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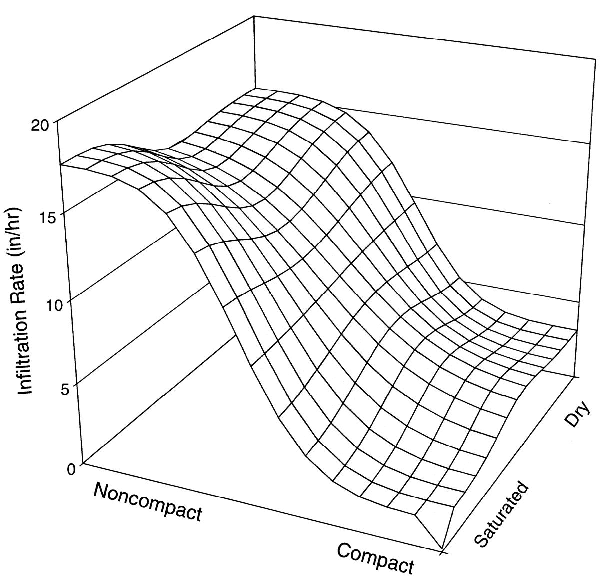
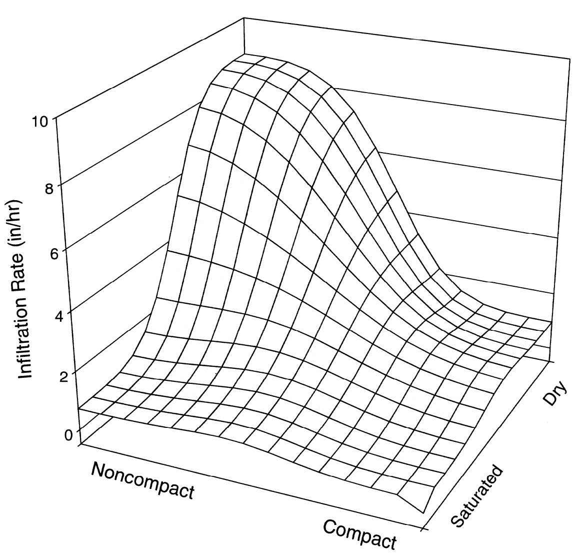
Urban Soil Sampling and Testing – Standard Operating Procedure

Introduction
Hydrologic models must contain a process to address the infiltration of rain water into the soil. The infiltration process in most models is usually dependent on the porosity and moisture content of the soil: in an unsaturated soil, infiltration usually is initially rapid but then declines to a constant value as the soil becomes saturated. Soil infiltration is an issue in urban watershed management due to concerns of groundwater contamination and because poor infiltration conditions after land development, which is one of the causes of increased surface runoff (in addition to increased amounts of impervious surfaces) (Pitt, *et al.* 1994 and 1995). It has been well documented that during urbanization, soils are greatly modified, especially related to soil density. Increased soil compaction results in soils that do not behave in a manner predicted by traditional infiltration models. It is crucial, therefore, that stormwater engineers better understand infiltration in disturbed urban soils. Laboratory and field tests can be used to determine expected infiltration behavior of disturbed urban soils for a specific area. This standard operating procedure (SOP) describes these tests that can be used to determine the behavior of disturbed urban soils.

Since the early 1990s, a series of laboratory and field tests have been developed and conducted on soils covering a wide range of soil textures, densities and stiffness (Pitt, *et al.* 1999). Selected results from these tests are summarized in a recent paper (Pitt, *et al*. 2008). As shown in the following figures, these field tests highlighted the importance of compaction on the infiltration rate of soils. For sandy soils, minimal effects are seen associated antecedent moisture conditions compared to soil compaction. For the clayey soils, both the compaction level and antecedent moisture conditions are likely important in determining the infiltration rate.



Three dimensional plot of infiltration rates for sandy soil conditions.



Three dimensional plot of infiltration rates for clayey soil conditions.

