Presented at the Low Impact Development Roundtable Conference, Baltimore, MD, July 2001.

Infiltration Through Compacted Urban Soils and Effects on Biofiltration Design

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Abstract
The effects of urbanization on soil structure can be extensive. Infiltration of rain water through soils can be greatly reduced, plus the benefits of infiltration and biofiltration devices can be jeopardized. This paper is a compilation of results from several recent and on-going research projects that have examined some of these problems, plus

possible solutions. Basic infiltration measurements in disturbed urban soils were conducted during the EPA-sponsored project by Pitt, *et al* (1999b), along with examining hydraulic and water quality benefits of amending these soils with organic composts. Prior EPA-funded research examined the potential of groundwater contamination by infiltrating stormwater (Pitt, *et al*, 1994, 1996, and 1999a). In addition to the information obtained during these research projects, numerous student projects have also been conduced to examine other aspects of urban soils, especially more detailed tests examining soil density and infiltration during lab-scale tests, and methods and techniques to recover infiltration capacity of urban soils. This paper is a summary of this information and it is hoped that it will prove useful to both stormwater practice designers and to modelers.

Prior research by Pitt (1987) examined runoff losses from paved and roofed surfaces in urban areas and showed significant losses at these surfaces during the small and moderate sized events of most interest for water quality evaluations. However, Pitt and Durrans (1995) also examined runoff and pavement seepage on highway pavements and found that very little surface runoff entered typical highway pavement. During earlier research, it was also found that disturbed urban soils do not behave as indicated by most stormwater models.

In an attempt to explain the variations observed in early infiltration tests in disturbed urban soils, tests were conducted in the Birmingham, AL, area by the authors, assisted by UAB hydrology students. About 150 individual double-ring infiltration tests were conducted, separated into eight categories of soil conditions (comprising a full factorial experiment). Factors typically considered to be responsible for infiltration rate variations are texture and soil-water content. These Alabama tests examined texture and soil-water content, plus soil compaction (as measured by a cone penetrometer). It was also hoped that age since disturbance and cover condition could also be used to explain some of the variation, but poor distributions of these conditions over the complete range of the main experimental test conditions did not allow complete statistical examinations of these additional factors.

The initial exploratory analyses of the data showed that sand was mostly affected by compaction, with little change due to soil-water content levels. However, the clay sites were affected by a strong interaction of compaction and soil-water content. The variations of the observed infiltration rates in each category were relatively large, but four distinct soil conditions were found to be significant, as shown in Table 1. The data from each individual test were fitted to the Horton equation, but the resulting equation coefficients were relatively imprecise, with the noncompacted sandy soil tests being the only soil category that had obvious infiltration rate variations that were well described by time since the start of the tests. When modeling runoff from most urban soils, it may be best to assume relatively constant infiltration rates throughout an event, and to utilize Monte Carlo procedures to describe the observed random variations about the predicted mean value.

Table 1. Infiltration Rates for Significant Groupings of Soil Texture, Soil-Water Content, and Compaction Conditions

Group	Number of tests	Average infiltration rate (in/hr)	COV
noncompacted sandy soils	36	13	0.4
compact sandy soils	39	1.4	1.3
noncompacted and dry clayey soils	18	9.8	1.5
all other clayey soils (compacted and dry, plus all wetter conditions)	60	0.2	2.4

Amendments to the soil were also found to significantly improve both the infiltration capacity of the soils and to better capture pollutants from the infiltrating water, significantly reducing the potential of groundwater contamination. Some organic amendments may leach nutrients for several years, but all were found to significantly reduce the transport of toxicants.

Background

Early unpublished double-ring infiltration tests conducted by the Wisconsin DNR in Oconomowoc, WI, (shown in Table 2) indicated highly variable infiltration rates for soils that were generally sandy (NRCS A and B hydrologic group soils) and dry. The median initial rate was about 75 mm/hr (3 in/hr), but ranged from 0 to 600 mm/hr (0 to 25 in/hr). The final rates also had a median value of about 75 mm/hr (3 in/hr) after at least two hours of testing, but ranged from 0 to 400 mm/hr (0 to 15 in/hr). Many infiltration rates actually increased with time during these tests. In about 1/3 of the cases, the observed infiltration rates remained very close to zero, even for these sandy soils. Areas that experienced substantial disturbances or traffic (such as school playing fields), and siltation (such as in some grass swales) had the lowest infiltration rates. It was hoped that more detailed testing could explain some of the large variations observed.

Table 2. Ranked Oconomowoc Double Ring Infiltration Test Results (dry conditions)

Initial Rate (in/hr)	Final Rate (after 2 hours) (in/hr)	Total Observed Rate Range (in/hr)
25	15	11 to 25
22	17	17 to 24
14.7	9.4	9.4 to 17
5.8	9.4	0.2 to 9.4
5.7	9.4	5.1 to 9.6
4.7	3.6	3.1 to 6.3
4.1	6.8	2.9 to 6.8
3.1	3.3	2.4 to 3.8
2.6	2.5	1.6 to 2.6
0.3	0.1	<0.1 to 0.3
0.3	1.7	0.3 to 3.2
0.2	<0.1	<0.1 to 0.2
<0.1	0.6	<0.1 to 0.6
<0.1	<0.1	all <0.1
<0.1	<0.1	all <0.1
<0.1	<0.1	all <0.1

Source: unpublished data from the WI Dept. of Natural Resources

Infiltration Mechanisms

Infiltration of rainfall into pervious surfaces is controlled by three mechanisms, the maximum possible rate of entry of the water through the soil/plant surface, the rate of movement of the water through the vadose (unsaturated) zone, and the rate of drainage through the bottom of the vadose zone. During periods of rainfall excess, infiltration is the least of these three rates, and the runoff rate after depression storage is filled is the excess of the rainfall intensity greater than the infiltration rate. The infiltration rate typically decreases during periods of rainfall excess. Storage capacity is recovered when the drainage from the vadose zone is faster than the infiltration rate.

The surface entry rate of water may be affected by the presence of a thin layer of silts and clay particles at the surface of the soil and vegetation. These particles may cause a surface seal that would decrease a normally high infiltration rate. The movement of water through the soil depends on the characteristics of the underlying soil. Once the surface soil layer is saturated, water cannot enter soil faster than it is being transmitted away, so this transmission rate affects the infiltration rate during longer events. The depletion of available storage capacity in the soil affects the transmission and drainage rates. The storage capacity of soils depends on the soil thickness, porosity, and the soil-water content. Many factors, such as texture, root development, soil insect and animal bore holes, structure, and presence of organic matter, affect the effective porosity of the soil.

The infiltration of water into the surface soil is responsible for the largest abstraction (loss) of rainwater in natural areas. The infiltration capacity of most soils allows low intensity rainfall to totally infiltrate, unless the soil voids became saturated or the underlain soil was much more compact than the top layer (Morel-Seytoux 1978). High intensity rainfalls generate substantial runoff because the infiltration capacity at the upper soil surface is surpassed, even though the underlain soil might still be very dry.

The classical assumption is that the infiltration capacity of a soil is highest at the very beginning of a storm and decreases with time (Willeke 1966). The soil-water content of the soil, whether it was initially dry or wet from a recent storm, will have a great effect on the infiltration capacity of certain soils (Morel-Seytoux 1978). Horton (1939) is credited with defining infiltration capacity and deriving an appropriate working equation. Horton defined infiltration capacity as "...the maximum rate at which water can enter the soil at a particular point under a given set of conditions" (Morel-Seytoux 1978).

Horton Equation

One of the oldest and most widely used infiltration equations used was developed by Horton (1939). This equation was used during these studies to compare the measured equation parameters with published literature values for a commonly used infiltration method. The equation is as follows:

$$f = f_c + (f_o - f_c)e^{-kt}$$

where:

- f= infiltration capacity (in/hr),
- f_o = initial infiltration capacity (in/hr),
- f_c = final capacity (in/hr),
- k = empirical constant (hr^{-1})

This equation assumes that the rainfall intensity is greater than the infiltration capacity at all times and that the infiltration rate decreases with time (Bedient and Huber 1992). The capacity of the soil to hold additional water decreases as the time of the storm increases because the pores in the soil become saturated with water (Bedient and Huber 1992). The Horton equation's major drawback is that it does not consider the soil storage availability after varying amounts of infiltration have occurred, but only considers infiltration as a function of time (Akan 1993).

It is recommended that f_c, f_o, and k all be obtained through field data, but they are rarely measured locally. More commonly, they are determined through calibration of relatively complex stormwater drainage models (such as SWMM), or by using values published in the literature. The use of published values in place of reliable field data is the cause of much concern (Akan 1993). The following lists include commonly used Horton infiltration parameter values:

Soil Type	**f_o (in/hr)**
Dry sandy soils with little to no vegetation	5
Dry loam soils with little to no vegetation	3
Dry clay soils with little to no vegetation	1
Dry sandy soils with dense vegetation	10
Dry loam soils with dense vegetation	6
Dry clay soils with dense vegetation	2
Moist sandy soils with little to no vegetation	1.7
Moist loam soils with little to no vegetation	1
Moist clay soils with little to no vegetation	0.3
Moist sandy soils with dense vegetation	3.3
Moist loam. soils with dense vegetation	2
Moist clay soils with dense vegetation	0.7

Soil Type	**f_c (in/hr)**	**k (1/min)**
Clay loam, silty clay loams	0 to 0.05	0.069
Sandy clay loam	0.05 to 0.15	0.069
Silt loam, loam	0.15 to 0.30	0.069
Sand, loamy sand, sandy loams	0.30 to 0.45	0.069

Source: Akan 1993.

The above k values are not divided into categories; a single value is used for all conditions (Akan 1993). The k value units are listed as 1/minute instead of 1/hr because the time steps commonly used in urban hydrology are measured in minutes, even though the infiltration rates are commonly measured in units of inches per hour.

Soil Modifications to Enhance Infiltration

Turf scientists have been designing turf areas with rapid infiltration capabilities for playing fields for many years. It is thought that some of these design approaches could be used in other typical urban areas to enhance infiltration and reduce surface runoff. Several golf course and athletic field test sites were examined in Alabama during this study to document how turf areas can be constructed to enhance infiltration. These areas were designed to rapidly dry-off following a rain to minimize downtime due to excessive soil-water levels. Turf construction techniques were reviewed at three sites: an intramural playing field at the University of Alabama at Birmingham (UAB), the UAB practice football field, and a local golf course. The UAB intramural field has a simple drainage design of parallel 100 mm (4in.) wide trenches with a filter fabric wrapped pipe laid 30 cm (12 in.) deep. A thick sand backfill was used and then the area was recapped with sod. The drainage pipe was directed to the storm drainage system. The drainage for the UAB practice field was done by a local engineering firm that chose a fishbone drainage design. A trunk line of 100 mm (4 in.) corrugated pipe is the "spine" of the system with smaller 75 mm (3 in.) pipes stemming off from the main line. All the pipes rest on a gravel base with a sand backfill. This system feeds to a larger basin that collects the stormwater and takes it to the existing storm drainage system. The golf course used the same basic fishbone design noted above, but differed in the sizes of the individual pipes. The drainpipes are 3 m (10 ft.) apart in trenches filled with 75 mm (3 in.) of gravel. The pipes are then covered with 30 cm (12 in.) of sand with the top 50 mm (2 in.) of the sand consisting of a blend of sand and peat moss. This particular mixture is known as the USGA greens sand mix and is readily available because of its popularity in golf course drainage design. If the backfill sand particles are too large, clay is added to the mixture to slow the drainage. However, if the sand particles are too small, the soil will compact too tightly and will not give the desired results. In all of these cases, standing water is rare after rain has stopped, even considering the generally flat playing fields and very high rainfall intensities occurring in the Birmingham area. It is likely that similar soil construction (without subsurface drainage in most cases) could be used in high density urban areas to enhance stormwater infiltration.

Other modifications include amending the soil with other materials. A later discussion in this paper summarizes the results of tests of amended soils and the effects on infiltration and groundwater protection.

Groundwater Impacts Associated with Stormwater Infiltration

One of the major concerns of stormwater infiltration is the question of adversely impacting groundwater quality. Pitt, *et al*. (1994, 1996 and 1999a) reviewed many studies that investigated groundwater contamination from stormwater infiltration. They developed a methodology to evaluate the contamination potential of stormwater nutrients, pesticides, other organic compounds, pathogens, metals, salts and other dissolved minerals, suspended solids, and gases, based on the concentrations of the contaminant in stormwater, the treatability of the contaminant, and the mobility of the contaminant through the vadose. Stormwater salts, some pathogens, 1,3-dichlorobenzene, pyrene, fluoranthene, and zinc, were found to have high potentials for contaminating groundwater, under some conditions. They concluded that there is only minimal potential of contaminating groundwaters from residential area stormwaters (chlorides in northern areas remains a concern), especially if surface infiltration is used.

