Presented at the 9th *International Conference on Urban Drainage*. IAHR, IWA, EWRI, and ASCE. Portland, Oregon, September 8-13, 2002.

Compacted Urban Soils Effects on Infiltration and Bioretention Stormwater Control Designs

Robert Pitt, P.E.* Shen-En Chen, P.E.** and Shirley Clark, P.E.**

*Department of Civil and Environmental Engineering, The University of Alabama, Tuscaloosa, AL 35487-0205
**Department of Civil and Environmental Engineering, The University of Alabama at Birmingham, Birmingham, AL 35226

Abstract

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. Additional tests were therefore conducted to investigate detailed infiltration behavior of disturbed urban soils.

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 bioretention devices can be jeopardized. Basic infiltration measurements in disturbed urban soils were conducted during an EPA-sponsored project by Pitt, *et al* (1999a), 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 1999b). 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 recently collected information and it is hoped that it will prove useful to both stormwater practice designers and to modelers.

Introduction and Summary

The role of urban soils in stormwater management cannot be under-estimated. Although landscaped areas typically produce relatively small fractions of the annual runoff volumes (and pollutant discharges) in most areas, they need to be considered as part of most control scenarios. In stormwater quality management, the simplest approach is to attempt to maintain the relative values of the hydrologic cycle components after development compared to pre-development conditions. This usually implies the use of infiltration controls to compensate for the increased pavement and roof areas. This can be a difficult objective to meet. However, with a better understanding of urban soil characteristics, and how they may be improved, this objective can be more realistically obtained.

Whenever one talks of stormwater infiltration, potential groundwater contamination questions arise. Prior EPA-funded research, an updated book, and a more recent review paper (Pitt, *et al*. 1994, 1996 and 1999b) discuss the potential for this problem. This material shows that is possible to incorporate many stormwater infiltration options in urban areas, as long as suitable care is taken. Infiltration controls should especially be considered in residential areas where the runoff is relatively uncontaminated and surface infiltration can typically be applied. Manufacturing industrial areas and subsurface injection should normally be excluded from stormwater infiltration consideration, in contrast.

Over the past few years, we have conducted several sets of tests, both in the field and in the laboratory. We have found that typical soil compaction results in substantial reductions in infiltration rates, especially for clayey soils, as expected. Sandy soils are better able to withstand compaction, although their infiltration rates are still significantly reduced.

A previous EPA report (Pitt 1999a) describes the results from a series of tests that have examined how the infiltration capacity of compacted soils can be recovered through the use of soil amendments (such as composts). This work has shown that these soil amendments not only allow major improvements in infiltration rates, but also provide added protection to groundwater resources, especially from heavy metal contamination. Newly placed compost amendments, however, may cause increased nutrient discharges until the material is better stabilized (usually within a couple of years). Information collected during research on stormwater filter media (Clark and Pitt 1999) has also allowed us to develop a listing of desirable traits for soil amendments and to recommend several media that may be good candidates as soil amendments.

The NRCS (2001), especially in New Jersey, have also been active in investigating problems associated with urban soils during land development.

Alternative stormwater management options can be examined using the Source Loading and Management Model (SLAMM) and this soil information. The use of bioretention controls, such as roof gardens for example, can result in almost complete removal of roof runoff from the surface runoff component. It must be recognized that matching pre-development runoff characteristics through stormwater controls at the time of development may not be possible. Certainly, the careful use of different types of infiltration and bioretention controls, especially in low and medium density developments, are more likely to meet pre-development conditions than if these controls are not used. Accurate hydrologic modeling and correct design of these practices that consider the unique features of urban soils will help in minimizing many types of urban receiving water problems.

Areas have increased runoff after development due to a number of reasons. The most important cause is usually the increased amount of pavement and roof areas. However, as noted in this paper, urban soils also undergo major modifications that also result in increased runoff. These soil modifications may mostly affect infiltration (as described in the following paper sections), but other soil changes also occur. Specifically, reductions in the organic content of the surface soil layers and removal of plants will reduce the evapotranspiration (ET) losses and contribute to increases in runoff. This is especially important in areas where surface soils are relatively shallow and located above impermeable layers (such as the glacial till in the Seattle area, the location of our research on amended soils that was conducted to increase the ET rates of urban soils, Harrison, et al. 1997 and Pitt, et al. 1999a).

