, and chemically adversely affects surface waters (Paul and Meyer 2001; O'Driscoll et al. 2010). Increased runoff volumes, rates, pollutant loadings, and decreased times to peak depend upon impervious area, specifically directly connected impervious areas (Booth et al. 2002; Lee and Heaney 2003; Hatt et al. 2006; Livingston et al. 2006).

Soil Compaction

Pervious areas are typically assumed to produce less runoff than impervious surfaces due to their infiltration capacity. Practices such as conservation design and low impact development incorporate reduced impervious surfaces to reduce hydrologic impacts from development (U.S. EPA 2000). However, development practices can compact soils in these areas if construction traffic is not controlled (Gregory et al. 2006; Alberty et al. 1984; Pitt et al. 1999). Vehicular traffic compacts soils in three ways, as follows: (1) the normal force of the vehicle weight, (2) shear from wheel slippage, and (3) vibrations from the engine (Kozlowski 1999; Gill and Vanden Berg 1968). Traffic can compact soils up to 1-m deep, but the greatest compaction effects typically occur within the top 30 cm of soil (Kozlowski 1999). Compaction occurs by rearranging soil particles and reducing the space between soil particles at the expense of large voids (Graecen and Sands 1980). The bulk density is increased while infiltration rates, porosity, and saturated hydraulic conductivities are decreased (Gregory et al. 2006; Graecen and Sands 1980). Gregory et al. (2006) reported that soil compaction coinciding with typical development activities and vehicle traffic reduced infiltration rates, from between 23 and 65 cm/h, to between 1 and 19 cm/h, and increased bulk densities, from between 1.20 and 1.42 g/cm^3, to between 1.48 and 1.52 g/cm^3, on fine sand soils in north central Florida. Pitt et al. (1999) reported a similar decrease of

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Note. This manuscript was submitted on May 27, 2014; approved on October 13, 2014; published online on November 17, 2014. Discussion period open until April 17, 2015; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Irrigation and Drainage Engineering***, © ASCE, ISSN 0733-9437/04014074(11)/$25.00.

average infiltration rates from 41.4 to 6.4 cm/h on sandy soils in Alabama.

Compaction Reversal and Mitigation

Natural processes have the potential to reverse the effects of compaction over time. Langmaack et al. (1999) reported that root cycling and earthworms regenerated soil structure after compaction. Bartens et al. (2008) found that tree roots could improve infiltration through subsoils that were compacted to densities in excess of growth limiting bulk densities after only 12 weeks. Other physical processes, such as freezing and thawing, wetting and drying, nonuniform water absorption, and soil dehydration by root system uptake can also reduce the effects of compaction, but cannot completely eliminate the effects (Kozlowski 1999). While recovery periods for surface layers of sandy soils can be between 4 and 9 years, recovery periods for some southern U.S. soils may be greater than 60 years without freeze-thaw cycles (Kozlowski 1999; Woltemade 2010; Radford et al. 2007).

Methods for mitigating soil compaction are typically land-use specific, but preventing compaction is typically much less expensive (Kozlowski 1999). Tillage of compacted soils increases infiltration rates by decreasing the bulk density and increasing porosity (Unger and Cassel 1991). Soil amendments have previously been studied to evaluate their potential for improving soil properties; however, almost exclusively in the context of agricultural production. Use of amendments in agriculture has generally been for increasing porosity, improving infiltration, soil moisture retention, and providing crop nutrients.

Compost

Compost can be classified based on the type of parent material, product maturity, amount of foreign matter in the product, particle size and organic matter content, and concentrations of heavy metals (Chapter 62–701, Florida Administrative Code). Amending agricultural soils with compost has shown to decrease bulk densities (Landschoot and McNitt 1994; Cogger 2005), increase infiltration rates (Landschoot and McNitt, 1994; Aggelides and Londra 2000; Curtis et al. 2007), and increase water holding capacity (Pandey 2005; Loper 2009; Weindorf et al. 2006). However, compost may become a significant source for nutrients in runoff or leachate, depending on the parent material of the compost and plant uptake (Cogger 2005; Jaber et al. 2005; Gilley and Eghball 2002).

In residential settings, compost is commonly recommended as an organic fertilizer and a top dressing, with soil aeration or tillage, for addressing compaction in lawns and gardens (Shober and Denny 2013; Whiting et al. 2013). However, Cogger (2005) noted that little research has been conducted on amended soils disturbed by urban development; specifically, lawn recommendations need to be developed and research compost amendments on water relations to the urban landscape. In one such study near Seattle, Washington, Pitt et al. (1999) improved soil characteristics by incorporating compost into compacted sandy soils. Total porosity increased from 41 to 48%, bulk density decreased from 1.7 to 1.1 g/cm^3, and particle density decreased from 2.5 to 2.1 g/cm^3. Infiltration rates for composted plots were 1.5–10× greater than nonamended soils.

Fly Ash

Fly ash, a byproduct of coal burning, primarily consists of silt sized, highly insoluble aluminosilicate particles that are known as cenospheres (Khandekar et al. 1997). In the United States, fly ash is classified by the combined content of silicon dioxide, aluminum oxide, and iron oxides (ASTM 2008). Class F fly ash is noncementitious, commonly produced from coal from the eastern United States, and has at least 70% oxide content, while Class C is cementitious and has less than 70% oxide content. Fly ash particle densities vary between 2.14 and 2.48 g/cm^3 (Torrey 1978; Pathan et al. 2003).