Prior to urbanization, groundwater recharge resulted from infiltration of precipitation through pervious surfaces, including grasslands and woods. This infiltrating water was relatively uncontaminated. With urbanization in humid areas, the permeable soil surface area through which recharge by infiltration could occur was reduced. This resulted in much less groundwater recharge and greatly increased surface runoff and reduced dry weather flows. In addition, the waters available for recharge generally carried increased quantities of pollutants. With urbanization, new sources of groundwater recharge also occurred, including recharge from domestic septic tanks, percolation basins and industrial waste injection wells, and from agricultural and residential irrigation. In arid areas, the groundwater recharge may actually increase with urbanization due to artificial irrigation, resulting in increase dry weather base flows.

The following paragraphs (from Pitt, *et al*. 1994 and 1996) describe the stormwater pollutants that have the greatest potential of adversely affecting groundwater quality during stormwater infiltration, along with suggestions on how to minimize these potential problems.

Relative Risks Associated with Stormwater Infiltration of Various Contaminants

Table 3 is a summary of the pollutants found in stormwater that may cause groundwater contamination problems for various reasons. This table does not consider the risk associated with using groundwater contaminated with these pollutants. Causes of concern include high mobility (low sorption potential) in the vadose zone, high abundance (high concentrations and high detection frequencies) in stormwater, and high soluble fractions (small fraction associated with particulates which would have little removal potential using conventional stormwater sedimentation controls) in the stormwater. The contamination potential is the lowest rating of the influencing factors. As an example, if no pretreatment was to be used before percolation through surface soils, the mobility and abundance criteria are most important. If a compound was mobile, but was in low abundance (such as for VOCs), then the groundwater contamination potential would be low. However, if the compound was mobile and was also in high abundance (such as for sodium chloride, in certain conditions), then the groundwater contamination would be high. If sedimentation pretreatment was to be used before infiltration, then much of the pollutants will likely be removed before infiltration. In this case, all three influencing factors (mobility, abundance in stormwater, and soluble fraction) would be considered important. As an example, chlordane would have a low contamination potential with sedimentation pretreatment, while it would have a moderate contamination potential if no pretreatment was used. In addition, if subsurface infiltration/injection was used instead of surface percolation, the compounds would most likely be more mobile, making the abundance criteria the most important, with some regard given to the filterable fraction information for operational considerations.

This table is only appropriate for initial estimates of contamination potential because of the simplifying assumptions made, such as the likely worst case mobility measures for sandy soils having low organic content. If the soil was clayey and/or had a high organic content, then most of the organic compounds would be less mobile than shown on this table. The abundance and filterable fraction information is generally applicable for warm weather stormwater runoff at residential and commercial area outfalls. The concentrations and detection frequencies (and corresponding contamination potentials) would likely be greater for critical source areas (especially vehicle service areas) and critical land uses (especially manufacturing industrial areas).

With biofiltration through amended urban soils, for example, the lowered groundwater contamination potential shown for surface infiltration with prior treatment, would generally apply. With gravel-filled infiltration trenches having no grass filtering or other pre-treatment, or with discharge in disposal wells, the greater groundwater contamination potentials shown for injection with minimal pretreatment would generally apply.

The stormwater pollutants of most concern (those that may have the greatest adverse impacts on groundwaters) include:

- nutrients: nitrate has a low to moderate groundwater contamination potential for both surface percolation and subsurface infiltration/injection practices because of its relatively low concentrations found in most stormwaters. However, if the stormwater nitrate concentration was high, then the groundwater contamination potential would also likely be high.

- pesticides: lindane and chlordane have moderate groundwater contamination potentials for surface percolation practices (with no pretreatment) and for subsurface injection (with minimal pretreatment). The groundwater contamination potentials for both of these compounds would likely be substantially reduced with adequate sedimentation pretreatment. Pesticides have been mostly found in urban runoff from residential areas, especially in dry-weather flows associated with landscaping irrigation runoff.

Table 3. Groundwater Contamination Potential for Stormwater Pollutants (Source: Pitt, *et al.* 1996)

	Compounds	Mobility (sandy/low organic soils)	Abundance in storm-water	Fraction filterable	Contamination potential for surface infilt. and no pretreatment	Contamination potential for surface infilt. with sediment-ation	Contamination potential for sub-surface inj. with minimal pretreatment
Nutrients	nitrates	mobile	low/moderate	high	low/moderate	low/moderate	low/moderate
Pesticides	2,4-D	mobile	low	likely low	low	low	low
	γ-BHC (lindane)	intermediate	moderate	likely low	moderate	low	moderate
	malathion	mobile	low	likely low	low	low	low
	atrazine	mobile	low	likely low	low	low	low
	chlordane	intermediate	moderate	very low	moderate	low	moderate
	diazinon	mobile	low	likely low	low	low	low
Other organics	VOCs	mobile	low	very high	low	low	low
	1,3-dichloro-benzene	low	high	high	low	low	high
	anthracene	intermediate	low	moderate	low	low	low
	benzo(a) anthracene	intermediate	moderate	very low	moderate	low	moderate
	bis (2-ethylhexyl) phthalate	intermediate	moderate	likely low	moderate	low?	moderate
	butyl benzyl phthalate	low	low/moderate	moderate	low	low	low/moderate
	fluoranthene	intermediate	high	high	moderate	moderate	high
	fluorene	intermediate	low	likely low	low	low	low
	naphthalene	low/inter.	low	moderate	low	low	low
	penta-chlorophenol	intermediate	moderate	likely low	moderate	low?	moderate
	phenanthrene	intermediate	moderate	very low	moderate	low	moderate
	pyrene	intermediate	high	high	moderate	moderate	high
Pathogens	enteroviruses	mobile	likely present	high	high	high	high
	Shigella	low/inter.	likely present	moderate	low/moderate	low/moderate	high
	Pseudomonas aeruginosa	low/inter.	very high	moderate	low/moderate	low/moderate	high
	protozoa	low/inter.	likely present	moderate	low/moderate	low/moderate	high
Heavy metals	nickel	low	high	low	low	low	high
	cadmium	low	low	moderate	low	low	low
	chromium	inter./very low	moderate	very low	low/moderate	low	moderate
	lead	very low	moderate	very low	low	low	moderate
	zinc	low/very low	high	high	low	low	high
Salts	chloride	mobile	seasonally high	high	high	high	high

• other organics: 1,3-dichlorobenzene may have a high groundwater contamination potential for subsurface infiltration/injection (with minimal pretreatment). However, it would likely have a lower groundwater contamination potential for most surface percolation practices because of its relatively strong sorption to vadose zone soils. Both pyrene and fluoranthene would also likely have high groundwater contamination potentials for subsurface infiltration/injection practices, but lower contamination potentials for surface percolation practices because of their more limited mobility through the unsaturated zone (vadose zone). Others (including benzo(a)anthracene, bis (2-ethylhexyl) phthalate, pentachlorophenol, and phenanthrene) may also have moderate groundwater contamination potentials, if surface percolation with no pretreatment, or subsurface injection/infiltration is used. These compounds would have low groundwater contamination potentials if surface infiltration was used with sedimentation pretreatment. Volatile organic compounds (VOCs) may also have high groundwater contamination potentials if present in the stormwater (likely for some industrial and commercial facilities and vehicle service establishments). The other organics, especially the volatiles, are mostly found in industrial areas. The phthalates are found in all areas. The PAHs are also found in runoff from all areas, but they are in higher concentrations and occur more frequently in industrial areas.

- pathogens: enteroviruses likely have a high groundwater contamination potential for all percolation practices and subsurface infiltration/injection practices, depending on their presence in stormwater (likely if contaminated with sanitary sewage). Other pathogens, including *Shigella, Pseudomonas aeruginosa*, and various protozoa, would also have high groundwater contamination potentials if subsurface infiltration/injection practices are used without disinfection. If disinfection (especially by chlorine or ozone) is used, then disinfection byproducts (such as trihalomethanes or ozonated bromides) would have high groundwater contamination potentials. Pathogens are most likely associated with sanitary sewage contamination of storm drainage systems, but several bacterial pathogens are commonly found in surface runoff in residential areas.

- heavy metals: nickel and zinc would likely have high groundwater contamination potentials if subsurface infiltration/injection was used. Chromium and lead would have moderate groundwater contamination potentials for subsurface infiltration/injection practices. All metals would likely have low groundwater contamination potentials if surface infiltration was used with sedimentation pretreatment. Zinc is mostly found in roof runoff and other areas where galvanized metal comes into contact with rainwater.

- salts: chloride would likely have a high groundwater contamination potential in northern areas where road salts are used for traffic safety, irrespective of the pretreatment, infiltration or percolation practice used. Salts are at their greatest concentrations in snowmelt and early spring runoff in northern areas.

Disturbed Urban Soil Field Infiltration Measurements

Experimental Design and Measurement Methodologies

A series of 153 double ring infiltrometer tests were conducted in disturbed urban soils in the Birmingham, and Mobile, Alabama, areas. The tests were organized in a complete 2^3 factorial design (Box, *et al*. 1978) to examine the effects of soil-water, soil texture, and soil compactness on water infiltration through historically disturbed urban soils. Turf age was also examined, but insufficient sites were found to thoroughly examine these effects. Ten sites were selected representing a variety of desired conditions (compaction and texture) and numerous tests were conducted at each test site area. Soil-water content and soil texture conditions were determined by standard laboratory soil analyses. Compaction was measured in the field using a cone penetrometer and confirmed by the site history. Soil-water levels were increased using long-duration surface irrigation before most of the saturated soil tests. From 12 to 27 replicate tests were conducted in each of the eight experimental categories in order to measure the variations within each category for comparison to the variation between the categories. The categories tested were as follows:

Category	Soil Texture	Compaction	Soil-Water Content	Number of Tests
1	Sand	Compact	Saturated	18
2	Sand	Compact	Dry	21
3	Sand	Non-compact	Saturated	24
4	Sand	Non-compact	Dry	12
5	Clay	Compact	Saturated	18
6	Clay	Compact	Dry	15
7	Clay	Non-compact	Saturated	27
8	Clay	Non-compact	Dry	18

Soil infiltration capacity was expected to be related to the time since the soil was disturbed by construction or grading operations (turf age). In most new developments, compact soils are expected to be dominant, with reduced infiltration compared to pre-construction conditions. In older areas, the soil may have recovered some of its infiltration capacity due to root structure development and from soil insects and other digging animals. Soils having a variety of times since development, ranging from current developments to those about 50 years old, were included in the sampling program. Again, because these sites were poorly distributed in their representation of the other primary test conditions, these effects were not directly determined. The WI Dept. of Natural Resources and the University of Wisconsin (Bannerman, personal communication) have conducted some soil infiltration tests on loamy soils to examine the effects of age of urbanization on soil infiltration rates. Their preliminary tests have indicated that as long as several decades may be necessary before compacted loam soils recover to conditions similar to pre-development conditions.

Infiltration Rate Measurements

The infiltration test procedure included several measurements. Before a test was performed, the compaction of the soil was measured with the DICKEY-john Soil Compaction Tester Penetrometer and a sample was obtained to analyze soil-water content. TURF-TEC Infiltrometers were used to measure the infiltration rates. These small devices have an inner ring about 64 mm (2.5 in.) in diameter and an outer ring about 110 mm (4.25 in.) in diameter. The water depth in the inner compartment starts at 125 mm (5 in.) at the beginning of the test, and the device is pushed into the ground 50 mm (2 in.). The rings are secured in a frame with a float in the inner chamber and a pointer next to a stop watch. These units are smaller than standard double-ring infiltrometers, but their ease of use allowed many tests under a wide variety of conditions to be conducted. The use of three infiltrometers placed close together also enabled better site variability to be determined than if larger units were used.

Three infiltrometers were inserted into the turf within a meter from each other to indicate the infiltration rate variability of soils in close proximity. Both the inner and outer compartments were filled with clean water by first filling the inner compartment and allowing it to overflow into the outer compartment. As soon as the measuring pointer reached the beginning of the scale, the timer was started. Readings were taken every five minutes for a duration of two hours. The incremental infiltration rates were calculated by noting the drop of water level in the inner compartment over the five minute time period.