The soil compaction during construction and use likely causes most of the reduced infiltration capacity of urban soils. In addition, many more subtle changes will also reduce infiltration, such as the replacement of native plants which typically have much deeper root systems with shallow-rooted grasses. Many of these subtle changes contribute to the variations in the measured infiltration rates noted during these experiments reported in this paper. The removal of the native surface soils results in the removal of organic matter, mature and deep-rooted plants, and the soils themselves, often exposing a deeper soil material that is much less able to allow infiltration or evapotranspiration.

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 from the vadose zone into the saturated zone. During periods of rainfall excess, long-term 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 soil 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).

Natural infiltration is significantly reduced in urban areas due to several factors: the decreased area of exposed soils, removal of surface soils and exposing subsurface soils, and compaction of the soils during earth moving and construction operations. The decreased areas of soils are typically associated with increased runoff volumes and peak flow rates, while the effects of soil disturbance are rarely considered. Infiltration practices have long been applied in many areas to compensate for the decreased natural infiltration areas, but with limited success. Silting of the infiltration areas is usually responsible for early failures of these devices, although compaction from heavy traffic is also a recognized problem. More recently, "bioretention" practices, that rely more on surface infiltration in extensively vegetated areas, are gaining in popularity and appear to be a more robust solution than conventional infiltration trenches. These bioretention devices also allow modifications of the soil with amendments.

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 1999b) 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 zone. Stormwater salts, some pathogens, 1,3-dichlorobenzene, pyrene, fluoranthene, and zinc, were found to have high potentials for contaminating groundwater, under some conditions. Generally, there is only a 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 increased 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. Table 1 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 most of the particulate-bound 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, 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.

Table 1. Groundwater Contamination Potential for Stormwater Pollutants (Source: Pitt, *et al.* 1996)

	Compounds	Mobility (sandy/low organic soils)	Abundance in stormwater	Fraction filterable	Contamination potential for surface infilt. and no pretreatment	Contamination potential for surface infilt. with sedimentation	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

- 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.

- 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.

Prior Infiltration Measurements in Disturbed Urban Soils. A series of 153 double ring infiltrometer tests were conducted in disturbed urban soils in the Birmingham, and Mobile, Alabama, areas (Pitt, *et al.* 1999a). The tests were organized in a complete 23 factorial design (Box, *et al.* 1978) to examine the effects of soil-water, soil texture, and soil density (compaction) on water infiltration through historically disturbed urban soils. 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. 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:

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, compacted 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. These test sites did not adequately represent a wide range of age conditions for each test condition, so the effects of age could not be directly determined. The WI Dept. of Natural Resources and the University of Wisconsin (Roger Bannerman, WI DNR, 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.

Three TURF-TEC Infiltrometers were used within a meter from each other to indicate the infiltration rate variability of soils in close proximity. These 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.). 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. 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 each five minute time period.

The weather occurring during this testing phase 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 sunny, hot days. The saturated tests were conducted after through soaking of the ground by natural rain or by irrigation. The soil-water content was measured in the field using a portable soil moisture meter and in the laboratory using standard soil-moisture content methods. Saturated conditions occurred for most soils when the soil-moisture content exceeded about 20%.

The texture of the samples were determined by ASTM standard sieve analyses (ASTM D 422 –63 (*Standard Test Method For Particle Size Analysis of Soils*). "Clayey" soils had 30 to 98% clay, 2 to 45% silt, and 2 to 45% sand. This category included clay and clay loam soils. "Sandy" soils had 65 to 95% sand, 2 to 25% silt, and 5 to 35% clay. This category included sand, loamy sand, and sandy loam soils. No natural soils were tested that were predominately silt or loam.

The soil compaction at each site was measured using a cone penetrometer (DICKEY-john Soil Compaction Tester Penetrometer). Penetrometer measurements are sensitive to water content. Therefore, these 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 vehicle 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.

Figures 1 and 2 are 3D plots of the field infiltration data, illustrating the effects of soil-moisture and compaction, for both sands and clays. Four general conditions were observed to be statistically unique, as listed on Table 2. 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 clayey soils, with saturated and compacted clayey soils having very little effective infiltration.