As a waste product, its use as a soil amendment has been researched in various applications from geotechnical to agricultural. In geotechnical applications, the cohesive properties have made fly ash a suitable material for embankment construction and repair in much of the United States for the past 40 years (United States Department of Transportation 2012). Multiple researchers have noted that fly ash incorporations reduced infiltration rates of agricultural (noncompacted) soils, ranging from sand to sandy clay loam. (Kalra et al. 1998; Gangloff et al. 2000; Pathan et al. 2003). However, other studies have found that fly ash either has no influence (Adriano et al. 2001) or increased infiltration rates (Chang et al. 1977). Chang et al. (1977) reported that for silty clay and two sandy loam soils the hydraulic conductivity decreased when fly ash fractions were above 10% by volume, but for sandy loam and loam soils, hydraulic conductivities increased with fly ash additions for fractions up to 25% by volume. Researchers posited that different hydraulic conductivity responses to increasing fly ash might have resulted from soil pH effects on pozzolanic reactions, between soil and fly ash that cement soil particles. While fly ash may reduce the benefits (increased infiltration and reduced bulk density) of tillage alone, fly ash may provide additional water quality benefits (inhibiting nitrogen fixing organisms and increasing sorption of nutrients) or horticultural benefits (providing and improving availability of macronutrients and micronutrients to plants; Pandey and Singh 2010). Previous research that investigated fly ash incorporation into compacted urban soils was not found.

Objectives

The purpose of the research reported in this paper was to evaluate the mitigation potential of tillage with and without two amendments at two incorporation depths on soils representative of compacted urban soils in Florida. The objectives of the research reported in this paper were as follows:

- Evaluate the effects of tillage on compacted soil properties (soil bulk density and cone index profiles) and hydrologic response [runoff production using natural resource conservation service (NRCS) curve number (CN) analysis];
- Evaluate the effects of tillage depth (10 and 20 cm) on compacted soil bulk density, infiltration rate, and runoff production; and
- Evaluate the effects of incorporating compost and fly ash with tillage on compacted soil bulk density, infiltration rate, and runoff production.

Methods and Materials

Two soils, Arredondo fine sand (Soil A) and Orangeburg loamy fine sand (Soil O) were used in the research reported in this paper. The Arredondo soil was obtained from a site previously used for agricultural research on the University of Florida campus. The Orangeburg soil was collected from a stockpile at the North Florida Research and Education Center near Quincy, Florida. The Orangeburg soil initially contained large aggregates but these were removed by screening (openings, 7.6 × 3.8 cm).

Two soil amendments used in the research reported in this paper were (1) Black Kow composted cow manure (N-P-K, 0.5-0.5-0.5, Amendment C) and Class F fly ash (Amendment F) from Gainesville Regional Utilities' Deerhaven power plant (Gainesville, Florida). Black Kow is composted dairy cattle manure

Table 1. Summary of Properties for Soils and Amendments Included in the Research Reported in This Paper

Property	Arredondo	Orangeburg	Compost	Fly ash
Sand (%)[a]	94	61	81	23
Silt (%)	3	13	11	71
Clay (%)	3	26	8	6
Soil texture	Sand	Sandy clay loam	Loamy sand	Silty loam
Natural Resource Conservation Service hydrologic soil group	A	B	—	—
Particle density (g/cm^3)	2.41	2.56	2.26	2.10
Organic matter by loss on ignition (%)[b]	1	5	79	51
Maximum proctor density (g/cm^3)	1.77	1.77	—	—

[a]Sand, silt, and clay content determined by hydrometer (ASTM 2007a) and used to calculate soil texture.
[b]The loss on ignition is for 3 h at 550°C.

produced by the Black Gold Composting from Oxford, Florida, that is commonly available to consumers at home and garden retailers.

Soils and amendments physical properties were characterized (Table 1). Organic matter content by mass was quantified for five samples of each soil and amendment by loss on ignition (LOI; Heiri et al. 2001). Both soils and amendments were analyzed for texture by particle-size analysis (ASTM 2007a). Particle density was measured for each soil and amendment as well (Blake and Hartge 1986). While the Orangeburg texture is listed as sandy loam by NRCS (1993) soil surveys, soils analysis indicated a finer texture of sandy clay loam. Standard maximum proctor densities were also determined from samples of each soil (ASTM 2007b).

Lysimeters

The study site was located on the University of Florida campus in Gainesville, Florida. Forty-two fiberglass lysimeters, measuring $0.8 \times 0.8 \times 0.8$ m, were manufactured specifically for the research reported in this paper. Lysimeters had two 2.5-cm diameter horizontal outlets installed, one each for runoff conveyance into collection tanks and leachate collection (Fig. 1). The outlets were centered on a common side and leachate outlets were within 4.0 cm of the lysimeter bottom, while the runoff outlets were typically centered 5.0 cm below the top lip. Well screen (1.3-cm diameter, 0.025-cm slot) was installed from the inside of the drainage outlet and extended to just short of the opposite interior wall. The exterior of the drainage outlet was fitted with a 2-cm diameter ball-valve to control drainage and allow for sampling. Lysimeters were elevated (9 cm) above a cement pad by wooden footers to allow for transport by forklift during lysimeter filling and placement.

Approximately 23 cm of No. 57 (ASTM 2003a) quartz stone was laid in the bottom of each lysimeter as a drainage layer. A geotextile was installed over the drainage layer and below the soil column to minimize migration of soil particles into the drainage layer pore space. Approximately 53 cm of soil was laid over the geotextile for the soil column.

Lysimeter soils were allowed to consolidate for approximately 8 months. During this time, vegetation growth and establishment were controlled by herbicides for 3 months and by semiopaque landscape fabric for 5 months.

Data Collection Methods

Bulk density, infiltration rate, and cone penetrometer measurements were collected from each lysimeter just before compaction. Bulk density measurements (± 0.01 g/cm^3) were performed using the intact core method (Blake and Hartge 1986). Voids left behind from soil sampling for bulk density measurements were refilled and manually tamped flush with the surrounding soil surface. The infiltration rate measurement procedure was based on ASTM D3385 (ASTM 2003b) using a double ring infiltrometer (± 1 cm/h). A Mariotte siphon maintained a constant hydraulic head within the inner ring, while an equivalent water level was maintained manually using a 38-L water supply tank (Gregory et al. 2005). The replenishment rate to maintain a constant head within the inner ring equaled the vertical infiltration rate. Due to rapid infiltration rates and limited water supplies, measurements were continued until either the outer tank or Mariotte siphon water was exhausted.