Soil –Water Measurements

The soil-water content at each test site was an important test factor. The weather occurring during the testing enabled most site locations to produce a paired set of dry and wet tests. The dry tests were taken during periods of little rain, which typically extended for as long as two weeks with no rain and with sunny, hot days. The saturated tests were conducted after through artificial soaking of the ground, or after prolonged rain. The soil-water content was measured in the field using a portable meter (for some tests) and in the laboratory using standard soil-water content methods (for all tests). The soil-water content, as defined by Das (1994), is the ratio of the weight of water to the weight of solids in a given volume of soil. This was obtained by weighing the soil sample with its natural water content and recording the mass. The sample was then oven dried and its dry weight recorded. Saturated conditions occurred for most soils with soil-water contents greater than about 20%.

Soil Texture Measurements

The texture of the samples were determined by ASTM standard sieve analyses to verify the soil conditions estimated in the field and for comparison to the NRCS soil maps. The sieve analysis used was method ASTM D 422 –63 (*Standard Test Method For Particle Size Analysis of Soils*) for particles larger than the No. 200 sieve, along with ASTM D 2488 - 93 (*Standard Practice for Description and Identification of Soils (Visual - Manual Procedure*). The sample was prepared based on ASTM 421 (*Practice for Dry Preparation of Soil Samples for Particle Size Analysis and Determination of Soil Constants*). After the material was dried and weighed, it was then crushed for sieve analysis. The sample was then treated with a dispersing agent (sodium hexarnetaphosphate) and water at the specified quantities. The mixture was then washed over a No. 200 sieve to remove all soil particles smaller than the 0.075 mm (75 µm) openings. The sample was then dried and a dry weight obtained. The remaining sample was then placed in a sieve stack containing No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, No. 200 sieves, and the bottom pan. The sieves were then shaken in a mechanical shaker and separated onto their respective sieve sizes. The cumulative weight retained on each sieve was then recorded, and the amount of clay, silt, and sand was determined.

The designation for the sand or clay categories follows the *Unified Soil Classification System*, ASTM D 2487. Sandy soils required that more than half of the material be larger than the No. 200 sieve, and more than half of that fraction be smaller than the No. 4 sieve. Similarly, for clayey soils, more than half of the material is required to be smaller than the No. 200 sieve. The "clayey" soils category included soils having from 30 to 98% clay, 2 to 45% silt, and 2 to 45% sand. This category included clay and clay loam soils. The "sandy" soils category included soils having from 65 to 95% sand, 2 to 25% silt, and 5 to 35% clay. This category included sand, loamy sand, and sandy loam soils. No soils were tested that were predominately silt or loam.

Soil Compaction Measurements

The extent of compaction at each site was also measured before testing using a cone penetrometer. Cone penetrometer measurements are sensitive to water content. Soils, especially clay soils, are obviously more spongy and soft when wet compared to hard conditions when extremely dry. Therefore, the penetrometer measurements were not made for saturated conditions and the degree of soil compaction was also determined based on the history of the specific site (especially the presence of parked vehicles, unpaved lanes, well-used walkways, etc.).

Compact soils were defined as having a reading of greater than 300 psi at a depth of three inches. Other factors that were beyond the control of the experiments, but also affect infiltration rates, include bioturbation by ants, gophers and other small burrowing animals, worms, and plant roots.

Infiltration Test Site Descriptions

Birmingham, Alabama, near many of the test locations, has about 1370 mm (54 in.) of rain per year, distributed between about 110 events per year. Typical antecedent dry periods range from about 2 to 5 days. It is rare to have more than 10 days without recorded rainfall. The driest months are October and November, averaging 66 and 91 mm (2.6 and 3.6 in.), respectively, while March is the wettest month averaging 460 mm (6.3 in.) of rainfall. Snow is rare, with snowfalls of at least 125 mm (5 in.) occurring only about once every 10 years. The growing season (higher than -2° C, or 28° F) is at least 243 days per year in 5 out of 10 years. Average daily maximum temperatures are about 32° C (90° F) in the summer months (June through August) and about 13° C (55° F) in the winter months (December through February). Average daily minimum temperatures in the summer are about 18 to 21° C (65 to 70° F), and in the winter are about 1° C (34° F). The extreme recorded temperatures in Birmingham have ranged from about –18 to 43° C (0 to 110° F). Many of the sandy soil tests were located near Mobile, AL, where the rainfall averages about 250 mm (10 in.) more than in Birmingham, and the summers are even hotter and more humid. Table 4 briefly describes the test locations and site conditions, while Figure 1 is a soil texture diagram showing the distribution of the soil texture classifications at the different test sites.

Results

The first analysis involved the preparation of 3D plots of the infiltration data, illustrating effects of soil-water levels and compaction, for both sand and clay. These plots are shown in Figures 2 and 3. Four general conditions were observed to be statistically unique, as previously listed on Table 1. Compaction has the greatest effect on infiltration rates in sandy soils, with little detrimental effects associated with higher soil-water content conditions. Clay soils, however, are affected by both compaction and soil-water content. Compaction was seen to have about the same effect as saturation on these soils, with saturated and compacted clayey soils having very little effective infiltration.

The Horton infiltration equation was fitted to each set of individual site test data and the equation coefficients were statistically compared for the different site conditions. Figures 4 through 7 are the plots showing the observed infiltration rates, and the fitted Horton equation parameters for the four general conditions.

Figure 4 is for the noncompacted sand conditions, the urban soil conditions having the greatest infiltration potential. In addition, this condition is the only one of the four major conditions that had an obvious decrease in infiltration with time during the tests. The observed infiltration rates occur in a relatively even, but broad, band. Three of the 36 tests had very low initial rates, but were within the typical band of observations after about ten minutes. Some initial wetting or destruction of a surface crust was apparently necessary before the site infiltration rate stabilized. Table 5 summarizes the observed Horton equation parameter values, compared to the typical published parameter values, for sandy soil conditions.

Table 4. Infiltration Test Site Locations and Conditions

Site #	Location	Predominant Land Use	Age (years)	Texture	Compaction (psi)
1a 1b	Homewood Park	Recreational	>40	Clay loam	100-200 >300
2a 2b	Chadwich, Helena	Medium density residential	<1	Clay loam Clay loam	150 >300
3a 3b 3c	South Lakeshore Drive	Commercial	>25	Sandy loam Sandy loam Clay loam	>300 225 280
4a 4b 4c	Private Residence Backyard (West Jefferson)	Low density residential	>30	Clay loam Clay loam Sandy loam	200 >300 200-250
5a 5b	Private Residence Backyard (Trussville)	Medium density residential	>30	Clay loam Sandy loam	150-200 >300
6	Littlefield Farms	Agricultural	>10	Sandy loam	>300
7a 7b	Wildwood Apartment Complex (Homewood)	High density residential	<1	Clay loam	>300 <150
8	Private Residence Backyard (Birmingham)	Medium density residential	>30	Clay loam	>300
9a 9b 9c	Jasper Golf Course (Walker County)	Recreational	<5 <5 >10	Sand Sand Sand	150-175 >300 100
10	Private Residence Backyard (Gulf Shores)	Medium density residential	>20	Loamy sand	100

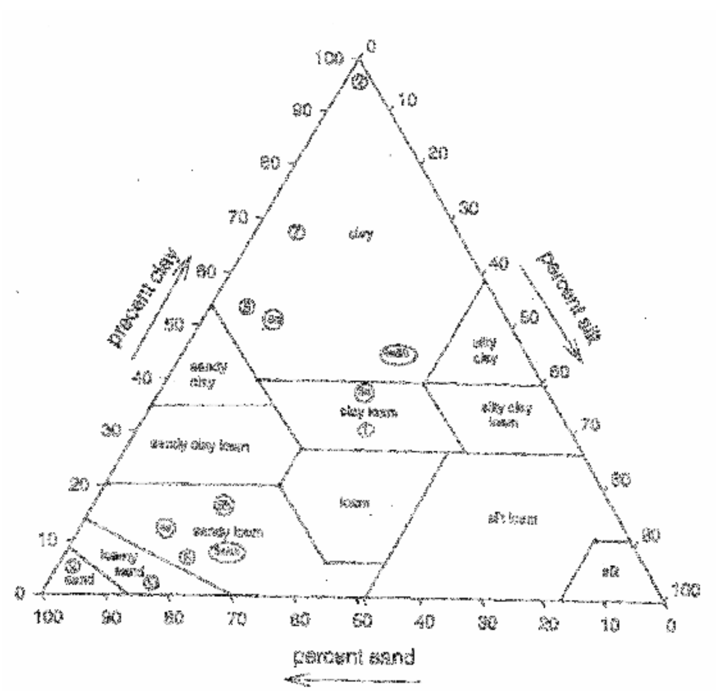

Figure 1. Soil texture classifications for test sites.

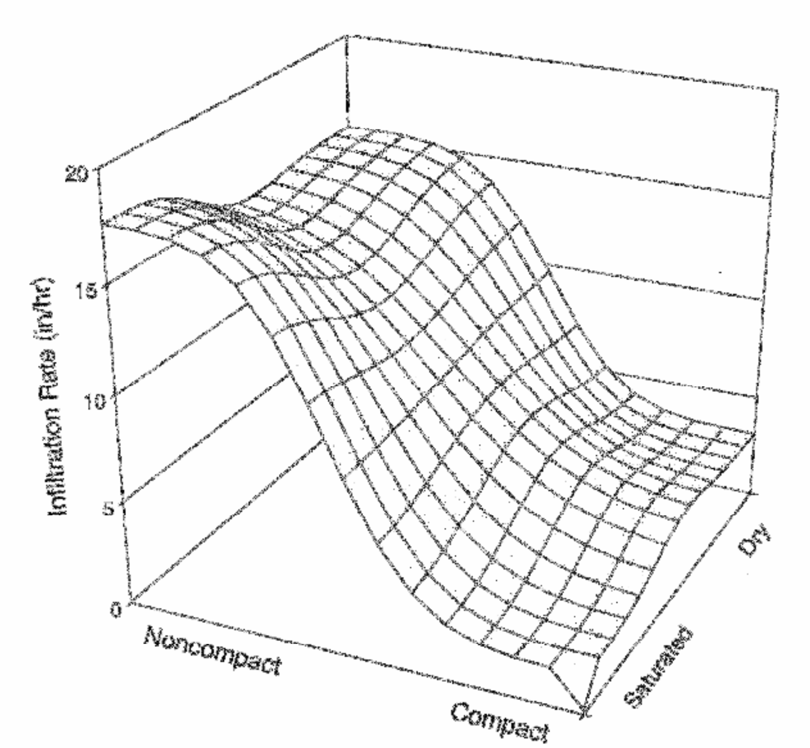

Figure 2. Three dimensional plot of infiltration rates for sandy soil conditions.

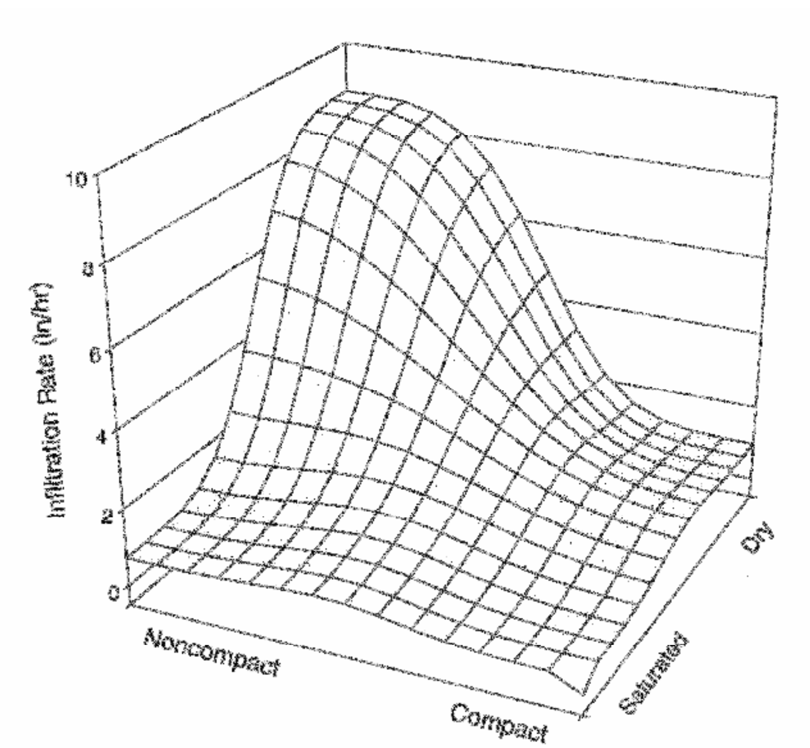

Figure 3. Three dimensional plot of infiltration rates for clayey soil conditions.