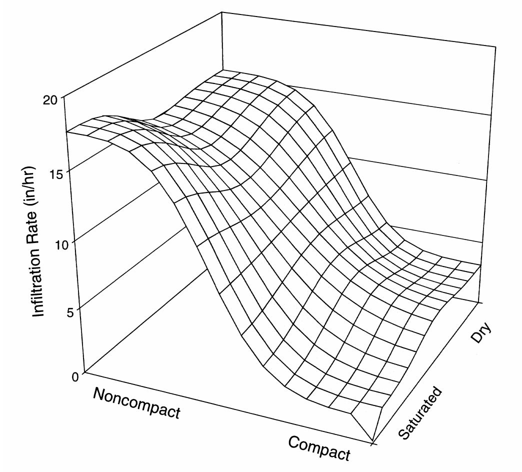


Figure 1. Three dimensional plot of infiltration rates for sandy soil conditions.

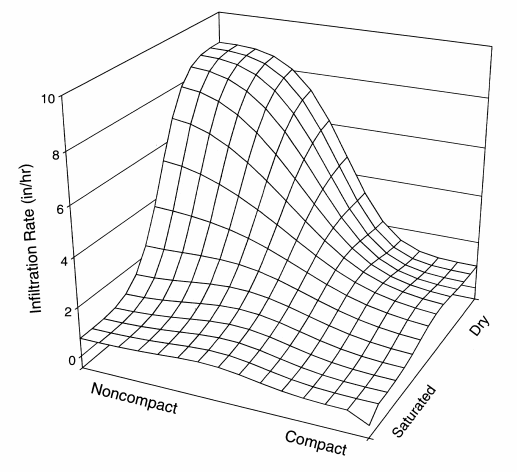


Figure 2. Three dimensional plot of infiltration rates for clayey soil conditions.

Table 2. 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

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. 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 best to use a Monte Carlo stochastic component in a runoff model to describe these variations for disturbed urban soils.

As one example of an approach, Table 3 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 3 through 6 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 not possible.

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:

Table 3. Soil Infiltration Rates for Different Categories and Storm Durations (all rate values are in inches per hour)

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

- 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 4 (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.

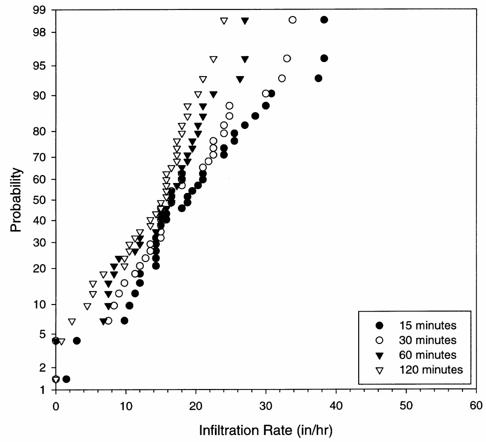


Figure 3. Probability plots for infiltration measurements for noncompacted, sandy soil, conditions.

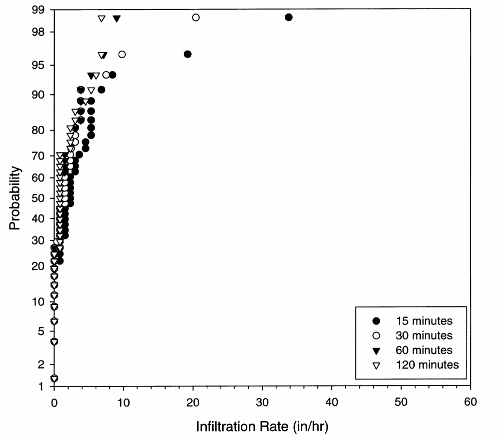
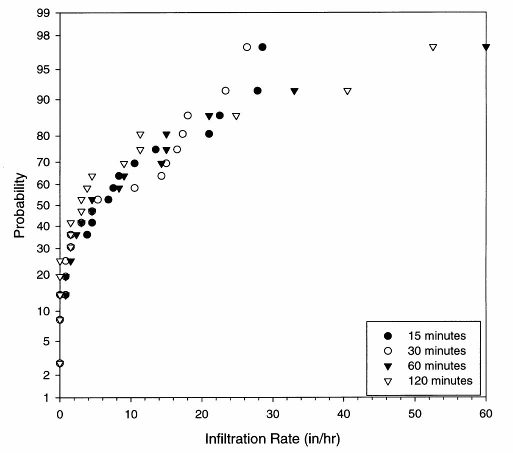


Figure 4. Probability plots for infiltration measurements for compacted, sandy soil, conditions.