Effects of soil moisture and soil compaction on infiltration rates (Pitt, *et al.* 1999).

Methodology

Site soil evaluations have several components, including infiltration measurements, along with soil density, texture, and moisture determinations. The following describe these tests, with appropriate references to standard protocols.

Infiltration Measurements

Small-scale infiltrometers have been used to measure infiltration rates in disturbed urban soils and in other locations. Using several of these units simultaneously, and in relatively close proximity, enables measurements of variability to be determined. These tests are also relatively rapid, enabling several sites to be investigated in one day, if 6 units are used. This is substantially faster, and results in better measurements of infiltration variability, than is possible if using traditional double-ring infiltrometers. However, any standard or small double-ring infiltrometer likely over-estimates the actual infiltration rates for a specific site. The relatively small areas being tested, even with the larger traditional units, have substantial edge effects, especially if the area's soils are not saturated. The most precise measurements of infiltration, and which should be used in areas where large infiltration units are being designed, should rely on full-scale tests. These are typically large trenches, constructed to penetrate the depths of soil that the final units will use for infiltration, and use large volumes of water over extended periods of time. For small stormwater biofiltration units, this approach is usually not warranted, while it would be for infiltration galleries that are critical for drainage in enclosed areas.

The procedure described here uses three TURF-TEC Infiltrometers (Turf-Tec, Coral Springs, FL, http://www.turf-tec.com/IN2lit.html) for each area. A small crew of two field personnel can usually conduct two sets simultaneously, if six infiltrometers are available, and if the sites are in relatively close proximity. Three of these units are used, usually within a meter or so of each other, to indicate the infiltration rate variability of soils in close proximity, such as for a single biofiltration facility. Readings are taken about every five minutes over a duration of two hours, or at least until a sustained period of constant infiltration is observed. The incremental infiltration rates are calculated by noting the drop of water level in the inner compartment of each infiltrometer over each five minute time period. In the following example, infiltration was measured at two locations having natural grass covers, and a third measure was for the infiltration after the grass sod was removed. This was done to investigate the influence of the surface vegetation on the infiltration rates. The tests should be done using the surface cover of interest. If measuring the infiltration rates for rainfall on typical turf landscaped areas, then the sod should remain in place (though trimmed in height) for the tests. For biofiltration devices that will be planted with discrete plants and shrubs, the sod should probably be removed to better represent the absence of surface grass thatch.

For tests with sod in place, the grass is cut to a height of several inches to facilitate work. The infiltrometers are then gently driven into the ground up to their "Saturn" ring (ensuring that the infiltrometers are 1 to 2 inches in the ground). After the soil and seal are inspected and ensured to be even and smooth, tap water is then carefully poured into the inner chamber and allowed to overflow into the outer ring. Measurements of water loss are then immediately started. These measurements can be taken every few minutes at the beginning of the test, and less frequently later in the test, or at a constant frequency of about every 5 minutes. The following are photographs of the test setups, along with a filled-out field sheet that was used for recording the water losses in the units.


Set of three Turf-Tec infiltrometers for infiltration measurements in pre-development soils.


Turf-Tec infiltrometer at bare soil location.


Infiltrometer at site with grass.

Turf-Tec infiltrometers


Traditional ASCE double-ring infiltrometer.

Test # NCWN-2 Test site location: Wildwood Apts
Exact location: In front of building #20
Date of test: 5-18-98 Time of day: 12:30 PM

Weather Conditions:
Sunny ✓ Cloudy ____ Windy ____ Calm ____
Other ____

Former rainfall / irrigation Information: dry - rain 7 days ago

Soil texture: clay Age of turf: < 1 yr.