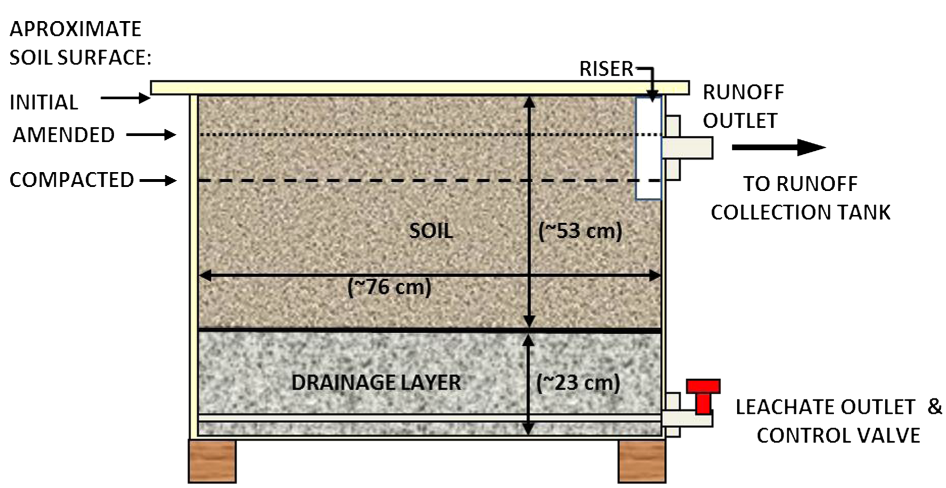

Fig. 1. Centerline, cross-sectional diagram of a lysimeter from the left side

Infiltration rates were estimated by regression of the infiltration rates and cumulative infiltration depth based on the Green-Ampt infiltration model

$$f = K[1 + (\Delta)(\theta)s/F] \quad (1)$$

where f = infiltration rate (cm/h); F = cumulative infiltration (cm); K = hydraulic conductivity in the wetting zone (cm/h); $\Delta\theta$ = change in water content (dimensionless); and s = suction parameter (cm), as per Green and Ampt (1911). The Green-Ampt model was fit to infiltration data to determine the soil hydraulic conductivity.

Three cone index profiles were collected from each lysimeter using a Field Scout SC 900 cone penetrometer (Spectrum Technologies, Plainfield, Illinois). The penetrometer measured the force applied to drive the cone tip deeper into the soil profile with a cone index range of 0–7,000 kPa (±35 kPa; Spectrum 2009). The cone penetrometer had a maximum depth of 45 cm and automatically logged the cone index at 2.5-cm intervals.

A rainfall simulator (RFS) was constructed to provide a controlled rainfall application to the lysimeters. Lysimeters were arranged in a completely randomized design. Translucent polyethylene curtains surrounded and separated each bay to prevent overspray between bays and minimize wind drift. The application rate for the RFS varied between 9.1 and 12.4 cm/h during the research reported in this paper, compared to the 10-year, 0.5-h return period depth of 5.3 cm (10.6 cm/h) for Alachua County, Florida (U.S. Weather Bureau 1961). Uniformity for the RFS was evaluated by the low quarter distribution uniformity DU_{lq} (Merriam and Keller 1978) and the coefficient of uniformity CU (Christiansen 1942). Complete uniformity is indicated by a value of 1.0 for both measurements. The DU_{lq} and CU for the RFS were 0.88 and 0.92, and compared to natural rainfall values of 0.93 and 0.95, respectively, indicating that the RFS had nearly the same uniformity as naturally occurring rainfall.

Natural rainfall and RFS event data were collected during events via a manual rain gauge and a Hobo (Onset Computing, Bourne, Massachusetts) data logging tipping bucket rain gauge with a tip resolution of 0.2 mm (Model RG3-M). Simulated rainfall events were allowed to run continuously while all runoff collection tanks had capacity remaining. Simulated events were ended once any runoff collection tank had filled nearly all its capacity to prevent over topping and loss of volume.

Hydrologic Event Analysis

Runoff from each lysimeter was diverted from the soil surface through a runoff outlet into a 38-L collection tank, equivalent to a runoff depth of approximately 6.3 cm. A measuring tape (±0.1 cm) was affixed to the external wall of the collection tank to measure runoff volumes using a calibrated depth to volume conversion equation. Runoff volumes were converted to runoff depths for hydrologic analysis. Rainfall events that produced no runoff from a lysimeter were excluded in the research reported in this paper.

Rainfall and runoff depths were used to calculate runoff coefficients

$$C_{RO} = Q/P \quad (2)$$

where C_{RO} = runoff coefficient (dimensionless); Q = event runoff depth (cm); and P = event rainfall depth (cm).

The NRCS (1986) CN method is a model for predicting runoff depths from various land uses and is commonly used for sizing stormwater control measures.

$$S = (2{,}540/\mathrm{CN}) - 25.4 \quad (3)$$

$$I_a = nS \quad (4)$$

$$Q = (P - I_a)^2/(P - I_a + S) \quad (5)$$

where I_a = initial abstraction (cm) or all losses that before runoff begins and is typically 20% ($n = 0.2$) of the potential maximum retention after runoff begins, S (cm). Curve numbers are dependent upon soil type, cover type, hydrologic condition, and antecedent runoff condition, and range from 0 to 100. Effective CNs were estimated from these data by (Hawkins 1993)

$$S = 5\left[P + 2Q - \sqrt{(4Q^2 + 5PQ)}\right] \quad (6)$$

$$CN = 2{,}540/(25.4 + S) \quad (7)$$

Statistical Analysis

Lysimeter layout was randomized at the research site with three replications for each amendment/incorporation treatment. One bulk density and effective curve number value were measured from each lysimeter. Median runoff coefficients from each lysimeter were used for statistical analyses. Median cone index values from profiles in each of the three replicate lysimeters were used to estimate profiles for each treatment.