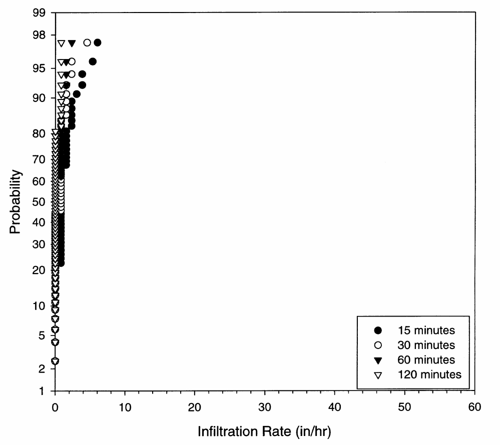


Figure 5. Probability plots for infiltration measurements for dry-noncompacted, clayey soil, conditions.	**Figure 6. Probability plots for infiltration measurements for wet-noncompacted, dry-compacted, and wet-compacted, clayey soil conditions.**

Table 4. 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

Laboratory Controlled Compaction Tests

Laboratory Test Methods. Previous research (Pitt, et al. 1999a), as summarized above, has identified significant reductions in infiltration rates in disturbed urban soils. The tests reported in the following discussion were recently conducted under more controlled laboratory conditions and represent a wider range of soil textures and known soil density values compared to 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.

Test samples were prepared by mixing known quantities of sand, silt, and clay to correspond to defined soil textures, as shown in Table 5. 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 6 lists the actual soil moisture levels at the beginning of the tests, along with the actual dry bulk soil densities and indications of root growth problems.

Three methods were used to modify the compaction of the soil samples: hand compaction, Standard Proctor Compaction, and Modified Proctor Compaction. Both Standard and Modified 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 head for these permeability tests 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°F.

Table 5. 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

Table 6. Soil Moisture and Density Values during Laboratory Tests

			Root Growth Potential Problems (NRCS 2001)				
Soil Types	**Compaction Method**	**Dry Bulk Density Before Test (g/cc)**	**Ideal Bulk Density**	**Bulk Densities that may Affect Root Growth**	**Bulk Densities that Restrict Root Growth**	**Before Test Moisture Content (%)**	**After Test Moisture Content (%)**
Silt	Hand	1.508		X		9.7	22.9
	Standard	1.680		X		8.4	17.9
	Modified	1.740			X	7.8	23.9
Sand	Hand	1.451	X			5.4	21.6
	Standard	1.494	X			4.7	16.4
	Modified	1.620		X		2.0	16.1
Clay	Hand	1.242		X		10.6	N/A
Sandy Loam	Hand	1.595		X		7.6	20.2
	Standard	1.653		X		7.6	18.9
	Modified	1.992			X	7.6	9.9
Silt Loam	Hand	1.504		X		8.1	23.0
	Standard	1.593		X		8.1	27.8
	Modified	1.690		X		8.1	27.8
Clay Loam	Hand	1.502		X		9.1	24.1
	Standard	1.703			X	9.1	19.0
	Modified	1.911			X	9.1	14.5
Clay Mix	Hand	1.399		X		8.2	42.2
	Standard	1.685			X	8.2	N/A

	Modified	1.929			X	8.2	N/A

As shown on Table 6, 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.

Also shown on Table 6 are indications of root growth problems for these soil densities, based on the NRCS Soil Quality Institute 2000 report, as summarized by the Ocean County Soil Conservation District (NRCS 2001). The only soil test mixtures that were in the “ideal” range for plant growth were the hand placed and standard compacted sands. Most of the modified compacted test mixtures were in the range that are expected to restrict root growth, the exceptions were the sand and silt loam mixtures. The rest of the samples were in the range that may affect root growth. These tests cover a wide range of conditions that may be expected in urban areas.

Laboratory Test Results. Figures 7 through 11 show the infiltration plots obtained during these laboratory compaction tests. Since the hydraulic heads for these experiments was a little more than 1 m, the values obtained would not be very applicable to typical rainfall infiltration values. However, they may be comparable to bioretention or other infiltration devices that have substantial head during operation. The final percolation values may be indicative of long-term infiltration rates, and these results do illustrate the dramatic effects of soil compaction and texture on the infiltration rates.