Table 5. Observed and Published Horton Equation Parameter Values for Sandy Soils

	f_o (in/hr)		f_c (in/hr)		k (1/min)	
	mean/ typical	range	mean/ typical	range	mean/ typical	range
Observed noncompacted sandy soils	39	4.2 to 146	15	0.4 to 25	9.6	1.0 to 33
Observed compact sandy soils	15	0.1 to 86	1.8	0.1 to 9.5	11	1.8 to 37
Published values	5	1.7 to 10		0.30 to 0.45	0.069	

The observed conditions differ greatly from the published values. The published values reflect soil-water content effects, while the observations indicated very small effects associated with soil-water for sandy soils, but very large effects associated with compaction. The observed constant final infiltration rates were greatly larger than typically assumed, with infiltration rates for noncompacted sandy soils of about 350 mm/hr (14 in/hr), ranging from about 125 to 635 mm/hr (5 to 25 in/hr) during the tests. The comparable published rates were less than 25 mm/hr (1 in/hr). The infiltration rates leveled-off to the constant final values after about 30 to 45 minutes.

Figure 4 shows the observed infiltration rates and fitted Horton equation parameter values for compacted sandy soil conditions. The observed rates are significantly less than for the above non-compacted conditions. The effects of compaction on sandy soils is very large, reducing the rates by between 5 and 10 times. Some initial rates are still very large, but the rates decreased quickly. After 20 to 30 minutes they are all within about 0 to 500 mm/hr (0 to 20 in/hr), with most of the 39 observations less than 125 mm/hr (5 in/hr).

Figure 5 is a similar plot for clayey soils that are dry and noncompacted, the highest infiltration rate category for clayey soils. No significant changes in infiltration rates are seen as a function of time, with all test average values within the range of 8 to 500 mm/hr (0.3 to 20 in/hr), with a mean rate of about 230 mm/hr (9 in/hr) for all 18 tests combined. Figure 6 shows the observed test results for the other clayey soil conditions (dry and compact, and all wetter conditions). These rates were the lowest observed. Some saturated noncompacted initial values were greater than later values, although most of the 60 sets of test data indicated infiltration rates within a relatively narrow range of less than 125 mm/hr (5 in/hr). Table 6 shows the observed Horton equation parameters compared to published values. The mean clayey soil infiltration rates observed were all greater than the published values, although the compacted and saturated clayey soils were much closer to the published values than the observed dry clayey soil rates.

Because of the wide range in observed rates for each of the major categories, it may not matter which infiltration rate equation is used. The residuals are all relatively large and it is much more important to consider the random nature of infiltration about any fitted model and to address the considerable effect that soil compaction has on infiltration. It may therefore be necessary to use a Monte Carlo stochastic component in a runoff model to describe this variation.

Table 6. Observed and Published Horton Equation Parameter Values for Clayey Soils

	f_o (in/hr)		f_c (in/hr)		k (1/min)	
	mean/ typical	range	mean/ typical	range	mean/ typical	range
Observed dry noncompacted clayey soils	18	2.5 to 58	6.6	0.1 to 24	8.8	-6.2 to 19
Published values for dry clayey soils		1 to 2		0 to 0.05	0.069	
Observed for all other clayey soils (compacted and dry, plus all saturated conditions)	3.4	0 to 48	0.4	-0.6 to 6.7	5.6	0 to 46
Published values for saturated clayey soils		0.3 to 0.7		0 to 0.05	0.069	

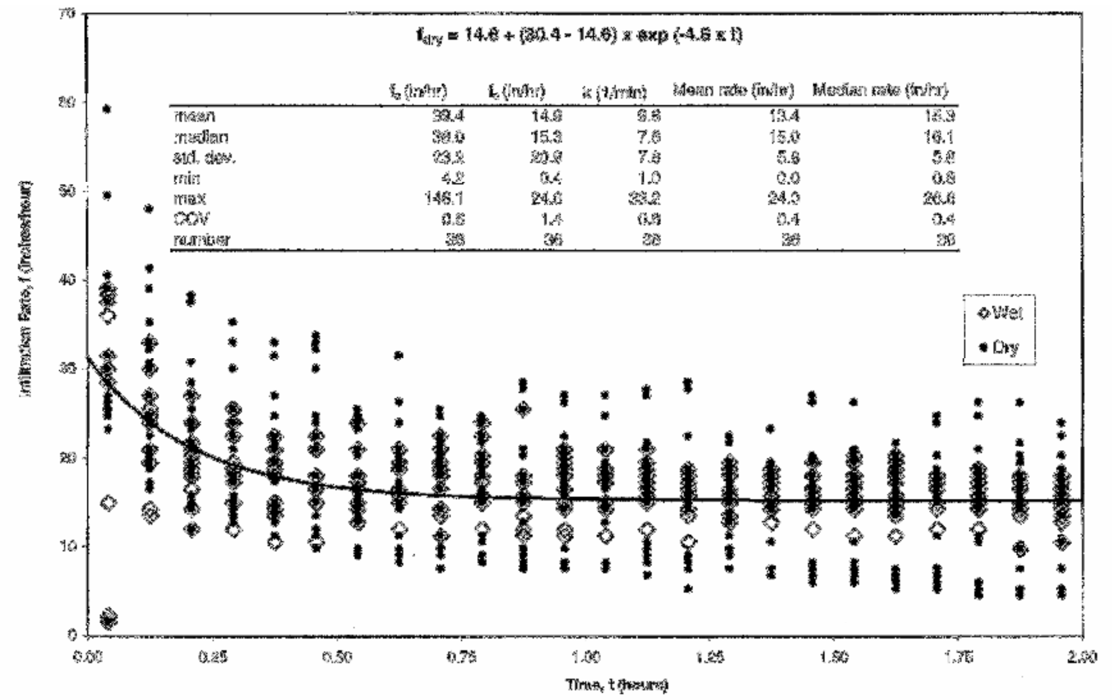

Figure 4. Infiltration measurements for noncompacted, sandy soil, conditions.

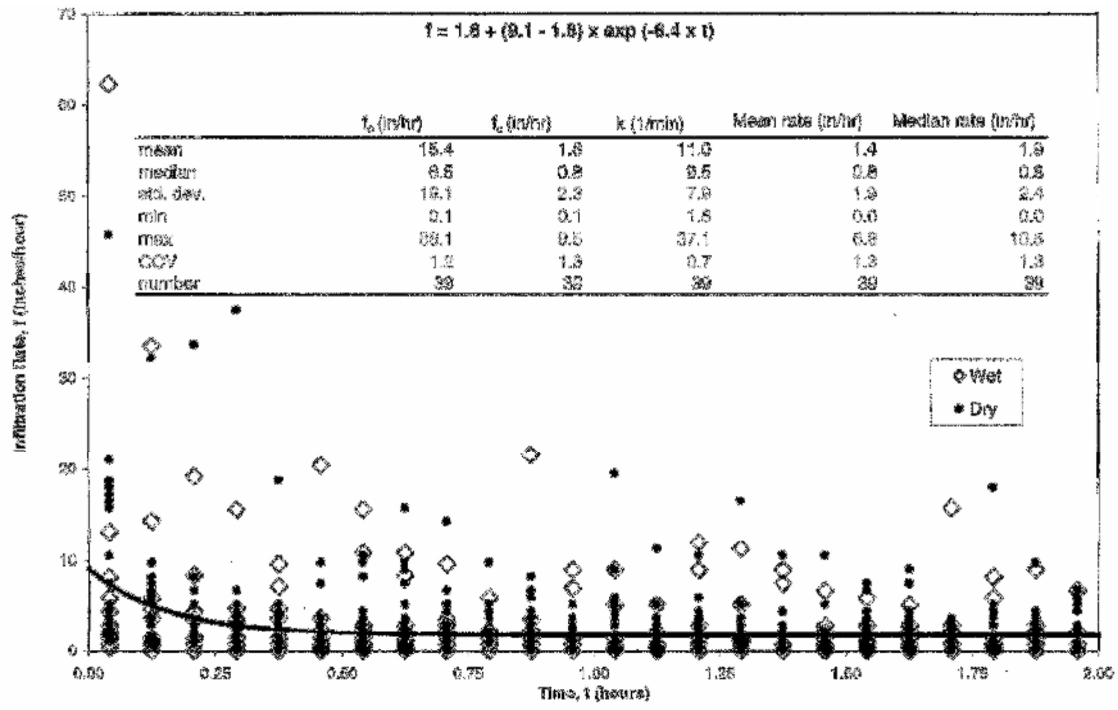

Figure 5. Infiltration measurements for compacted, sandy soil, conditions.

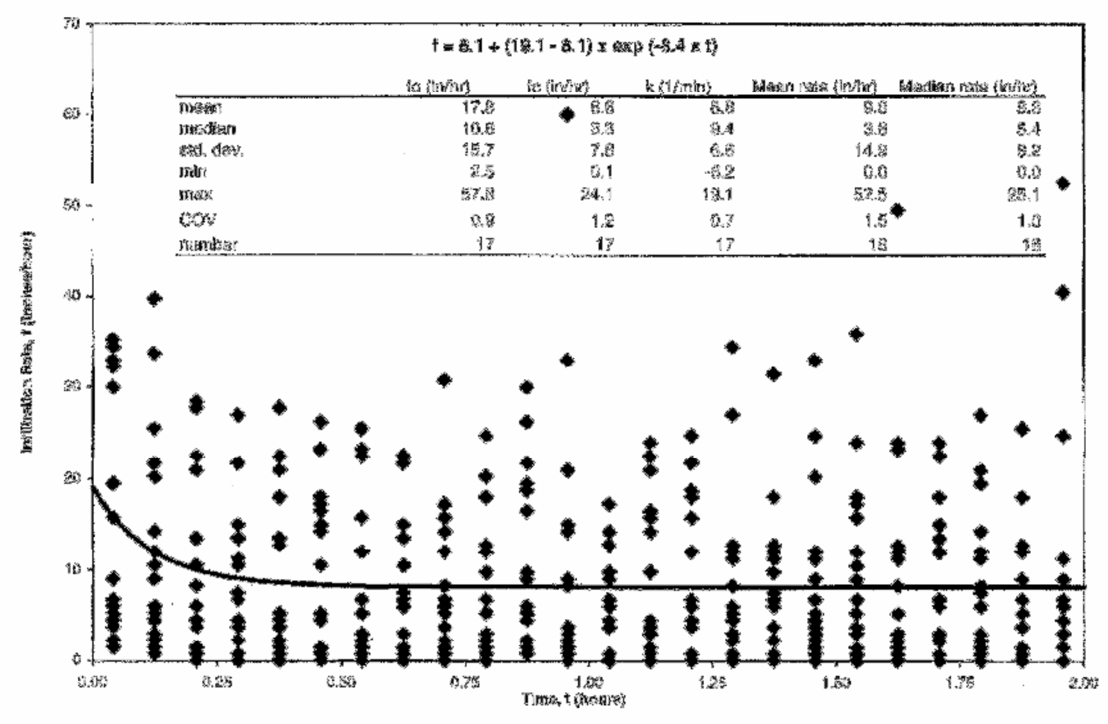

Figure 6. Infiltration measurements for dry-noncompacted, clayey soil, conditions.