Shapiro-Wilk tests indicated that infiltration rates of common treatments from this study were more accurately characterized by a log-normal distribution than a normal distribution. Infiltration rates have commonly been found to be log-normally distributed (Logsdon and Jaynes 1996; Kosugi 1996; Sission and Wierenga 1981). Statistical analyses of infiltration rates were performed on log-transformed infiltration rates. As a result, the expected value of a log-normal distribution is the geometric mean (GM) with a variance of the geometric standard deviation (GSD)

$$\mathrm{GM} = 10^{\sum \frac{\log(x_i)}{n}} \quad (8)$$

$$\mathrm{GSD} = 10^{\sqrt{\frac{\sum [\log(x_i) - \log(\mathrm{GM})]^2}{n-1}}} \quad (9)$$

where x = infiltration rate; and n = number of measurements.

Bulk densities, infiltration rates, runoff coefficients, and effective curve numbers were statistically analyzed using the Tukey-Kramer method for multiple pairwise comparisons. Significant differences between treatments were evaluated using the Tukey-Kramer method (SAS 2001).

Soil Compaction

A bulk density of 1.45 g/cm^3, midway between the maximum noncompacted and the minimum compacted values, was used as the Arredondo compacted threshold Gregory et al. (2006). A comparable compacted bulk density threshold for sandy clay loam soil (Orangeburg) was not found in the literature. Instead the growth limiting bulk density (GLBD; Daddow and Warrington 1983) was used as a reference for estimating a similar compacted threshold for the Orangeburg. The Arredondo compaction threshold was 81% of the GLBD for the soil texture (1.80 g/cm^3). The GLBD for the Orangeburg soil texture is 1.64 g/cm^3. Using an equivalent fraction of the GLBD, the Orangeburg compaction threshold was calculated as 1.32 g/cm^3. By comparison, compacted clay soils simulating urban compaction in Bartens et al. (2008) had bulk densities between 84 and 90% of the GLBD.

Large compaction equipment, such as plate compactors and jumping jack type compactors were considered for soil compaction, but ultimately avoided due to the spatial constraints (lysimeter surface area), uniformity concerns, and risk of structural failure to the lysimeters. Instead, soils were compacted by placing a square steel tamper on the soil surface and allowing a 5.8-kg tamper to drop approximately 1 m from the top of the handle and impact the plate. This procedure was repeated across the complete surface of each lysimeter. After each compaction iteration, bulk densities were measured for three lysimeters of each soil to determine whether the compaction threshold had been exceeded. Only three were sampled to limit cumulative soil disturbance during this phase.

For the initial compaction, the compaction procedure was applied once with dry soil conditions. For the second iteration, two compactions were applied to dry soil conditions. For the third iteration, two compactions were applied to wetted soil conditions. Prior to the fourth iteration the tamper surface area was reduced to 12.5 × 12.5 cm (one-quarter of the previous surface area) to increase the pressure applied to the soil surface. For the fourth iteration, the soil surface was soaked with water spray and two compactions were applied a wetted soil surface. After the fourth iteration, all lysimeters met their respective compaction standards. Compacted bulk densities for Arredondo lysimeters ranged from 1.50–1.59 g/cm^3 (83–88% of GLBD) and from 1.36–1.55 g/cm^3 (83–95% of GLBD) for Orangeburg lysimeters. Compacted Arredondo infiltration rates ranged from 29 to 44 cm/h while Orangeburg rates ranged from 0.3 to 14.9 cm/h. Arredondo rates were significantly ($p < 0.05$) greater than mean infiltration rates reported by Gregory et al. (2006) which ranged from 6.4–9.1 cm/h. Compacted infiltration rates for both soils (Arredondo, 28.5–44.2 cm/h; Orangeburg, 0.3–14.9 cm/h) were significantly ($p < 0.05$) less than noncompacted rates (Arredondo, 111–197 cm/h; Orangeburg, 110–318 cm/h). Cone index profiles were not measured during the compaction phase to avoid altering hydrologic responses from the lysimeters by creating preferential flow channels.

If the compaction process lowered the soil surface below a lysimeter runoff outlet invert, a new outlet was installed so that the invert was even with the compacted soil surface.

Soil Amending

Amendment treatments included all combinations of amendments [null (Amendment N), compost (Amendment C), and fly ash (Amendment F)] and incorporation depths (0, 10, and 20 cm), except for Amendments C and F at 0 cm, resulting in seven treatments. The seven treatments were applied in triplicate across the 21 lysimeters of each soil. Lysimeters for each soil were divided into three groups based on compacted bulk density values, as follows: (1) high (Arredondo, 1.56–1.59 g/cm^3; Orangeburg, 1.47–1.55 g/cm^3), (2) medium (Arredondo, 1.55–1.56 g/cm^3; Orangeburg, 1.42–1.47 g/cm^3), and (3) low (Arredondo, 1.50–1.55 g/cm^3; Orangeburg, 1.41–1.36 g/cm^3). Each treatment was applied to a lysimeter with a high, medium, and low bulk density to normalize for initial compaction variability. Three lysimeters of each soil served as controls and were not amended or tilled.

Amendments were applied at a 5-cm depth over the respective lysimeter surface areas. A Craftsman (Sears Brands, Hoffman Estates, Illinois) cultivator attached to a Craftsman trimmer four-cycle engine (Fig. 2) incorporated amendments 10 or 20 cm below the compacted soil surface. A depth gauge was attached to the cultivator during incorporation to ensure accurate incorporation depths. For 20-cm depths, the incorporation was completed in two parts due to equipment limitations. The top 10 cm of compacted soil was removed from a lysimeter and 2.5 cm of amendment was applied over the exposed soil. The amendment was then incorporated to the 20-cm incorporation depth. The removed soil and remaining 2.5 cm of amendment were returned to the lysimeter where they were incorporated together.

Fig. 2. Craftsman cultivator attached to a Craftsman trimmer four-cycle engine used to incorporate soil amendments into compacted soils

Soil amending raised the soil surface above the runoff outlet inverts for several lysimeters. Risers were installed flush with the soil surface, extending below the outlet invert along the lysimeter wall around the outlet. The risers allowed surface runoff to flow unrestricted directly into and through the runoff outlet, and into the runoff collection tanks, while limiting surface ponding.