Most recently, another series of controlled laboratory tests were conducted to better simulate field conditions and standard double-ring infiltration tests, as shown in Table 7. Six soil samples were tested, each at the three different compaction levels described previously. The same permeability test cylinders were used as in the above tests, but plastic extensions were used to enable small depths of standing water on top of the soil test mixtures (4.3 inches, or 11.4 cm, maximum head). Most of these tests were completed within 3 hours, but some were continued for more than 150 hours. Only one to three observation intervals were used during these tests, so they did not have sufficient resolution or enough data points to attempt to fit to standard infiltration equations. However, as noted previously, these longer-term averaged values may be more suitable for infiltration rate predictions due to the high natural variability observed during the initial field tests. As shown, there was very little variation between the different time periods for these tests, compared to the differences between the compaction or texture groupings. Also, sandy soils can still provide substantial infiltration capacities, even when compacted greatly, in contrast to the soils having clays that are very susceptible to compaction.

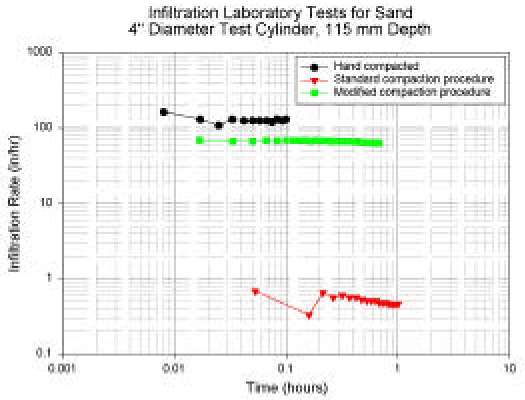


Figure 7. Sandy soil laboratory infiltration test results.

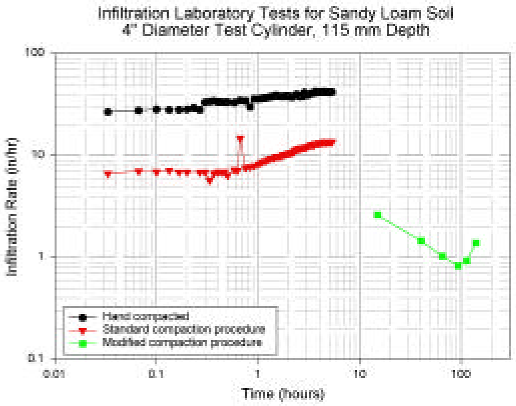


Figure 8. Sandy loam soil laboratory infiltration test results.

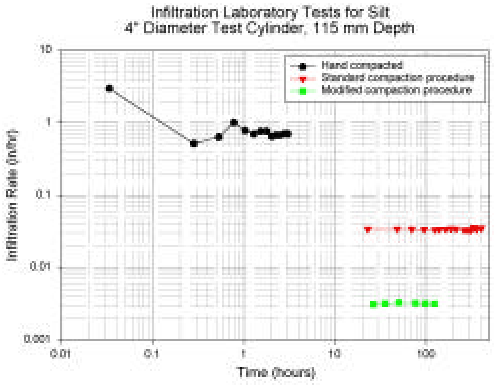


Figure 9. Silty soil laboratory infiltration test results.

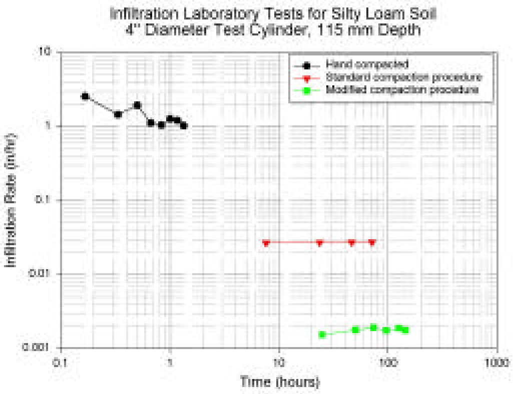


Figure 10. Silty loam soil laboratory infiltration test results.

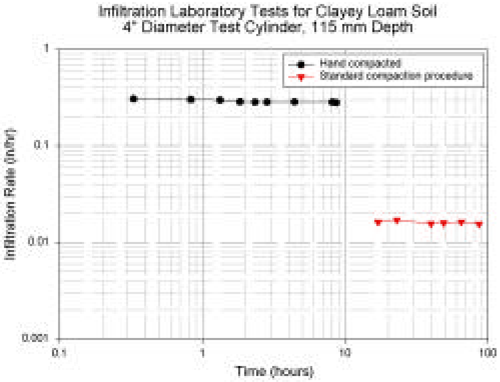


Figure 11. Clayey loam soil laboratory infiltration test results.