Compaction measurements (using the Dickey-john penetrometer)

Depth	(psi)
Surface	<150
3"	<150
6"	200

Moisture determination (lab)

Crucible Weight (g)	1.0231
Crucible Weight + Wet Sample Weight(g)	26.9686
Wet Sample Weight (g)	25.9455

Crucible Weight (g)	1.0231
Crucible Weight + Dry Sample Weight (g)	19.925
Dry Sample Weight (g)	18.9019

% Moisture 37.3

Infiltration rate measurement (using the Turf-Tec Infiltrometer)

Time	Infiltration rate ACTUAL (inches)	Infiltration rate ACTUAL (16th inch)	Infiltration rate CALCULATED (inches / hour)
5		6	4.5
10		4	3.0
15		3	2.3
20		3	2.3
25		1	0.8
30		1	0.8
35		1	0.8
40		1	0.8
45		0	0
50		0	0
55		1	0.8
60		0	0

Time	Infiltration rate ACTUAL (inches)	Infiltration rate ACTUAL (16th inch)	Infiltration rate CALCULATED (inches / hour)
65		1	0.8
70		0	0
75		1	0.8
80		1	0.8
85		0	0
90		0	0
95		1	0.8
100		1	0.8
105		0	0
110		0	0
115		1	0.8
120		0	0

Additional comments: Soil was moistened to saturation prior to testing.

Calculation of Infiltration Rates

One of the oldest and most widely used infiltration equations was developed by Horton (1939). This equation can be used to compare the measured equation parameters with published literature values. The equation is as follows:

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

where:

f = infiltration rate at time t (in/hr),
f_o = initial infiltration rate (in/hr),
f_c = final infiltration rate (in/hr),
k = first-order rate 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. 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). However, integrated forms of the equation can be used that do consider the amount of water added to the soil.

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 by many (Akan 1993). The following lists shows commonly used Horton infiltration parameter values, as summarized by Akan (1993):

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

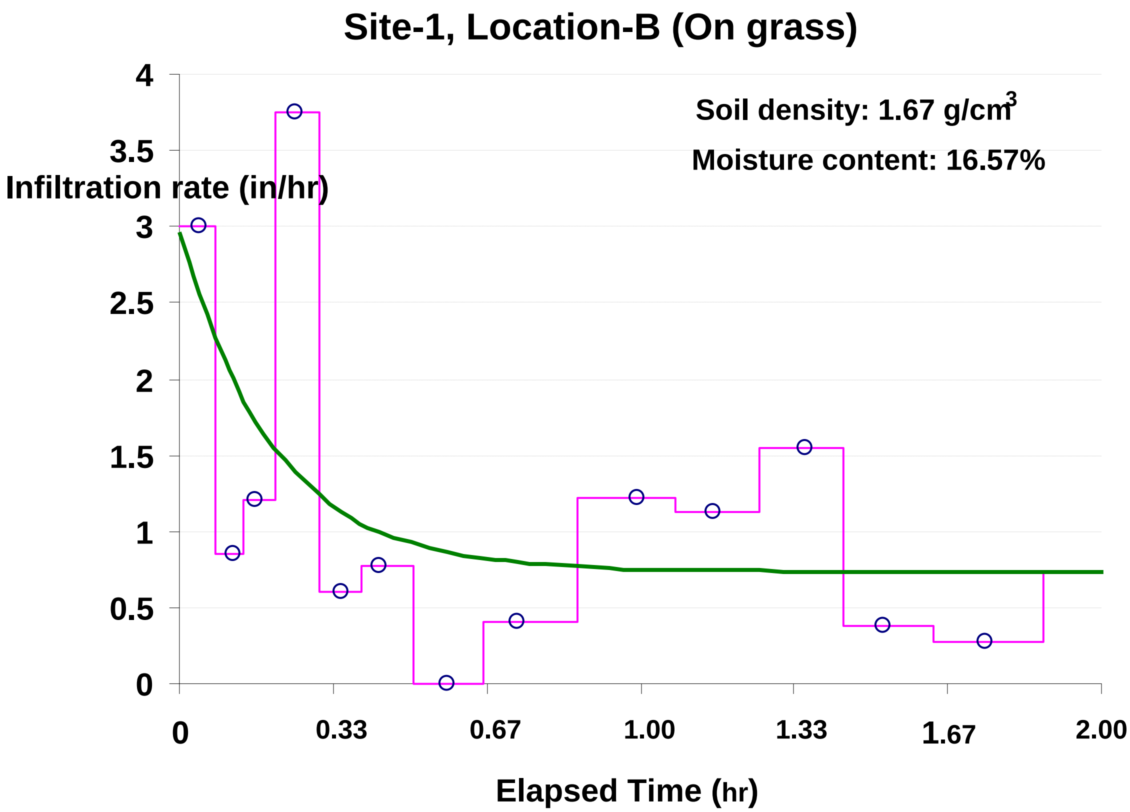
The following table summarizes the Horton equation coefficients as measured by Pitt, *et al.* 1999 for different urban soils, showing the dramatic effect soil density has on the infiltration characteristics:

Infilatration Parameter	Soil Group	90%	75%	Median	25%	10%
f_o (in/hr)	Clay - Dry Noncompact	42	24	11	7	5
	Clay - Other	7	3.75	2	1	0
	Sand - Compact	42	12	5	1.5	0
	Sand - Noncompact	52	46	34	24	0.25
f_c (in/hr)	Clay - Dry Noncompact	20	12	3	0.75	0.25
	Clay - Other	0.75	0.5	0.25	0	0
	Sand - Compact	5	1.25	0.5	0.25	0
	Sand - Noncompact	24	19	15	9	0
k	Clay - Dry Noncompact	18	13	9.5	4.5	3
	Clay - Other	11	6.5	3.75	1.75	0
	Sand - Compact	17	12	6	3	1
	Sand - Noncompact	19	12	5	2	0
15 minutes averaged (in/hr)	Clay - Dry Noncompact	28	14	6	3	2
	Clay - Other	4	2	1	0.25	0
	Sand - Compact	12	8	4	2	0.5
	Sand - Noncompact	37	29	25	17.5	6.5
30 minutes averaged (in/hr)	Clay - Dry Noncompact	23	19	6	2	1.75
	Clay - Other	2.5	1.75	1	0.25	0
	Sand - Compact	8	6	2.75	1.75	0.25
	Sand - Noncompact	29	26	20	16	5
60 minutes averaged (in/hr)	Clay - Dry Noncompact	23	17	6	2	1.5
	Clay - Other	2	1	0.5	0.25	0
	Sand - Compact	0.75	5	2	1	0.25
	Sand - Noncompact	26	22	17.5	12	4
120 minutes averaged (in/hr)	Clay - Dry Noncompact	22.5	16	5	1	0.75
	Clay - Other	1.25	0.75	0.5	0.25	0
	Sand - Compact	6	4	1	0.5	0
	Sand - Noncompact	24	20	16	11	3

The following is an example of infiltration measurements, showing the spreadsheet summary and the resulting plot of infiltration. It is important that the units be consistent during these analyses. Even though the time was noted in minutes and the water loss readings in 16th of an inch, these were both converted to elapsed time in hours and depth in decimal inches. The incremental infiltration rate is therefore expressed as in/hr and the plot shows these infiltration rates with time, in hours. In this example for one infiltrometer, the resulting rates do not decrease very smoothly, but show the common irregularity common for disturbed urban soils. The early rates are larger than the final rates, as expected, but that may not always be true. The use of at least 3 infiltrometers in an area helps determine the variability of infiltration in an area of interest. Also, due to the highly variable nature of the measured infiltration values, it probably does not matter which infiltration "model" is used to predict infiltration. In our work, we use a probability distribution of the infiltration rates and random rates described by these probability plots. The preceding table shows some of the probability values for the equation parameters, and also shows the actual infiltration rates averaged for different rain durations and soil conditions.