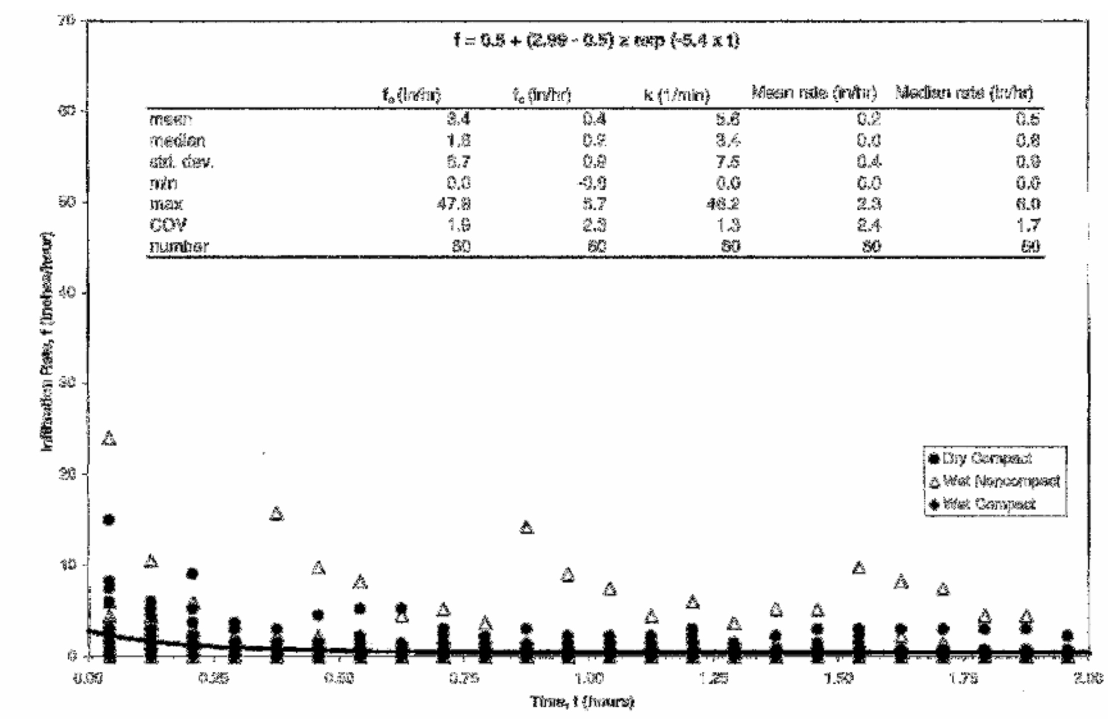

Figure 7. Infiltration measurements for wet-noncompacted, dry-compacted, and wet-compacted, clayey soil conditions.

As one example of an approach, Table 7 shows the measured infiltration rates for each of the four major soil categories, separated into several time increments. This table shows the observed infiltration rates for each test averaged for different storm durations (15, 30, 60, and 120 minutes). Also shown are the ranges and COV values for each duration and condition. Therefore, a routine in a model could select an infiltration rate, associated with the appropriate soil category, based on the storm duration. The selection would be from a random distribution (likely a log-normal distribution) as described from this table.

Figures 8 through 11 are probability plots showing the observed infiltration rates for each of the four major soil categories, separated by these event durations. Each figure has four separate plots representing the storm event averaged infiltration rates corresponding to four storm durations from 15 minutes to 2 hours. As indicated previously, the infiltration rates became relatively steady after about 30 to 45 minutes during most tests. Therefore, the 2 hour averaged rates could likely be used for most events of longer duration. There is an obvious pattern on these plots which show higher rates for shorter rain durations, as expected. The probability distributions are closer to being log-normally distributed than normally distributed. However, with the large number of zero infiltration rate observations for three of the test categories, log-normal probability plots were misleading.

The soil texture and compaction classification would remain fixed for an extended simulation period (unless the soils underwent an unlikely recovery operation to reduce the soil compaction), but the clayey soils would be affected by the antecedent interevent period which would define the soil-water level at the beginning of the event. Recovery periods are highly dependent on site specific soil and climatic conditions and are calculated using various methods in continuous simulation urban runoff models. The models assume that the recovery period is much longer than the period needed to produce saturation conditions. As noted above, saturation (defined here as when the infiltration rate reaches a constant value) occurred under an hour during these tests. A simple estimate of the time needed for recovery of soil-water levels is given by the USDA’s Natural Resources Conservation Service (NRCS) (previously the Soil Conservation Service, SCS) in TR-55 (McCuen 1998). The NRCS developed three antecedent soil-water conditions as follows:

- Condition I: soils are dry but not to the wilting point
- Condition II: average conditions
- Condition III: heavy rainfall, or lighter rainfall and low temperatures, have occurred within the last five days, producing saturated soil.

McCuen (1998) presents Table 8 (from the NRCS) that gives seasonal rainfall limits for these three conditions. Therefore, as a rough guide, saturated soil conditions for clay soils may be assumed if the preceding 5-day total rainfall was greater than about 25 mm (one inch) during the winter or greater than about 50 mm (two inches) during the summer. Otherwise, the “other” infiltration conditions for clay should be assumed.

Laboratory Compaction Tests

Method

Previous research (Pitt, *et al.* 1999b), as summarized above, has identified significant reductions in infiltration rates in disturbed urban soils. More than 150 prior tests were conducted in predominately sandy and clayey urban soils in the Birmingham and Mobile, Alabama, areas. Infiltration in clayey soils was found to be affected by an interaction of soil moisture and compaction, while infiltration in sandy soils was affected by soil compaction alone. The tests reported in the following discussion were conducted under more controlled laboratory conditions and represent a wider range of soil textures and specific soil density values than the previous field tests.

Laboratory permeability test setups were used to measure infiltration rates associated with different soils having different textures and compactions. These tests differed from normal permeability tests in that high resolution observations were made at the beginning of the tests to observe the initial infiltration behavior. The tests were run for up to 20 days, although most were completed (when steady low rates were observed) within 3 or 4 days.

Table 7. Soil Infiltration Rates for Different Categories and Storm Durations

Sand, Non-compacted

	15 minutes	30 minutes	60minutes	120 minutes
mean	19.5	17.4	15.2	13.5
median	18.8	16.5	16.5	15.4
std. dev.	8.8	8.1	6.7	6.0
min	1.5	0.0	0.0	0.0
max	38.3	33.8	27.0	24.0
COV	0.4	0.5	0.4	0.4
number	36	36	36	36

Sand, Compacted

	15 minutes	30 minutes	60minutes	120 minutes
mean	3.6	2.2	1.6	1.5
median	2.3	1.5	0.8	0.8
std. dev.	6.0	3.6	2.0	1.9
min	0.0	0.0	0.0	0.0
max	33.8	20.4	9.0	6.8
COV	1.7	1.6	1.3	1.3
number	39	39	39	39

Clay, Dry Non-compacted

	15 minutes	30 minutes	60minutes	120 minutes
mean	9.0	8.8	10.8	9.3
median	5.6	4.9	4.5	3.0
std. dev.	9.7	8.8	15.1	15.0
min	0.0	0.0	0.0	0.0
max	28.5	26.3	60.0	52.5
COV	1.1	1.0	1.4	1.6
number	18	18	18	18

All other clayey soils (compacted and dry, plus all saturated conditions)

	15 minutes	30 minutes	60minutes	120 minutes
mean	1.3	0.7	0.5	0.2
median	0.8	0.8	0.0	0.0
std. dev.	1.6	1.4	1.2	0.4
min	0.0	0.0	0.0	0.0
max	9.0	9.8	9.0	2.3
COV	1.2	1.9	2.5	2.4
number	60	60	60	60

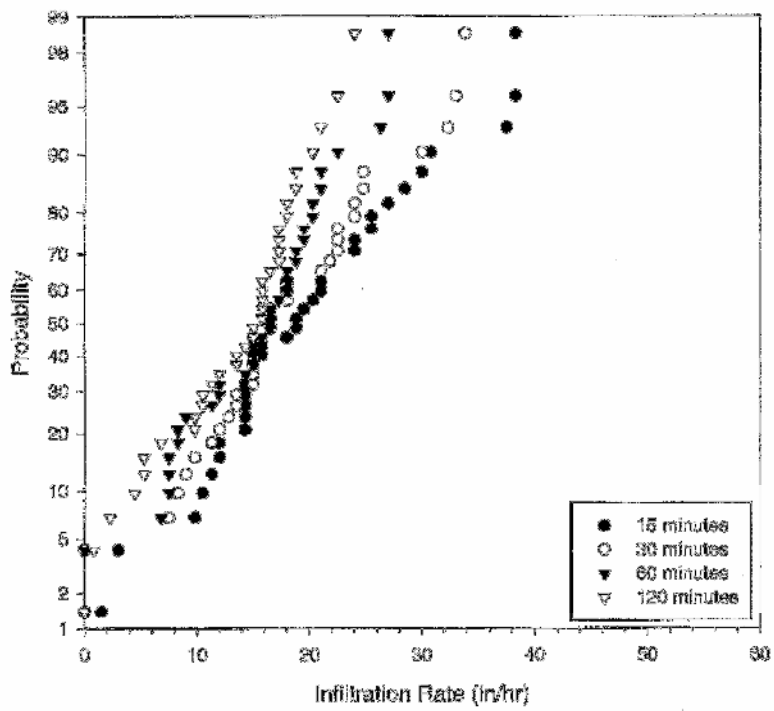

Figure 8. Probability plots for infiltration measurements for noncompacted, sandy soil, conditions.

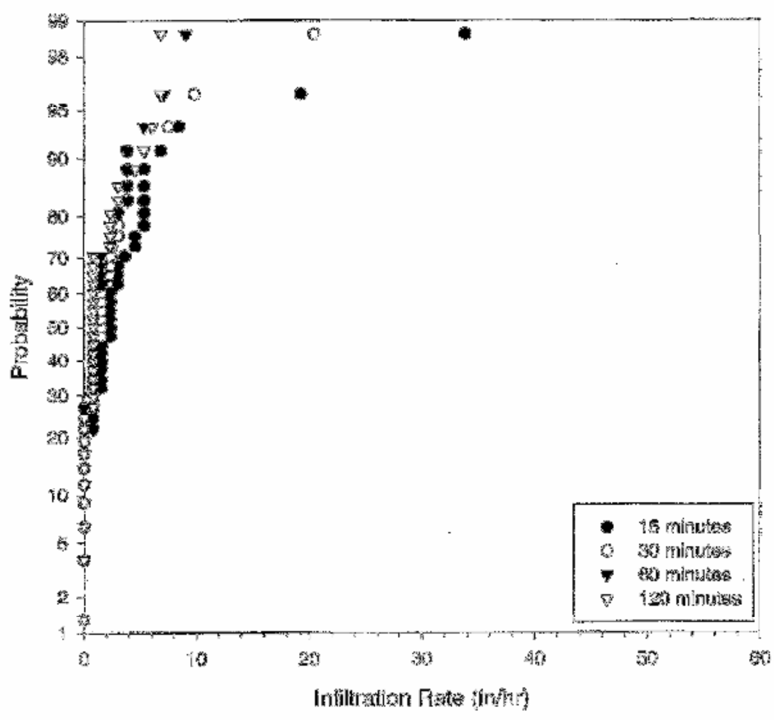

Figure 9. Probability plots for infiltration measurements for compacted, sandy soil, conditions.

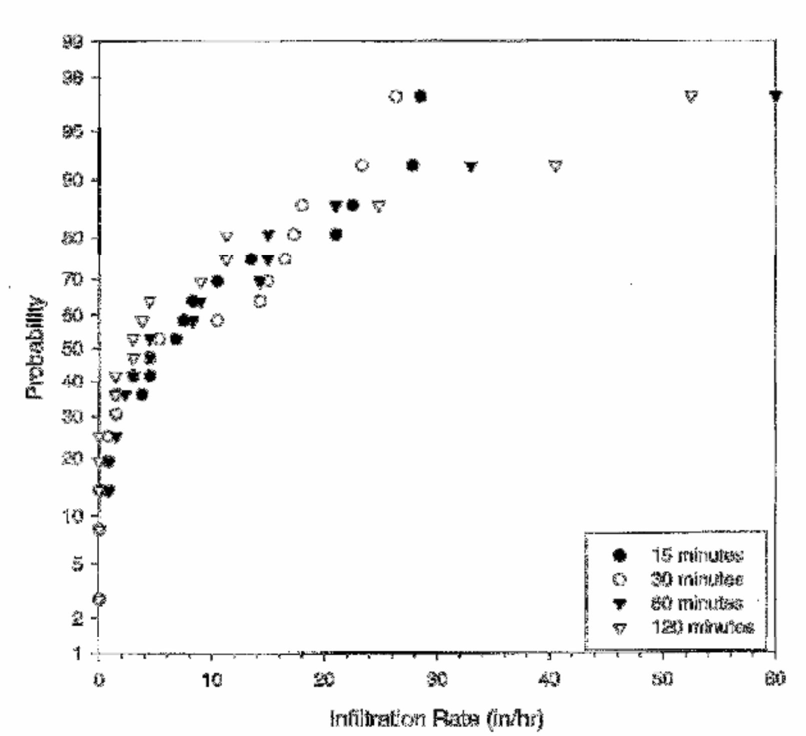

Figure 10. Probability plots for infiltration measurements for dry-noncompacted, clayey soil, conditions.