Table 7. Low-Head Laboratory Infiltration Tests for Various Soil Textures and Densities (densities and observed infiltration rates)

	Hand Compaction	Standard Compaction	Modified Compaction
Sand (100% sand)	Density: 1.36 g/cc (ideal for roots) 0 to 0.48 hrs: 9.35 in/hr 0.48 to 1.05 hrs: 7.87 in/hr 1.05 to 1.58 hrs: 8.46 in/hr	Density: 1.71 g/cc (may affect roots) 0 to 1.33 hrs: 3.37 in/hr 1.33 to 2.71 hrs: 3.26 in/hr	Density: 1.70 g/cc (may affect roots) 0 to 0.90 hrs: 4.98 in/hr 0.90 to 1.83 hrs: 4.86 in/hr 1.83 to 2.7 hrs: 5.16 in/hr
Silt (100% silt)	Density: 1.36 g/cc (close to ideal for roots) 0 to 8.33 hrs: 0.26 in/hr 8.33 to 17.78 hrs: 0.24 in/hr 17.78 to 35.08 hrs: 0.25 in/hr	Density: 1.52 g/cc (may affect roots) 0 to 24.22 hrs: 0.015 in/hr 24.22 to 48.09: 0.015 in/hr	Density: 1.75 g/cc (will likely restrict roots) 0 to 24.20 hrs: 0.0098 in/hr 24.20 to 48.07: 0.0099 in/hr
Clay (100% clay)	Density: 1.45 g/cc (may affect roots) 0 to 22.58 hrs: 0.019 in/hr 22.58 to 47.51 hrs: 0.016 in/hr	Density: 1.62 g/cc (will likely restrict roots) 0 to 100 hrs: <2X10-3 in/hr	Density: 1.88 g/cc (will likely restrict roots) 0 to 100 hrs: <2X10-3 in/hr
Sandy Loam (70% sand, 20% silt, 10% clay)	Density: 1.44 g/cc (close to ideal for roots) 0 to 1.17 hrs: 1.08 in/hr 1.17 to 4.37 hrs: 1.40 in/hr 4.37 to 7.45 hrs: 1.45 in/hr	Density: 1.88 g/cc (will likely restrict roots) 0 to 3.82 hrs: 0.41 in/hr 3.82 to 24.32 hrs: 0.22 in/hr	Density: 2.04 g/cc (will likely restrict roots) 0 to 23.50 hrs: 0.013 in/hr 23.50 to 175.05 hrs: 0.011 in/hr
Silty Loam (70% silt, 20% sand, 10% clay)	Density: 1.40 g/cc (may affect roots) 0 to 7.22 hrs: 0.17 in/hr 7.22 to 24.82 hrs: 0.12 in/hr 24.82 to 47.09 hrs: 0.11 in/hr	Density: 1.64 g/cc (will likely restrict roots) 0 to 24.62 hrs: 0.014 in/hr 24.62 to 143.52 hrs: 0.0046 in/hr	Density: 1.98 g/cc (will likely restrict roots) 0 to 24.62 hrs: 0.013 in/hr 24.62 to 143.52 hrs: 0.0030 in/hr
Clay Loam (40% silt, 30% sand, 30% clay)	Density: 1.48 g/cc (may affect roots) 0 to 2.33 hrs: 0.61 in/hr 2.33 to 6.13 hrs: 0.39 in/hr	Density: 1.66 g/cc (will likely restrict roots) 0 to 20.83 hrs: 0.016 in/hr 20.83 to 92.83 hrs: 0.0066 in/hr	Density: 1.95 g/cc (will likely restrict roots) 0 to 20.83 hrs: <0.0095 in/hr 20.83 to 92.83 hrs: 0.0038 in/hr

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, and to better design bioretention stormwater control devices. 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 field measurements of 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. Also, 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 bioretention devices).

Table 8 compares the infiltration test results from these field and laboratory investigations. The low-head laboratory and field results were similar, except for the higher rates observed for the noncompacted clay field tests. These higher results could reflect actual macro-structure conditions in the natural soils, or the compaction levels obtained in the laboratory were unusually high compared to field conditions. In addition, the high-head laboratory test results produced infiltration rates substantially greater than for the similar low-head results for sandy soil conditions, but not for the other soils. We have scheduled a "final" series of tests over the coming summer to examine some of these issues again. We expect to report these results during the conference presentation. Specifically, we anticipate repeating the low-head laboratory infiltration tests, but with higher resolution measurements. In addition, we will conduct a new series of field measurements, and will specifically measure soil density along with moisture and texture. Finally, we will use selected field soil samples for controlled compaction tests in the laboratory. These tests should enable us to specifically investigate alternative conventional infiltration equations, and examine needed modifications for typical compaction conditions; we will confirm a simple method to measure compaction in the field; and we will verify the laboratory measurements for field applications.