Site 1, Location-B (on Grass)

Time (Reading)	Total Elapsed Time (min)	Total Elapsed Time (hr)	Reading (inch)	Reading (inch)	Incremental Infiltration rate (in/min)	Incremental Infiltration rate (in/hour)
0" (water added)	**0**	**0**	**-2/16**	**-0.125**	0.05	3.00
2' 30"	2.5	0.042	0/16	0	0.05	3.00
5' 54"	6.9	0.115	1/16	0.0625	0.01	0.85
10' 00"	10.0	0.167	2/16	0.125	0.02	1.21
10' 00" (water added)	**10.0**	**0.167**	**-2/16**	**-0.125**	0.06	3.75
15' 00"	15.0	0.250	3/16	0.1875	0.06	3.75
21' 13"	21.2	0.353	4/16	0.25	0.01	0.60
26' 05"	26.1	0.435	5/16	0.3125	0.01	0.77
35' 02"	35.0	0.583	5/16	0.3125	0.00	0.00
35' 02" (water added)	**35.0**	**0.583**	**-2/16**	**-0.125**	0.01	0.41
44' 07"	44.1	0.735	-1/16	-0.0625	0.01	0.41
59' 30"	59.5	0.992	4/16	0.25	0.02	1.22
1, 09' 30"	69.5	1.158	7/16	0.4375	0.02	1.13
1, 09' 30" (water added)	**69.5**	**1.158**	**-2/16**	**-0.125**	0.03	1.55
1, 21' 35"	81.6	1.360	3/16	0.1875	0.03	1.55
1, 31' 30"	91.5	1.525	4/16	0.25	0.01	0.38
1, 44' 55"	104.9	1.748	5/16	0.3125	0.00	0.28
1, 44' 55" (water added)	**104.9**	**1.748**	**-2/16**	**-0.125**	0.01	0.74
2, 00' 09"	120.2	2.003	1/16	0.0625	0.01	0.74



Soil Density and Moisture Measurements

As noted above, infiltration is strongly affected by the soil density. In fact, for sandy soils, Pitt, *et al.* (1999 and 2008) shows that soil density has a greater effect on infiltration rates than soil moisture, while for clayey soils, soil density has about the same effect on infiltration as does soil moisture. Unfortunately, most stormwater models effectively track soil moisture, but they ignore soil density. It is important to also measure soil density, along with the infiltration rates. The following table shows the effects of soil bulk densities on root growth and typical soil density values:

Bulk Densities and Root Growth (NRCS 2001)

	Ideal bulk density (g/cc)	Bulk densities that may affect root growth (g/cc)	Bulk densities that restrict root growth (g/cc)
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

Most of the measured densities of disturbed urban soils are in the range of values having likely affects on root growth.

Cone penetrometer
One way to quickly determine soil compaction is with a cone penetrometer (DICKEY-john Soil Compaction Tester Penetrometer) and confirmed by the site history. Compacted soils were generally found to have readings of greater than 2070 kP (300 psi) at a depth of 7.5 cm (3 in). However, the cone penetrometer readings decreased when the same soils had higher levels of soil moisture, so this method should only be used for relative measurements in a small area and with soils having the same moisture levels. A cone penetrometer should be used to predict the general soil compaction of an area before the direct soil density measurements are completed in the laboratory. It can also be used in the smallest sites, such as for a rain garden.


Cone penetrometer measurement.

Direct Measurements of Soil Density and Moisture

More precise measurements of soil density (and simultaneous soil moisture determinations) are needed for urban soil investigations. It is possible to directly measure the soil moisture and soil density at the same time as the infiltration tests using a modification of the historical “sand and balloon” test method. In this procedure, the surface vegetation is removed from the test area and a small hole is carefully excavated with a hand trowel. The excavated soil (not including the removed sod) is placed in a zip lock plastic bag to seal in the moisture and is then transported to the laboratory. The preferred sizes of the holes range from about 1 to 2 L in volume (about 6 inches deep and wide), and have smooth sides. After the hole is dug and the soil carefully placed in the zip lock bag, the hole is then filled with clean laboratory Ottawa test sand (or other free-flowing sand) from a graduated cylinder up to the level of the excavated soil. The volume of sand added to fill the hole to the excavated depth is carefully determined and noted. The soil sample is then brought to the laboratory and weighed. It is then dried in a drying oven at 105^{o}C and weighed again to determine the moisture content. The density of the soil is determined by dividing the dry soil mass by the sand volume used to re-fill the hole. The soil moisture content is also determined through the soil drying process. The dried soil can also be used in a sieve analysis to determine the soil texture.