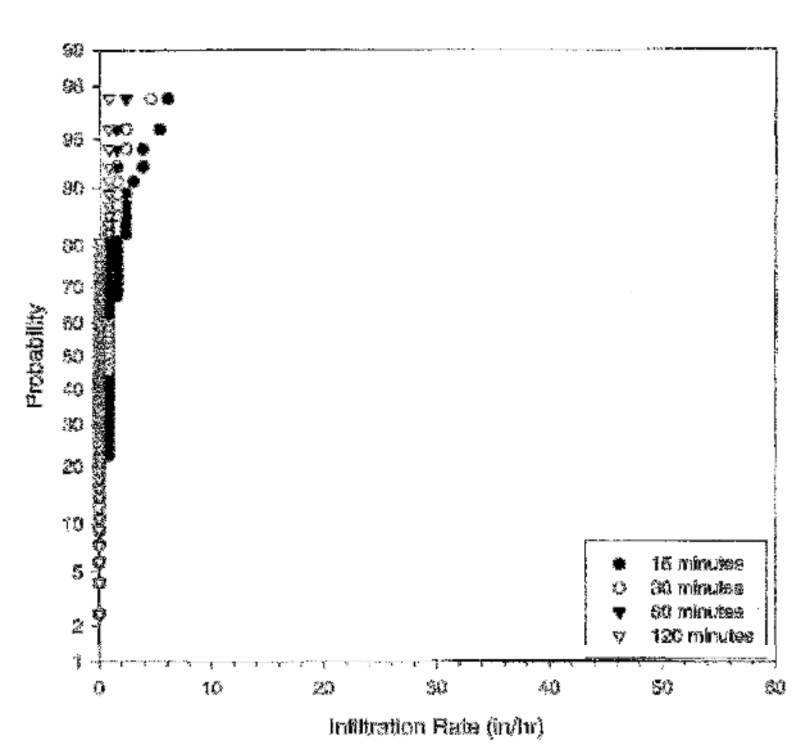

Figure 11. Probability plots for infiltration measurements for wet-noncompacted, dry-compacted, and wet-compacted, clayey soil conditions.

Table 8. Total Five-Day Antecedent Rainfall for Different Soil-Water Content Conditions (in.)

	Dormant Season	Growing Season
Condition I	<0.5	<1.4
Condition II	0.5 to 1.1	1.4 – 2.1
Condition III	>1.1	> 2.1

Test samples were prepared by mixing known quantities of sand, silt, and clay to correspond to defined soil textures, as shown in Table 9. The initial sample moistures were determined and water was added to bring the initial soil moistures to about 8%, per standard procedures (ASTM D1140-54), reflecting typical “dry” soil conditions and to allow water movement through the soil columns. Table 10 lists the actual soil moisture levels at the beginning of the tests.

Three methods were used to modify the compaction of the soil samples: hand compaction, Modified Proctor Compaction, and Standard Proctor Compaction. Both Modified and Standard Proctor Compactions follow ASTM standard (D 1140-54). All tests were conducted using the same steel molds (115.5 mm tall with 105 mm inner diameter, having a volume of 1000 cm^3). The Standard Proctor compaction hammer is 24.4 kN and has a drop height of 300 mm. The Modified Proctor hammer is 44.5 kN and has a drop height of 460 mm. For the Standard Proctor setup, the hammer was dropped on the test soil in the mold 25 times on each of three soil layers, while for the Modified Proctor test, the heavier hammer was also dropped 25 times, but on each of five soil layers. The Modified Proctor test therefore resulted in much more compacted soil. The hand compaction was done by gentle hand pressing to force the soil into the mold with as little compaction as possible. A minimal compaction effort was needed to keep the soil in contact with the mold walls and to prevent short-circuiting during the tests. The hand compacted soil specimens therefore had the least amount of compaction. The compacted specimens in the compaction molds were transferred to the permeability test setup. The head for the permeability test was 1.14 meter (top of the water surface to the top of the compaction mold). The water temperature during the test was kept consistent at 75^oF.

Table 9. Test Mixtures During Laboratory Tests

	Pure Sand	Pure Clay	Pure Silt	Sandy Loam	Clayey Loam	Silt Loam	Clay Mix
% Sand	100			72.1	30.1	19.4	30
% Clay		100		9.2	30.0	9.7	50
% Silt			100	18.7	39.9	70.9	20

As shown on Table 10, a total of 7 soil types were tested representing all main areas of the standard soil texture triangle. Three levels of compaction were tested for each soil, resulting in a total of 21 tests. However, only 15 tests resulted in observed infiltration. The Standard and Modified Proctor clay tests, the Modified Proctor clay loam, and all of the clay mixture tests did not result in any observed infiltration after several days and those tests were therefore stopped. The “after test” moisture levels generally corresponded to the “saturated soil” conditions of the earlier field measurements.

Table 11 is a summary table from the NRCS Soil Quality Institute 2000, Urban Technical Note 2, as reported by Ocean County Soil Conservation District. The bulk densities of the laboratory soil test specimens are seen to cover the range of natural soils for the different textures, with the Modified Proctor tests causing conditions that would restrict root growth and the hand placed specimens generally within the ideal range for plant growth.

Table 10. Soil Moisture and Density Values during Laboratory Tests

Soil Types	Compaction Method	Dry Bulk Density Before Test (g/cc)	Before Test Moisture Content (%)	After Test Moisture Content (%)
Silt	Hand	1.508	9.7	22.9
	Standard	1.680	8.4	17.9
	Modified	1.740	7.8	23.9
Sand	Hand	1.451	5.4	21.6
	Standard	1.494	4.7	16.4
	Modified	1.620	2.0	16.1
Clay	Hand	1.242	10.6	N/A
Sandy Loam	Hand	1.595	7.6	20.2
	Standard	1.653	7.6	18.9
	Modified	1.992	7.6	9.9
Silt Loam	Hand	1.504	8.1	23.0
	Standard	1.593	8.1	27.8
	Modified	1.690	8.1	27.8
Clay Loam	Hand	1.502	9.1	24.1
	Standard	1.703	9.1	19.0
	Modified	1.911	9.1	14.5
Clay Mix	Hand	1.399	8.2	42.2
	Standard	1.685	8.2	N/A
	Modified	1.929	8.2	N/A

Table 11. General Relationship of Soil Bulk Density to Root Growth based on Soil Texture (adapted from NRCS 2001)

Soil Texture	Ideal bulk density (g/cm^3)	Bulk densities that may affect root growth (g/cm^3)	Bulk densities that restrict root growth (g/cm^3)
Sands, loamy sands	<1.60	1.69	>1.80
Sandy loams, loams	<1.40	1.63	>1.80
Sandy clay loams	<1.40	1.60	>1.75
Loams, clay loams	<1.40	1.60	>1.75
Silts, silt loams	<1.30	1.60	>1.75
Silt loams, silty clay loams	<1.10	1.55	>1.65
Sandy clays, silty clays, clay loams (35 to 45% clay)	<1.10	1.49	>1.58
Clays (>45% clay)	<1.10	1.39	>1.47

Results

Figures 12 through 17 show the infiltration plots obtained during these compaction tests. Table 12 presents the calculated Horton equation coefficient values for these tests, using the nonlinear curve fitting routines in SigmaStat, (SPSS, Inc.). Also shown on this table are the ANOVA tests for the complete model, indicating if the complete models were significant (or if a constant infiltration value should be used), and if the individual equation coefficients are significant. Only seven of the models were significant at least at the 0.10 level. All of the calculated Fo (initial infiltration rates) were significant, except for the hand compacted sand and the Modified Proctor compacted sand. Fewer Fc (final infiltration rates) and k (rate constants) were significant.

Table 12. Horton Equation Coefficients and ANOVA Results

Soil Types	Compaction Method	Overall Significance of Model (ANOVA P value[a]	Overall Model Adjusted R^2	Fo value (in/hr)	Significance of Fo coefficient (ANOVA P value)[a]	Fc value (in/hr)	Significance of Fc coefficient (ANOVA P value)[a]	k value (1/hr)	Significance of k coefficient (ANOVA P value)[a]
Silt	Hand	<0.0001	0.96	3.001	<0.0001	0.717	<0.0001	7290	0.99
	Standard	0.99	0	0.034	<0.0001	0.034	<0.0001	0.13	0.99
	Modified	0.45	0.02	0.003	<0.0001	0.003	<0.0001	0.21	0.73
Sand	Hand	NA	0	3.03	0.97	3.09	1.0	-0.004	1.0
	Standard	0.088	0.18	0.60	<0.0001	-0.076[b]	0.99	0.25	0.94
	Modified	NA	0	3.21	0.91	3.16	1.0	0.004	1.0
Clay	Hand	<0.0001	0.87	0.157	<0.0001	0.108	<0.0001	0.039	0.015
Sandy Loam	Hand	<0.0001	0.75	32.0	<0.0001	-350[b]	0.95	-0.007	0.95
	Standard	<0.0001	0.81	7.15	<0.0001	-209[b]	0.94	-0.007	0.94
	Modified	0.028	0.85	2.63	0.002	1.04	0.006	0.060	0.17
Silt Loam	Hand	0.022	0.70	2.50	0.0003	1.13	0.0018	4.33	0.15
	Standard	0.11	0.96	0.0269	0.0014	0.0276	0.0018	0.052	0.22
	Modified	0.12	0.59	0.0015	0.0004	0.0018	<0.0001	0.089	0.54
Clay Loam	Hand	0.10	0.37	0.30	<0.0001	0.87	0.99	-0.0038	0.99
	Standard	0.50	0	0.0166	<0.0001	0.0154	0.0068	0.021	0.82

[a] ANOVA P values of <0.05 are typically accepted as being significant. If the P value is large, the Fc and Fo values are likely very close in values, and the k parameter is likely close to zero and insignificant. Under these conditions, very little changes in the infiltration rates were observed during the duration of the tests.
[b] negative Fc rate values should be considered as zero.

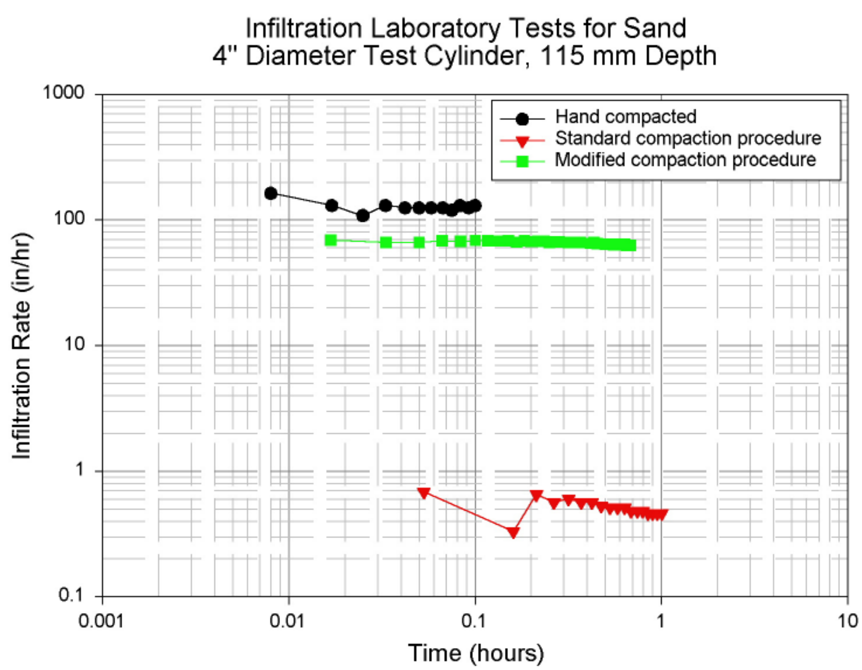

Figure 12. Sandy soil laboratory infiltration test results.