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 (Pitt, *et al*. 1999a). 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 the 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 8. Comparison of Infiltration Rates from Different Test Series

Group	Field Test Average Infiltration Rates (in/hr and COV)	Low-head Laboratory Test Results	High-head Laboratory Test Results
Noncompacted sandy soils	13 (0.4)	8 to 9.5 in/hr	30 to 120 in/hr
compact sandy soils	1.4 (1.3)	3 to 5 in/hr	0.5 to 60 in/hr
Noncompacted and dry clayey soils	9.8 (1.5)	0.4 to 0.6 in/hr	0 to 0.3 in/hr
All other clayey soils (compacted and dry, plus all wetter conditions)	0.2 (2.4)	0 to 0.4 in/hr	0 to 0.02 in/hr
Noncompacted silty and loamy soils	na	0.25 to 0.6 in/hr	0.5 to 3 in/hr
Compacted silty and loamy soils	na	0 to 0.02 in/hr	0 to 0.04 in/hr

This information can be effectively used in the modeling of small-scale stormwater controls, such as bioretention devices located near buildings and grass swales. As an example of the benefits these devices may provide in typical urban areas, WinSLAMM, the Source Loading and Management Model (www.winslamm.com) (Pitt and Voorhees 1995) was used to calculate the expected reductions in annual runoff volumes for several different controls. Table 9 illustrates these example reductions for Phoenix (9.3 in/year of rainfall), Seattle (33.4 in/yr), and Birmingham, AL (52.5 in/yr). The reductions are only for roof runoff control, but illustrate the magnitude of the reductions possible. The calculations are based on long-term continuous simulations (about 5 years of historical rain records were used). The test site is a single-family residential area with silty soils and directly connected roofs. In this type of area, directly connected residential roofs produce about 30 to 35% of the annual runoff volume for the rain conditions in these three cities.

Table 9. Example Calculations of Benefits of On-Site Stormwater Controls (% reduction of annual roof runoff volumes).

	Phoenix, AZ	Seattle, WA	Birmingham, AL
Roof garden (1in/hr amended soils, 60ft^2 per house)	96%	100%	87%
Cistern for stormwater storage and reuse of roof water (375ft^3 per house)	88	67	66
Disconnect roof runoff to allow drainage onto silty soils	91	87	84
Green roof (vegetated roof surface)	84	77	75

The roof garden option using amended soils provides large reductions, even for a relatively small treatment area. This is especially useful for sites with extremely poor soils or small landscaped areas. Bioretention options can be sized to provide specifically desired runoff reductions, considering actual, or improved, soil conditions. This table also shows potential runoff reductions associated with storage of roof runoff for later reuse for on-site irrigation, and an option for a green roof, where the roof surface is actually vegetated allowing increased evapotranspiration.

This table shows that even for a wide range of rainfall conditions, these options can provide substantial reductions in runoff volume from residential roofs. An estimated 20 to 35% reductions in annual runoff volumes for the complete drainage areas would be expected for these alternatives. Obviously, these controls can be applied to the runoff from other areas, in addition to the roofs, for additional runoff reductions.

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. EPA support was also provided for the research on potential groundwater contamination associated with stormwater infiltration. Thomas O'Connor was the EPA project officer and provided valuable project guidance.

References

Akan, A. O., *Urban Stormwater Hydrology: A Guide to Engineering Calculations*. Lancaster. PA: Technomic Publishing Co., Inc., 1993.

American Society of Testing and Materials. 1996 *Annual Book of ASTM Standards*. West Conshohocken. PA: ASTM vol. 04.08,1994.

Bedient, P.B., and Huber, W.C. *Hydrology and Floodplain Analysis.* New York: Addison-Wesley Publishing Co., 1992.

Box, G.E.P., Hunter, W.G., and Hunter, J.S.. *Statistics for Experimenters*. John Wiley and Sons, New York, 1978.

Clark, S. and R. Pitt. *Stormwater Treatment at Critical Areas, Vol. 3: Evaluation of Filtration Media for Stormwater Treatment*. U.S. Environmental Protection Agency, Water Supply and Water Resources Division, National Risk Management Research Laboratory. EPA/600/R-00/016, Cincinnati, Ohio. 442 pgs. October 1999.