Direct soil density measurement; filling excavated hole with sand.

The laboratory soil moisture is obtained using ASTM method D 2974-87 (*Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils*), while the soil texture is determined by sieve analyses. The samples were prepared based on ASTM 421 *Practice for Dry Preparation of Soil Samples for Particle Size Analysis and Determination of Soil Constants.* The sieve analysis used was the ASTM D 422-63 *Standard Test Method For Particle Size Analysis of Soils* for the particles larger than the No. 200 sieve, along with ASTM D 2488-93 *Standard Practice for Description and Identification of Soils (Visual - Manual Procedure).*

Soil Chemical Measurements

A portion of the dried soil sample should also be sent to the state horticultural lab for further analyses to supplement the above described physical tests. As an example, we use the Auburn University Soil Testing Laboratory where soil texture (% sand, % silt, and % clay), organic matter, cation exchange capacity (CEC), and general nutrients (and fertilizer recommendations) can be analyzed at a very good price. It would have been beneficial to also have organic carbon content measured to supplement the CEC and the organic matter results, if available. Other state agricultural schools likely offer similar services.

The following tables show an example summary of all of the soil test data for a series of recent samples from an agricultural area that is being developed as an industrial park. These analyses were conducted to accurately predict pre-development conditions, and to identify locations where post-development biofiltration controls may be most efficient. These results were also used to predict the performance of regional drainage system components that were built in undisturbed soil areas. A brief example narrative of these results is also provided. These tables also include volatile solids results which were also analyzed in-house.

All of the soils are silt loam, with an average of 72% silt, 23% sand, and 5% clay, with little variation in texture over the test site. The sustained infiltration rates (final constant values) for all the sites averaged about 2.8 inches/hr, with an overall range of 0.3 to 7.4 in/hr. Sites 1 and 2 are lower than the other sites, and are both located on the upper end of the western main drainage, in a grass field that has not been cultivated for some time, but is harvested for hay. Sites 7, 8, and 11 all have larger sustained infiltration rates than the others and are located in the central drainage area, also in harvested hay fields, but near the edges of the field. Site 9 has the highest rate, and was in the cultivated area of the corn field. The soil densities are inversely related to the sustained infiltration rate, in general, except for the corn field site that had the highest density and the highest infiltration rate. Site 11, the other high infiltration rate site, had the lowest soil density observed. The areas having the highest sustained infiltration rates also had the highest initial infiltration rates, some being as high as 25 inches/hour. The sustained final infiltration rate was observed from 10 to 60 minutes after the start of the tests, with an average of about 24 minutes.

The organic matter content of the soils averaged 5.6% (ranged from 2.4 to 7.3), and the associated volatile solids content averaged 131g/kg (ranged from 67 to 238g/kg). These values are consistent with a silt loam soil. For comparison, soils in the Central Great Plains have organic contents ranging between 1 and 2% for cultivated soils, and about 1.5 to 3.0% for native grasslands. Agricultural yield is usually regarded as sustainable at organic contents of about 2%. Soils with large amounts of clay generally require large amounts or organic matter. Soils with a higher organic matter content will have a higher cation exchange capacity (CEC), higher water holding capacity, and better tilth than soils with a lower organic matter content. Generally, healthy soil has between 3% and 5% organic material. Only site 9 (located in the cultivated portion of the corn field) had less than this amount (at 2.4%).