During the amended phase, nine natural and 10 simulated events fell on the lysimeters with depths ranging from 4 to 114 mm (Table 2). Rainfall depth and runoff volumes were recorded after each event. Outlets were cleared of sediment and soil surfaces leveled as necessary to avoid depressional storage. Risers were adjusted as necessary to remain flush with the soil surface. Bulk density, infiltration rate, and cone index profile measurements were performed on each lysimeter to conclude the amendment phase.

Table 2. Rainfall Events and Depths Included in the Research Reported in This Paper

Date	Type	Depth (mm)
September 23, 2009	Simulated	114
September 30, 2009	Simulated	77
October 7, 2009	Simulated	62
October 14, 2009	Simulated	67
October 21, 2009	Simulated	55
October 28, 2009	Natural	4
November 4, 2009	Simulated	75
November 10, 2009	Natural	12
November 12, 2009	Simulated	50
November 18, 2009	Simulated	72
November 23, 2009	Simulated	70
November 25, 2009	Natural	59
December 2, 2009	Natural	15
December 5, 2009	Natural	35
December 18, 2009	Natural	5
January 1, 2010[a]	Natural	25
January 13, 2010	Simulated	72
January 17, 2010	Natural	30
January 22, 2010	Natural	19

[a]The event depth from January 1, 2010, also included the rainfall depth from December 25, 2009, since runoff collection tanks were not emptied between events.

Results and Discussion

Bulk Densities

While mean bulk densities for tillage without amendment treatments tended to be lower than the respective compacted soils, only 10-cm tillage on Orangeburg soils had significantly ($p < 0.05$) lower bulk densities (Table 3). However, incorporating either compost or fly ash with tillage at both depths on both soils significantly ($p < 0.05$) reduced bulk densities compared to compacted soils. Fly ash and compost amended mean bulk densities were less than the compacted soils by 0.28–0.44 g/cm^3 for the Arredondo soil and by 0.24–0.43 g/cm^3 for Orangeburg soils.

Tillage decreased bulk densities due to increased soil porosity, while lower density amendments also reduced bulk densities by displacing higher density soil particles. Compost treatments tended to have lower bulk densities than fly ash treatments due to the lower particle density of compost compared to fly ash. In addition, bulk densities tended to be greater when amendments were incorporated at 20 cm compared to 10 cm, distributing the same amendment quantity throughout a greater soil depth, resulting in lower overall amendment fractions.

Cone Index Profiles

Median cone index profiles are shown in Fig. 3, grouped by soil (columns) and amendments (rows). Profiles show the relative compaction with soil depth. Comparing treatments with the controls shows how effectively the compaction was mitigated for each treatment. The position of the soil surface and two incorporation depths are shown in Fig. 3 as bold lines labeled as 0, 10, and 20 cm, respectively. After amending, the 10 and 20-cm treatments lifted above the compacted soil surface by up to 5 cm.

Based on the control profiles, the maximum compaction for Arredondo soils occurred approximately 10 cm below the compacted surface and generally decreased until a depth of approximately 27.5 cm where indices reached a constant value over the remainder of the profile. For Orangeburg profiles, the maximum compaction occurred approximately 5 cm below the soil surface and decreased until a depth of approximately 22.5 cm before indices remained constant. By comparison, Gregory et al. (2006) reported that the limiting layers within compacted profiles were approximately 25 cm below the surface and Randrup and Lichter (2001) reported that compaction effects can exceed 40 cm below the soil surface. Soils below the depth of compaction influence were likely minimally affected in comparison to the noncompacted state and may have had characteristics more similar to the noncompacted of overlying soils, which would not be expected in compacted urban profiles. In addition, the maximum median cone index value for control lysimeters was 772 kPa for the Arredondo soil and 597 kPa for the Orangeburg soil. Gregory et al. (2006) reported compacted cone index maximums over 2,000 kPa and Pitt et al. (1999) used 2,100 kPa as a threshold for compaction. While surficial bulk densities were compacted, the median maximum cone index values and depth of compaction influence indicate that soil columns in the research reported in this paper were not compacted to the values reported for urban profiles.

Paired *t*-test analyses were performed between cone indices of treatment and control cone indices at common soil depths. All treatment cone indices were significantly ($p < 0.05$) less than compacted values between the compacted soil surface and the respective incorporation depths (referenced from the top of the drainage layer). Cone index profiles indicated that both 10 and 20-cm incorporation depths were below the depth of maximum compaction for both compacted soils and 20-cm incorporations on Orangeburg soils may have completely mitigated the compacted soil profile. Thus the maximum soil compaction was mitigated by tillage, which allowed subsoils to control infiltration rates. While incorporation depths partially or completely eliminated the limiting soil layer due to shallower compaction in the research reported in this paper, the same treatments may not exceed the most compacted soil layer depth on in situ compacted soil profiles that have compaction effects deeper than 20–25 cm.

Table 3. Mean Bulk Densities and Geometric Infiltration Rates for Treatment and Control Lysimeters

Amendment	Incorporation depth (cm)	Bulk density (g/cm^3) Mean		SD	Infiltration rate (cm/h) Geometric mean		Geometric SD
Arredondo							
Null	0	1.51	a[a]	0.07	24.7	bcd[a]	1.2
	10	1.35	abc	0.07	39.6	abc	1.4
	20	1.31	abcd	0.05	84.0	ab	1.4
Fly ash	10	1.13	def	0.13	4.4	ef	1.8
	20	1.23	bcde	0.02	12.7	cde	1.5
Compost	10	1.01	fg	0.05	75.7	ab	1.2
	20	1.07	efg	0.07	92.7	ab	1.1
Orangeburg							
Null	0	1.42	ab	0.07	1.6	f	2.1
	10	1.19	cdef	0.03	9.3	de	1.4
	20	1.27	bcde	0.10	94.0	a	1.3
Fly ash	10	1.07	efg	0.05	5.0	ef	2.7
	20	1.18	cdef	0.01	6.5	e	1.7
Compost	10	0.91	g	0.04	105.7	a	1.0
	20	0.99	fg	0.11	112.1	a	1.1

[a]Values with the same letter within a column are not significantly different ($p < 0.05$). Means and geometric means were analyzed using Tukey multiple pairwise comparison.