Das, B.M. *Principals of Geotechnical Engineering* Boston: PWS Publishing Co., 1994.

Dickey-John Corporation. *Installation Instructions Soil Compaction Tester.* Auburn, Illinois:, 1987.

Gilbert, R.O., *Statistical Methods for Environmental Pollution Monitoring* New York: Van Nostrand Reinhold Publishing Co., 1987.

Harrison, R.B., M.A. Grey, C.L. Henry, and D. Xue. *Field Test of Compost Amendment to Reduce Nutrient Runoff*. Prepared for the City of Redmond. College of Forestry Resources, University of Washington, Seattle. May 1997.

Horton, R.E. "An approach toward a physical interpretation of infiltration capacity." *Transactions of the American Geophysical Union*. Vol. 20, pp. 693 – 711. 1939.

McCuen, R. *Hydrologic Analysis and Design, 2nd edition*. Prentice Hall. 1998.

Morel-Seytoux, H.J. "Derivation of Equations for Variable Rainfall Infiltration." *Water Resources Research. pp.* 1012-1020. August 1978.

NRCS. Soil Quality Institute 2000, Urban Technical Note 2, as reported by Ocean County Soil Conservation District, Forked River, NJ. 2001.

Pitt, R. *Small Storm Urban Flow and Particulate Washoff Contributions to Outfall Discharges*, Ph.D. Dissertation, Civil and Environmental Engineering Department, University of Wisconsin, Madison, WI, November 1987.

Pitt, R., S. Clark, and K. Parmer. *Protection of Groundwater from Intentional and Nonintentional Stormwater Infiltration*. U.S. Environmental Protection Agency, EPA/600/SR-94/051. PB94-165354AS, Storm and Combined Sewer Program, Cincinnati, Ohio. 187 pgs. May 1994.

Pitt, R. and S.R. Durrans. *Drainage of Water from Pavement Structures*. Alabama Dept. of Transportation. 253 pgs. September 1995.

Pitt, R. and J. Voorhees. "Source loading and management model (SLAMM)." *Seminar Publication: National Conference on Urban Runoff Management: Enhancing Urban Watershed Management at the Local, County, and State Levels*. March 30 – April 2, 1993. Center for Environmental Research Information, U.S. Environmental Protection Agency. EPA/625/R-95/003. Cincinnati. Ohio. pp. 225-243. April 1995.

Pitt, R., S. Clark, K. Parmer, and R. Field. *Groundwater Contamination from Stormwater Infiltration*. Ann Arbor Press. Chelsea, Michigan. 218 pages. 1996.

Pitt, R. "Small storm hydrology and why it is important for the design of stormwater control practices." In: *Advances in Modeling the Management of Stormwater Impacts, Volume 7.* (Edited by W. James). Computational Hydraulics International, Guelph, Ontario and Lewis Publishers/CRC Press. 1999.

Pitt, R., J. Lantrip, R. Harrison, C. Henry, and D. Hue. *Infiltration through Disturbed Urban Soils and Compost-Amended Soil Effects on Runoff Quality and Quantity.* U.S. Environmental Protection Agency, Water Supply and Water Resources Division, National Risk Management Research Laboratory. EPA 600/R-00/016. Cincinnati, Ohio. 231 pgs. 1999a.

Pitt, R., S. Clark, and R. Field. "Groundwater contamination potential from stormwater infiltration practices." *Urban Water*. Vol. 1, no. 3, pp. 217-236. 1999b.

Pitt, R. and J. Lantrip. "Infiltration through disturbed urban soils." In: *Advances in Modeling the Management of Stormwater Impacts, Volume 8*. (Edited by W. James). Computational Hydraulics International, Guelph, Ontario. 2000.

Turf Tec International. *Turf Tec Instructions.* Oakland Park, Florida. 1989.

United States Department of Agriculture, Soil Conservation Service (now Natural Resources Conservation Service). *Soil Survey of Chilton County,* Alabama. October 1972.

United States Department of Agriculture, Soil Conservation Service (now Natural Resources Conservation Service), *Soil Survey of Jefferson County,* Alabama. August 1982.

United States Department of Agriculture, Soil Conservation Service (now Natural Resources Conservation Service), *Soil Survey of Shelby County,* Alabama. July 1984.

Willeke, G.E., "Time in Urban Hydrology." *Journal of the Hydraulics Division Proceedings of the American Society of Civil Engineers.* pp. 13-29. January 1966.