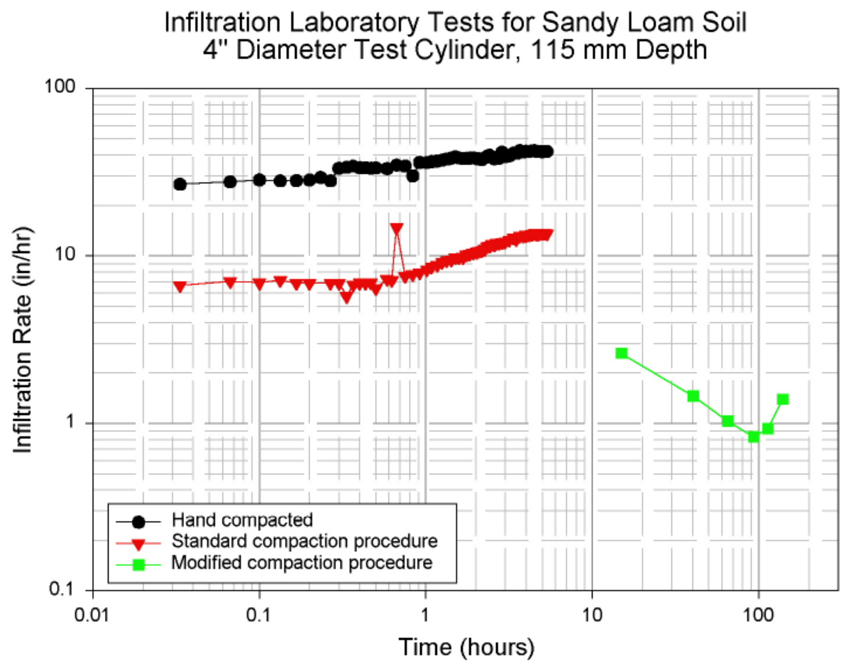

Figure 13. Sandy loam soil laboratory infiltration test results.

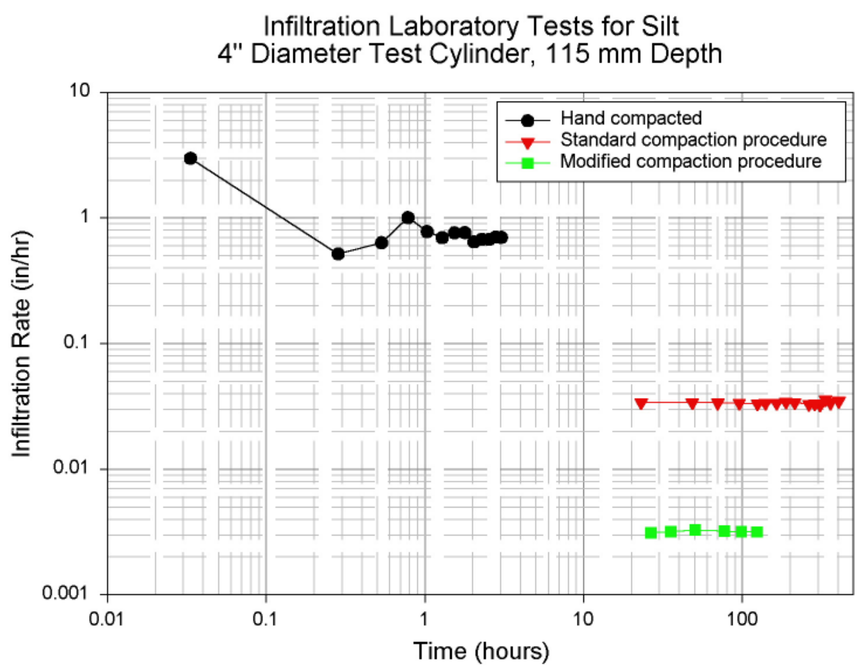

Figure 14. Silty soil laboratory infiltration test results.

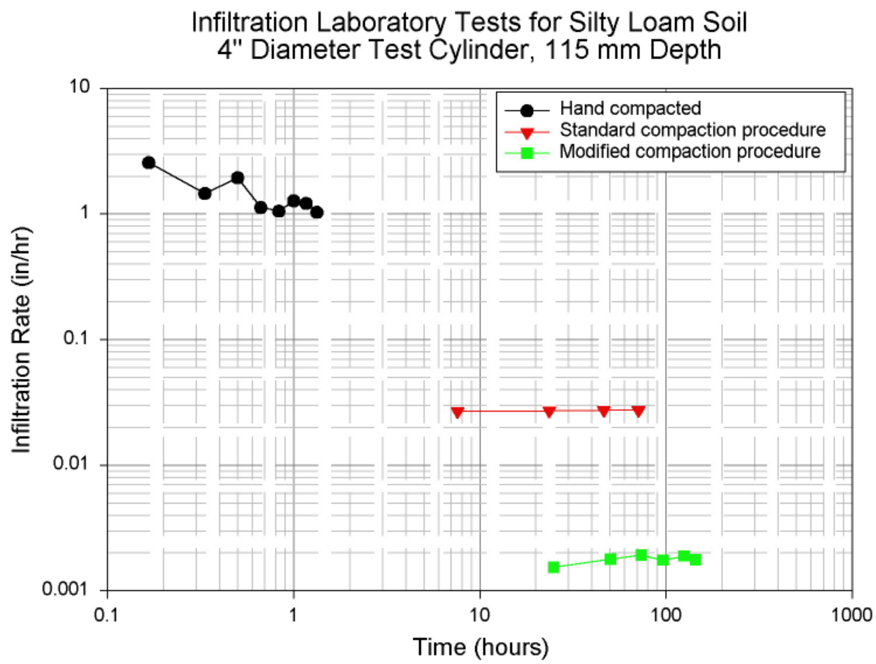

Figure 15. Silty loam soil laboratory infiltration test results.

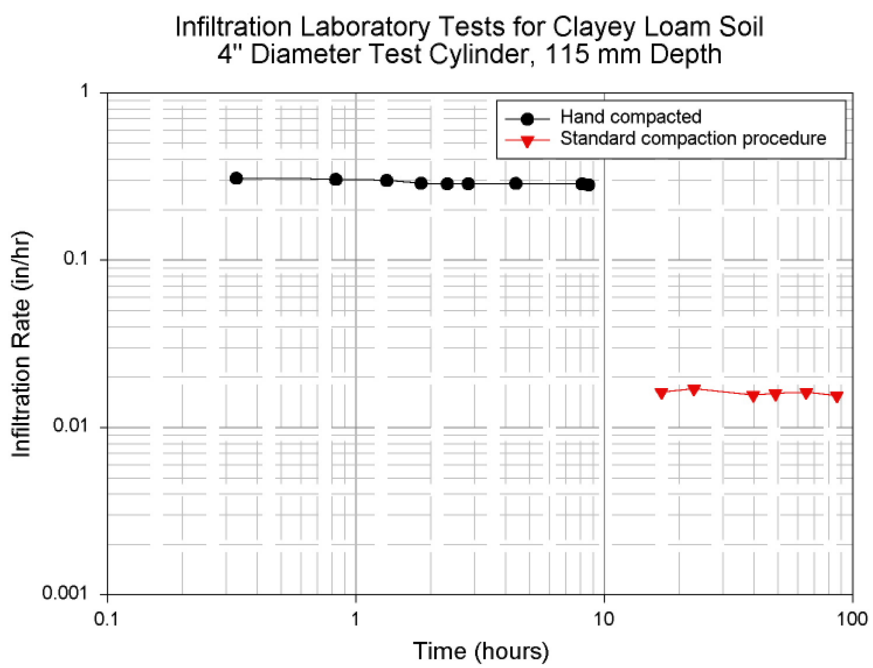

Figure 16. Clayey loam soil laboratory infiltration test results.

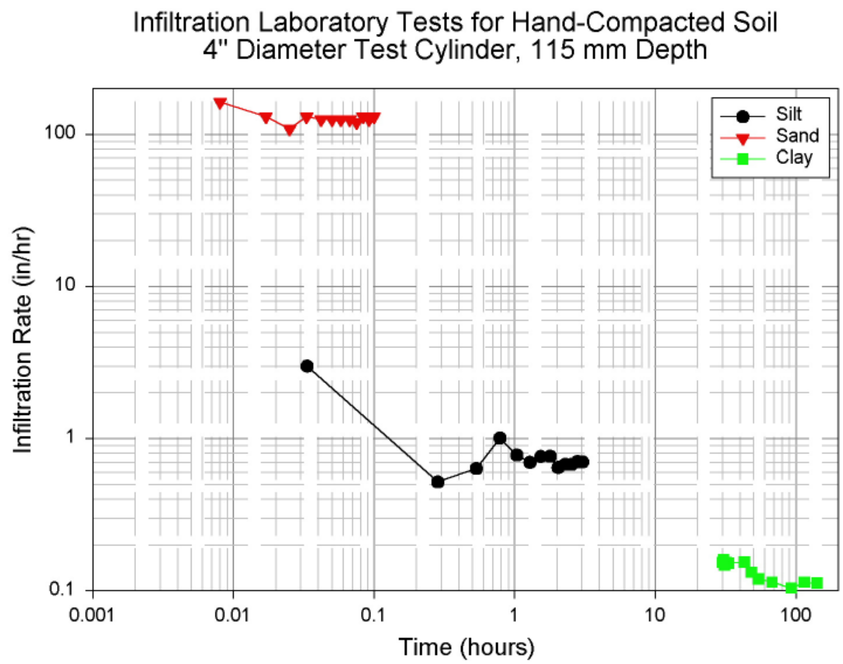

Figure 17. Comparison of hand compacted test results for sand, silt, and clay.

Soil Amendments to Improve Urban Soil Performance

Water Quality and Quantity Effects of Amending Soils with Compost

Another component of the EPA-sponsored project that included the field infiltration tests was conducted by the College of Forestry Resources at the University of Washington (under the direction of Dr. Rob Harrison) in the Seattle area to measure the benefits of amending urban soils with compost (Pitt, *et al.* 1999b). It was found that compost-amended soils could improve the infiltration characteristics of these soils, along with providing some filtration/sorption benefits to capture stormwater pollutants before they enter the groundwater.

Existing facilities at the University of Washington's Center for Urban Horticulture were used for some of the test plot examinations of amended soils. Two additional field sites were also developed, one at Timbercrest High School and one at WoodMoor High School in Northern King County, Washington. Both of these sites are located on poorly-sorted, compacted Glacial Till soils of the Alderwood soil series. Large plywood bays were used for containing soil and soil-compost mixes.

At the UW test facilities, two different Alderwood glacial till soils were mixed with compost. Two plots each of glacial till-only soil and 2:1 mixtures of soil:compost were studied. The soil-compost mixture rates were also the same for the Timbercrest and Woodmoor sites, using Cedar Grove compost. The two composts used at the UW sites were Cedar Grove and GroCo. The GroCo compost-amended soil at the UW test site is a sawdust/municipal waste mixture (3:1 ratio, by volume) that is composted in large windrows for at least 1 year. The Cedar Grove compost is a yard waste compost that is also composted in large windrows.

Plots were planted using a commercial turfgrass mixture during the Spring 1994 season for the Urban Horticulture sites and in the fall of 1997 for the Timbercrest and Woodmoor sites. Fertilizer was added to all plots during plot establishment (16-4-8 N-P_2O_5-K_2O) broadcast spread over the study bays at the rate recommended on the product label (0.005 lb fertilizer/ft^2). Due to the poor growth of turf on the control plots, and in order to simulate what would have likely been done anyway on a typical residential lawn, an additional application of 0.005 lb/ft^2 was made to the UW control plots on May 25, 1995. At the new test plots at Timbercrest and Woodmoor , glacial till soil was added to the bays and compacted before adding compost. Cedar Grove compost was added at a 2:1 soil:compost rate and rototilled into the soil surface. Once installed, all bays were cropped with perennial ryegrass.

Sub-surface flows and surface runoff during rains were measured and sampled using special tipping bucket flow monitors (Harrison, *et al.* 1997). The flow amounts and rates were measured by use of tipping bucket type devices attached to an electronic recorder. Each tip of the bucket was calibrated for each site and checked on a regular basis to give rates of surface and subsurface runoff from all plots. Surface runoff decreased by five to ten times after amending the soil with compost (4 inches of compost tilled 8 inches in the soil), compared to unamended sites. However, the concentrations of many pollutants increased in the surface runoff, especially associated with leaching of nutrients from the compost. The surface runoff from the compost-amended soil sites had greater concentrations of almost all constituents, compared to the surface runoff from the soil-only test sites. The only exceptions being some cations (Al, Fe, Mn, Zn, Si), and toxicity, which were all lower in the surface runoff from the compost-amended soil test sites. The concentration increases in the surface runoff and subsurface flows from the compost-amended soil test site were quite large, typically in the range of 5 to 10 times greater. Subsurface flow concentration increases for the compost-amended soil test sites were also common and about as large. The only exceptions being for Fe, Zn, and toxicity. Toxicity tests indicated reduced toxicity with filtration at both the soil-only and at the compost-amended test sites, likely due to the sorption or ion exchange properties of the compost.