Infiltration Rates

Infiltration rates and bulk densities were expected to be closely linked based on changes in porosity and the relative distribution of pore space within the soils. Tillage with and without compost significantly ($p < 0.05$) increased geometric mean infiltration rates compared to compacted infiltration rates only on Orangeburg. This was likely due to increased pore fractions within the amended soil matrix (Table 3). Incorporating compost with tillage also increased geometric mean infiltration rates compared to compacted infiltration rates. However, only the 20-cm fly ash incorporation on Orangeburg had geometric mean infiltration rates greater than compacted soils. While previous selected research reported increased hydraulic conductivities for fly ash amendment fractions up to 25% by volume (Chang et al. 1977), amendment fractions of at least 20% in the research reported in this paper did not increase infiltration rates compared to tillage alone. On the Arredondo soil, 10-cm fly ash incorporation treatments had significantly ($p < 0.05$) lower average infiltration rates than the average compacted infiltration rates. While fly ash tended to reduce the bulk densities, the finer texture of fly ash likely reduced pore size distributions as well, compared to tillage with or without compost, resulting in reduced infiltration rates. The surface of fly ash treatments appeared to be sealed by fly ash particles based on discoloration and texture of the soil surface.

Since previous research reported that fly ash reduced infiltration rates when incorporated into agricultural soils, it was expected that

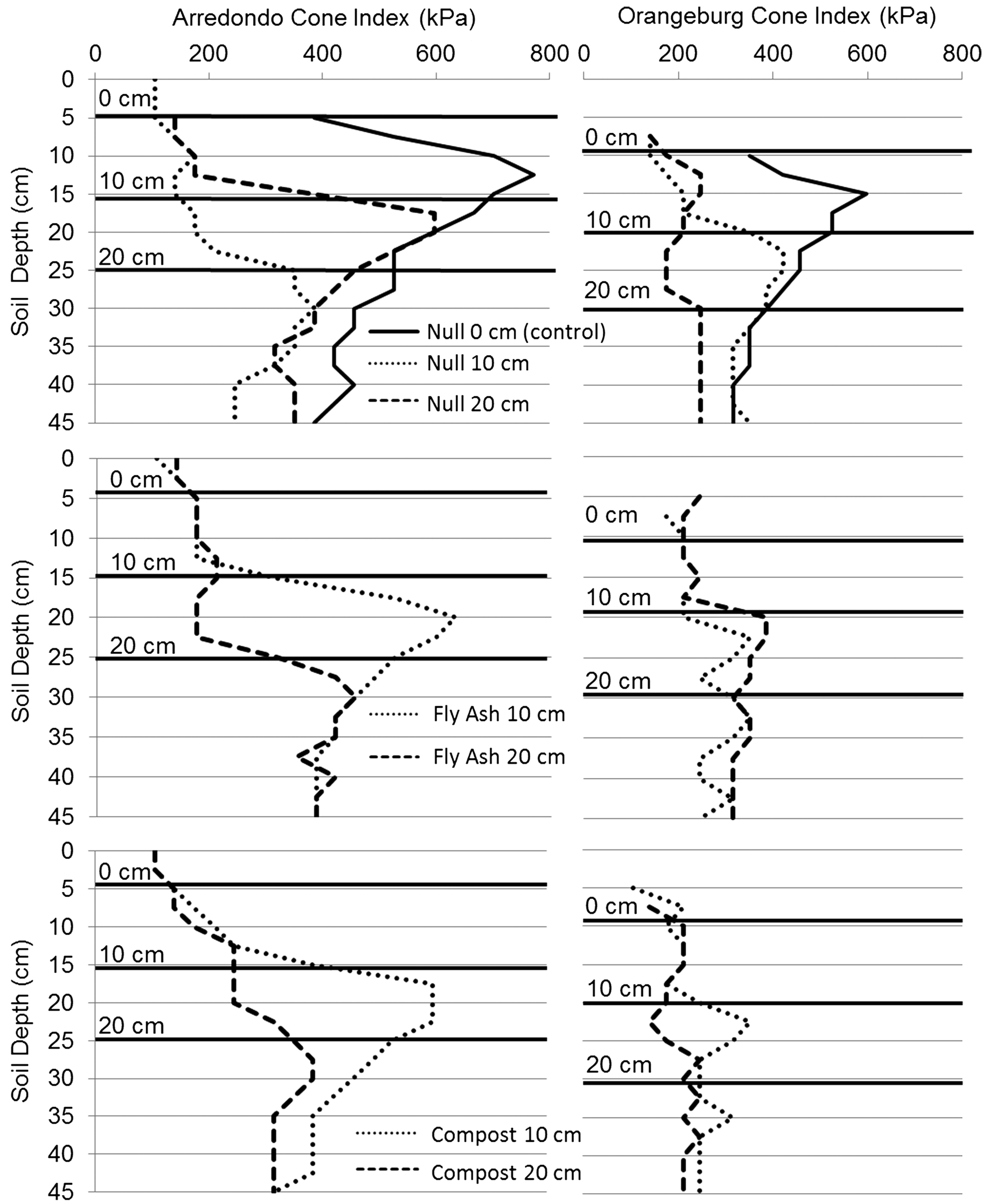

Fig. 3. Median cone index profiles for controls and treatments; soil depths are referenced to the top of the drainage layer as 45 cm; relative elevations of the respective compacted soil surface and two incorporation depths are shown and labeled on each chart

fly ash would likely produce slower infiltration rates than tillage with and without compost. However, tillage with fly ash was not expected to produce infiltration rates equal to or less the compacted infiltration rates. It can be concluded that adding fly ash sufficiently counteracted increased porosity from tillage, such that infiltration rates were unchanged or decreased.

Tillage treatments with or without compost were not expected to produce infiltration rates on the order of 100 cm/h. All noncompacted infiltration rates were greater than 109 cm/h (with a maximum of 320 cm/h). Except for fly ash, treatment infiltration rates were not limited by the amended soil matrix based on cone index profiles but rather the subsoil with any residual compaction effects. Based on the rapid infiltration rates and low cone index values, soils below the compaction layer were not likely representative of soils to be found below compacted urban soils. Therefore, infiltration rates of 100 cm/h should not be expected when applying these treatments to compacted urban soils, due to more restrictive subsoils below the amended profile. Despite this, results of the research reported in this paper show that tillage with and without compost can effectively mitigate effects of soil compaction within the depth of tillage, which is important and applicable to managing urban stormwater runoff.

Runoff Coefficients

Median runoff coefficients for lysimeter replicates within each treatment were averaged and are reported in Table 4. The compacted soils had mean median runoff coefficients of 0.19 and 0.46 for the Arredondo and Orangeburg soils, respectively.

Fly ash amended soils produced significantly ($p < 0.05$) greater runoff coefficients than all other treatments. Runoff coefficients for fly ash treatments closely reflected infiltration rates. For example, the 20-cm Arredondo incorporation tended to have slightly greater infiltration rates and lower runoff coefficients than the other fly ash

Table 4. Average Median Runoff Coefficients and Effective Curve Numbers, for Treatment and Control Lysimeters

Amendment	Incorporation depth (cm)	Median runoff coefficient Mean		Median runoff coefficient SD	Effective curve number Mean		Effective curve number SD
Arredondo							
Null	0	0.19	b[a]	0.15	75	b[a]	6
	10	<0.005	c	<0.005	49	d	8
	20	<0.005	c	0.01	44	d	1
Fly ash	10	0.53	a	0.07	91	a	3
	20	0.39	a	0.11	86	a	4
Compost	10	<0.005	c	0.01	40	d	2
	20	<0.005	c	<0.005	44	d	9
Orangeburg							
Null	0	0.46	a	0.05	87	a	2
	10	0.14	bc	0.08	71	bc	3
	20	0.03	bc	0.01	64	bc	5
Fly ash	10	0.51	a	0.08	89	a	1
	20	0.52	a	0.06	88	a	3
Compost	10	0.03	bc	0.04	62	c	5
	20	0.03	bc	0.01	62	c	3

[a]Runoff coefficients and effective curve numbers with the same letter are not significantly ($p < 0.05$) different via Tukey multiple pairwise comparison of means.

treatments, and fly ash amendments incorporated at both depths significantly increased runoff production from both compacted soils as a result of lower infiltration rates.

Adding compost to tillage did not significantly ($p < 0.05$) affect runoff coefficients compared with tillage alone at either depth for either soil. Adding compost to 10-cm tillage depth on Orangeburg soils was expected to significantly decrease runoff coefficients based on infiltration rate measurement. However, runoff coefficients were not significantly different. This suggests that another cause, in addition to increased infiltration rates, contributed to reduced runoff production. Assuming infiltration rates of soils below the incorporation depth were less than at the soil surface, infiltration would occur in two steps, as follows: (1) infiltration and storage within the tilled profile, and (2) exfiltration into the subsoil. For a given rainfall intensity, profiles with greater subsoil infiltration rates would not require soil storage, while soils with slower infiltration rates could store water in excess of the soil field capacity and allow infiltration without runoff production, assuming sufficient soil storage.

Effective Curve Numbers

Average effective CNs for each treatment are listed in Table 4. Compacted lysimeters had average effective CNs of 75 and 87 for the Arredondo and Orangeburg soils, respectively. By comparison the CNs dirt roads on hydrologic soil group (HSG) A and B soils are 72 and 82 (NRCS 1986), and thus runoff produced from the compacted lysimeters was slightly greater than would be expected from dirt roads.

Mean effective CNs for fly ash ranged from 86 to 91. Fly ash treatment means were not lower than effective CNs for compacted soils and fly ash incorporated on Arredondo soils significantly ($p < 0.05$) increased effective curve numbers over the compacted soil. These results coincide with and were attributed to equal or slower infiltration rates on fly ash amended soils compared to the compacted infiltration rates.

Tillage with and without compost for both incorporation depths significantly ($p < 0.05$) decreased the effective curve numbers compared to the compacted soils. Mean effective CNs for tillage with and without compost ranged from 40 to 49 for Arredondo soils and from 62 to 71 on Orangeburg soils. By comparison, the NRCS CN for urban vegetated open spaces, including lawns, parks, golf courses, and cemeteries, in fair condition (assuming 50–75% grass coverage) is 49 for HSG A soil and 69 for HSG B soils. Due to the scale of the research reported in this paper, these effective CNs should not be applied to large scales but are for comparison to demonstrate the potential that soil tillage could have for reducing runoff volumes.

Neither adding compost, increasing the incorporation depth, nor the combination produced significantly different effective CNs for a given soil though. However, the highest mean effective CNs among the four treatments on both soils resulted from 10-cm tillage. These results suggest that including compost with tillage or increasing incorporation depth from 10 to 20 cm would not significantly ($p < 0.05$) reduce runoff further.