Compost-amended soils caused increases in concentrations of many constituents in the surface runoff. However, the compost amendments also significantly decreased the amount of surface runoff leaving the test plots. Table 13 summarizes these expected changes in surface runoff and subsurface flow mass pollutant discharges associated with compost-amended soils. All of the surface runoff mass discharges from the amended soil test plots were reduced from 2 to 50 percent compared to the unamended discharges. However, many of the subsurface flow mass discharges increased, especially for ammonia (340% increase), phosphate (200% increase), plus total phosphorus, nitrates, and total nitrogen (all with 50% increases). Most of the other constituent mass discharges in the subsurface flows decreased. During later field pilot-scale tests, Clark and Pitt (1999) also found that bacteria was reduced by about 50% for every foot of travel through columns having different soils and filtration media.

Table 13. Changes in Pollutant Discharges from Surface Runoff and Subsurface Flows at New Compost-Amended Sites, Compared to Soil-Only Sites

Constituent	Surface Runoff Discharges (mass), Amended-Soil Compared to Unamended Soil	Subsurface Flow Discharges (mass), Amended-Soil Compared to Unamended Soil
Runoff Volume	0.09	0.29
Phosphate	0.62	3.0
Total phosphorus	0.50	1.5
Ammonium nitrogen	0.56	4.4
Nitrate nitrogen	0.28	1.5
Total nitrogen	0.31	1.5
Chloride	0.25	0.67
Sulfate	0.20	0.73
Calcium	0.14	0.61
Potassium	0.50	2.2
Magnesium	0.13	0.58
Manganese	0.042	0.57
Sodium	0.077	0.40
Sulfur	0.21	1.0
Silica	0.014	0.37
Aluminum	0.006	0.40
Copper	0.33	1.2
Iron	0.023	0.27
Zinc	0.061	0.18

Selection of Material for use as Soil Amendments

Additional useful data for soil amendments and the fate of infiltrated stormwater has also been obtained during media filtration tests conducted as part of EPA and WERF-funded projects (Clark and Pitt 1999). A current WERF-funded research at the University of Alabama also includes a test parallel swale where amended soil (with peat and sand) is being compared to native conditions. Both surface and subsurface quantity and quality measurements are being made.

The University of Washington and other Seattle amended soil test plots (Pitt, *et al.* 1999b and Harrison 1997) examined GroCo compost-amended soil (a sawdust/municipal waste mixture) and Cedar Grove compost-amended soil (yard waste compost). In addition, an older GroCo compost test plot was also compared to the new installations. These were both used at a 2:1 soil:compost rate. As noted previously, these compost-amended soils produced significant increases in the infiltration rates of the soils, but the new compost test sites showed large increases in nutrient concentrations in surface runoff and the subsurface percolating water. However, most metals showed major concentration and mass reductions and toxicity measurements were also decreased at the amended soil sites. The older compost-amended test plots still indicated significant infiltration benefits, along with much reduced nutrient concentrations. Table 14 shows the measured infiltration rates at the old and new compost-amended test sites in the Seattle area (all Alderwood glacial till soil).

Table 14. Measured Infiltration Rates at Compost-Amended Test Sites in Seattle (Pitt, et al. 1999b)

	Average Infiltration Rate (cm/hr) (in/hr)
UW test plot 1 Alderwood soil alone	1.2 (0.5)
UW test plot 2 Alderwood soil with Ceder Grove compost (old site)	7.5 (3.0)
UW test plot 5 Alderwood soil alone	0.8 (0.3)
UW test plot 6 Alderwood soil with GroCo compost (old site)	8.4 (3.3)
Timbercrest test plot Alderwood soil alone	0.7 (0.3)
Timbercrest test plot Alderwood soil with Cedar Grove compost (new site)	2.3 (0.9)
Woodmoor test plot Alderwood soil alone	2.1 (0.8)
Woodmoor test plot Alderwood soil with Cedar Grove compost (new site)	3.4 (1.3)

The soil that was not amended with either compost had infiltration rates ranging from 0.7 to 2.1 cm/hr (0.3 to 0.8 in/hr). The old compost amended soil sites had infiltration rates of 7.5 and 8.4 cm/hr (3.0 and 3.3 in/hr), showing an increase of about 6 to 10 times. The newer test plots of compost-amended soil had infiltration rates of 2.3 and 3.4 cm/hr (0.9 to 1.3 in/hr), showing increases of about 1.5 to 3.3 times. The older compost-amended soil test sites showed better infiltration rates that the newer test sites. It is likely that the mature and more vigorous vegetation in the older test plots had better developed root structures and were able to maintain good infiltration conditions, compared to the younger plants in the new test plots. Therefore, the use of amended soils can be expected to significantly increase the infiltration rates of problem soils, even for areas having shallow hard pan layers as in these glacial till soils. There was no significant difference in infiltration between the use of either compost during these tests.

Our earlier work on the performance of different media for use for stormwater filtration is useful for selecting media that may be beneficial as a soil amendment, especially in providing high infiltration rates and pollutant reductions. As reported by Clark and Pitt (1999), the selection of the media needs to be based on the desired pollutant removal performance and the associated conditions, such as land use. The following is the general ranking we found in the pollutant removal capabilities of the different media we tested with stormwater:

- Activated carbon-sand mixture (very good removals with minimal to no degradation of effluent)

• Peat-sand mixture (very good removals, but with some degradation of effluent with higher turbidity, color, and COD)
• Zeolite-sand mixture and sand alone (some removals with minimal degradation of effluent)
• Enretech (a cotton processing mill waste)-sand mixture (some removals with minimal degradation of effluent)
• Compost-sand mixture (some removals but with degradation of effluent with higher color, COD, and solids)

All of the media performed better after they are aged because they have the potential to build up a biofilm that will aid in permanent retention of pollutants. These materials act mostly as ion-exchange materials. This means that when ions are removed from solution by the material, other ions are then released into the solution. In most instances, these exchangeable ions are not a problem in groundwaters. During these tests and for the materials selected, the exchangeable ion for activated carbon was mostly sulfate; while the exchangeable ion for the compost was usually potassium. The zeolite appears to exchange sodium and some divalent cations (increasing hardness) for the ions it sorbs.

Conclusions

Very large errors in soil infiltration rates can easily be made if published soil maps are used in conjunction with most available models for typically disturbed urban soils, as these tools ignore compaction. Knowledge of compaction (which can be measured using a cone penetrometer, or estimated based on expected activity on grassed areas, or directly measured) can be used to more accurately predict stormwater runoff quantity. In most cases, the mapped soil textures were similar to what was actually measured in the field. However, important differences were found during many of the 153 tests. Table 2 showed the 2-hour averaged infiltration rates and their COVs in each of the four major groupings. Although these COV values are generally high (0.5 to 2), they are much less than if compaction was ignored. These data can be fitted to conventional infiltration models, but the high variations within each of these categories makes it difficult to identify legitimate patterns, implying that average infiltration rates within each event may be most suitable for predictive purposes. The remaining uncertainty can probably best be described using Monte Carlo components in runoff models.

The measured infiltration rates during these tests were all substantially larger than expected, but comparable to previous standard double-ring infiltrometer tests in urban soils. Other researchers have noted the general over-predictions of ponding infiltrometers compared to actual observations during natural rains. In all cases, these measurements are suitable to indicate the relative effects of soil texture, compaction, and soil-water on infiltration rates. However, the measured values can be directly used to predict the infiltration rates that may be expected from stormwater infiltration controls that utilize ponding (most infiltration and biofiltration devices).

Table 15 summarizes the overall test and analysis results from the laboratory tests. In many cases (those with significant and close Fc and Fo rates, but insignificant k coefficient), uniform infiltration rates would be most appropriate to describe soil infiltration. Some tests also indicated significant model results with differing infiltration equation coefficients (except that many of the rate coefficient values were not significant). Obviously, it is unlikely that any other infiltration model would provide significant coefficients for the conditions where no, or constant infiltration was observed. However, those conditions that generally were described by the Horton equation could likely be modeled successfully using alternative equations. These tests indicate that both texture and compaction were important in determining the infiltration rates, with time since the beginning of rain only important for less than half of the conditions tested.

Additional tests are planned in the field to compare the earlier infiltration rates observed by Pitt, *et al*. 1999b for a broader range of soil conditions. In addition, *in-situ* soil density values will be determined for comparison to these laboratory test results. Finally, tests should be conducted to compare rain induced infiltration with double-ring infiltration rates. Our earlier work indicated that the double-ring values could be substantially greater than observed during actual rains, but would be useful for designing biofiltration and other infiltration stormwater controls.

The use of soil amendments, or otherwise modifying soil structure and chemical characteristics, is becoming an increasingly popular stormwater control practice. However, little information is available to reasonably quantify benefits and problems associated with these changes. An example examination of appropriate soil chemical characteristics, along with surface and subsurface runoff quantity and quality, was shown during the Seattle tests. It is recommended that researchers considering soil modifications as a stormwater management option conduct similar local tests in order to understand the effects these soil changes may have on runoff quality and quantity. During these Seattle tests, the compost was found to have significant sorption and ion exchange capacity that was responsible for pollutant reductions in the infiltrating water. However, the newly placed compost also leached large amounts of nutrients to the surface and subsurface waters. Related tests with older test plots in the Seattle area found much less pronounced degradation of surface and subsurface flows with aging of the compost amendments. In addition, it is likely that the use of a smaller fraction of compost would have resulted in fewer negative problems, while providing most of the benefits. Again, local studies using locally available compost and soils, would be needed to examine this emerging stormwater management option more thoroughly.

Table 15. Significant Infiltration Models

Soil Types	Compaction Method	Dry Bulk Density Before Test (g/cc)	No Observed Infiltration during Tests (use 0 in/hr)	Model Not Significant, Use Constant Infiltration Rates (in/hr)	Use Horton (or other) Infiltration Model) (use coefficients shown on Table 12)
Silt	Hand	1.508			X (k not significant)
	Standard	1.680		X (0.034)	
	Modified	1.740		X (0.003)	
Sand	Hand	1.451		X (3.06)	
	Standard	1.494			X (use 0 for Fc, k not significant)
	Modified	1.620		X (3.19)	
Clay	Hand	1.242			X (all coefficients significant at <0.05)
	Standard	N/A	X		
	Modified	N/A	X		
Sandy Loam	Hand	1.595			X (use 0 for Fc, k not significant)
	Standard	1.653			X (use 0 for Fc, k not significant)
	Modified	1.992			X (k significant at 0.17 level)
Silt Loam	Hand	1.504			X (k significant at 0.15 level)
	Standard	1.593		X (0.027)	
	Modified	1.690		X (0.0017)	
Clay Loam	Hand	1.502			X (increase rate with time, Fc and k not significant)
	Standard	1.703		X (0.016)	
	Modified	1.911	X		
Clay Mix	Hand	1.399	X		
	Standard	1.685	X		
	Modified	1.929	X		

These data can be utilized by stormwater modelers to better predict the behavior of urban soils, by site developers to better plan and compensate for detrimental effects on soils associated with development, and by stormwater managers and drainage engineers for more appropriate designs of stormwater control devices. As an example, SLAMM, the Source Loading and Management Model (Pitt and Voorhees 1995, www.winslamm.com) incorporates this soil information (and Monte Carlo components) in the evaluation of biofiltration and infiltration devices, enabling more efficient evaluations of alternative stormwater controls and development options. It is relatively straight-forward to incorporate the effects of disturbed urban soils in many stormwater management models. However, site-specific calibration and verification monitoring is still highly recommended for the most useful results.

Acknowledgements

Much of the infiltration measurements were carried out as class projects by University of Alabama at Birmingham hydrology, experimental design, and soil mechanics students. Choo Keong Ong directed the laboratory compaction tests, while Janice Lantrip directed the field infiltration tests. Specific thanks are given to the following students who assisted with the projects summarized here: Robecca Martin, Stacey Sprayberry, Muhammad Salman, Wade Burcham, Brian Adkins, Sarah Braswell, Scott Lee, and Jennifer Harper. Partial support was provided by the Urban Watershed Management Branch, U.S. Environmental Protection Agency, Edison, NJ for portions of the field measurements, including the amended soil tests. Thomas O'Connor was the EPA project officer and provided valuable project guidance.

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