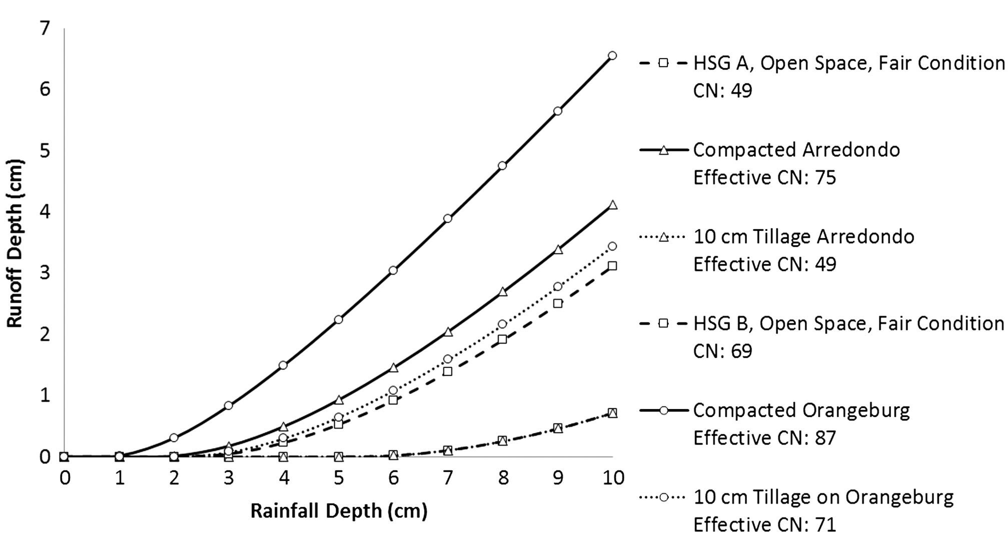

Fig. 4. Runoff depths for respective rainfall depths using the TR-55 (NRCS 1986) model for open spaces in fair conditions compared with compacted and 10-cm tillage results from the research reported in this paper

Results of the research reported in this paper suggest that significant reductions in runoff volumes could be achieved with minimal tillage and without including amendments for these two soil types. Fig. 4 shows the runoff predictions using the TR-55 NRCS (1986) methodology with CNs for fair condition open spaces on HSG A and B soils, compared with compacted and 10-cm tillage effective CNs, to demonstrate the potential differences between expected runoff production among expected open spaces, and compacted and tilled soils from the research reported in this paper. Expected runoff depths from open spaces in fair condition were more closely represented by runoff expected from 10-cm tillage treatments than from compacted soils.

Fig. 4 shows that the greatest relative reductions in runoff would be expected from 2 to 6 cm for Arredondo soils and from 1 to 3 cm events for Orangeburg soils. Based on model results, over these ranges of event depths, runoff production would be nearly eliminated compared to compacted soils. Since the frequency of events decreases with increasing depth, the frequency of runoff producing events may be expected to decrease runoff production with at least 10 cm of tillage applied to compacted soils.

Due to these reductions, tillage of compacted soils could offset the costs of conventional stormwater structures by reducing runoff volumes and basin volumes. Without considering land purchase, the costs of traditional retention basins are a power function of the basin volume [Southeastern Wisconsin Regional Planning Commission (SEWRPC) 1991] with exponents ranging from 0.51 to 0.75. Thus, reducing runoff volumes by half would reduce costs between 30 and 40% and increase the available area for land development, which could be a more valuable benefit.

Summary and Conclusions

Previous research has shown that urban soil compaction increases soil bulk densities, decreases infiltration rates, and increases runoff. While the compaction procedure in the research reported in this paper produced comparable soil bulk densities from just below the Arredondo soil surface, infiltration rates for compacted soils were greater and maximum cone indices were lower than values reported by Gregory et al. (2006) for a similar soil on actual construction sites.

The shallow (10-cm) tillage treatment produced significantly ($p < 0.05$) less runoff compared to compacted soils due to increased soil porosity, infiltration rates, and partial elimination of the most compacted soil layer. Although in situ soils have deeper compaction depths, tillage to 10-cm depth would increase infiltration rates and soil porosity at the surface, and would allow rainfall or runoff to be captured within the treated soil depth, and reducing runoff volumes. Soil water storage would subsequently be recovered by a combination of evapotranspiration and infiltration.

Increasing incorporation depths from 10 to 20 cm did not significantly reduce runoff production for rainfall events up to 114 mm. Although 20-cm tillage would increase the storage volume available above most compacted and limiting subsoils, overall runoff volumes reductions from tillage would diminish with greater incorporation depths due to decreasing frequency of larger rainfall events. Tillage depths shallower than 10 cm may be sufficient to significantly reducing runoff production from compacted soils since the greatest potential runoff production would be realized from small frequent rainfall events, rather than larger events that would exceed the available soil storage.

Class F fly ash is not recommended for use as a soil amendment to reduced runoff from coarse soils. While fly ash was expected to have lower infiltration rates and greater runoff than tilled soils based on previous research, fly ash additions were not expected to nearly eliminate the effects from tillage alone. Incorporating silt sized fly ash particles did not produce significantly less runoff than compacted soils. While fly ash treatments had significantly lower bulk densities than compacted soils, infiltration rates were not significantly increased. Similar increased infiltration rates attributed to increased pore volumes for tillage treatments likely were not duplicated due to reduced pore size distributions resulting from additions of the finer particle size distribution of fly ash. Additionally, the particle size and potential effects of incorporation on pore size distribution and infiltration rates for a potential amendment should be evaluated prior to use if concerns about these soil parameters exist.

While incorporating compost with tillage significantly reduced soil bulk densities, this did not typically translate to significantly greater infiltration rates or lower runoff production. However, compost may provide nutrients to aid establishment of vegetation, which could be a significant benefit for new construction when an organic soil is preferred for establishing vegetation. Adding vegetation such as turfgrass over amended soils would be expected to improve soil storage recovery by increasing evapotranspiration and root turnover may aid maintaining reduced runoff production. Soils with higher organic contents resist compaction better than lower organic content soils.

Acknowledgments

Financial support was provided by the Florida Department of Environmental Protection. The assistance of Christian Guzman and Lauren Coe were critical for data collection. The writers appreciate the assistance from the support staff of the University of Florida Agricultural and Biological Engineering Department, especially from Paul Lane and Danny Burch.

Notation

The following symbols are used in this paper:

C_{RO} = runoff coefficient (dimensionless);
CU = coefficient of uniformity (dimensionless);
DU_{lq} = low quarter distribution uniformity (dimensionless);
F = cumulative infiltration (cm);
f = infiltration rate (cm/h);
I_a = initial abstraction (cm);
K = hydraulic conductivity (cm/h);
n = ratio of initial abstraction to potential maximum storage after runoff begins (dimensionless);
P = event rainfall depth (cm);
Q = event runoff depth (cm);
S = potential maximum storage after runoff begins (cm);
s = suction parameter (cm); and
Θ = soil water content (dimensionless).

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