The cation exchange capacity is the sum of exchangeable bases plus total soil acidity at a specific pH value, usually 7.0 or 8.0. The cation exchange capacity of a soil is a measure of its ability to bind or hold exchangeable cations. It is a measure of the number of negatively-charged binding sites in the soil. It is expressed here in centimoles of charge per kilogram of exchanger (cmolckg-1). These units are equivalent to the more commonly reported meq/100g units. These soils had CEC values ranging from about 4.9 to 7.2 meq/100g (average of 5.7) and fall in the range of sands. Loam soils have CEC values in the 10 to 15 meq/100g range, while organic soils have CEC values in the high range of 50 to 100 meq/100g.

The pH of the soil ranged from 5.1 to 6.3 (average of 5.9) and had recommended limestone additions (from 0 to 3.5 tons per acre) to increase the pH to at least 6. The eastern half of the site required more neutralization than soils in the western half.

The phosphorus, potassium, magnesium, and calcium levels averaged 14, 21, 33, and 411 lbs/acre, respectively. There were no specific fertilizer recommendations provided with the soil report for these nutrients. The phosphorus is in a typical range for other silt loam soils, while the potassium may be lower than some silt loam soils.

Site ID	Location	Surface	Test duration (hour)	initial infilt. rate (in/hr)	final (constant) infiltr. rate (in/hr)	Time to constant rate (hr)	Soil density (g/cm^3)	Initial soil moisture (%)
Site-1	Location-A	grass	2	3.01	1.56	1.00	1.67	16.6
Site-1	Location-B	grass	2.00	3	0.73	0.67		
Site-1	Location-C	soil	1.99	4.66	0.89	0.33		
Site-2	Location-A	grass	2.00	11.40	1.9	0.15	1.59	13.8
Site-2	Location-B	grass	2.00	7.20	1.86	0.33		
Site-2	Location-C	soil	1.98	6.10	0.34	0.15		
Site-3	Location-A	grass	2.02	8.25	3.18	0.50	1.39	12.9
Site-3	Location-B	grass	2.01	8.23	2.97	0.50		
Site-3	Location-C	soil	2.00	4.99	0.54	0.15		
Site-4	Location-A	grass	1.77	9.66	4.24	0.33	1.52	12.6
Site-4	Location-B	grass	1.48	8.8	2.07	0.67		
Site-4	Location-C	soil	1.48	7.19	2.67	0.33		
Site-5	Location-A	soil	1.49	11.35	2.32	0.15	n/a	17.0
Site-5	Location-B	grass	1.48	19.10	5.31	0.33		
Site-5	Location-C	grass	1.49	5.46	1.7	0.83		
Site-7	Location-A	grass	1.34	8.63	3.6	0.15	1.37	13.5
Site-7	Location-B	grass	1.33	12.59	4.88	0.50		
Site-7	Location-C	soil	1.32	11.56	2.8	0.33		
Site-8	Location-A	soil	1.27	16.10	2.52	0.33	1.42	14.6
Site-8	Location-B	grass	1.26	14.20	2.86	0.33		
Site-8	Location-C	grass	1.25	14.10	4.43	0.33		
Site-9	Location-A	grass	1.85	25.00	7.22	1.00	1.66	10.8
Site-9	Location-B	soil	1.85	24.60	7.39	0.50		
Site-10	Location-A	grass	2.03	5.88	0.76	0.50	1.40	10.8
Site-10	Location-B	grass	1.85	1.57	1.00	0		
Site-10	Location-C	soil	1.65	7.42	0.86	0.15		
Site-11	Location-A	grass	0.99	16.80	6.82	0.15	1.21	12.1
Site-11	Location-B	soil	0.97	13.60	3.19	0.15		
Site-11	Location-C	grass	0.96	9.10	1.75	0.50		
Site-12	Location-A	grass	1.00	5.88	2.51	0.33	1.53	11.9
Site-12	Location-B	grass	0.99	5.81	0.85	0.33		
Site-12	Location-C	soil	0.98	8.36	1.11	0.33		

	initial infilt. rate (in/hr)	final (constant) infilt. rate (in/hr)	Time to constant rate (hr)	Soil density (g/cm^3)	Initial soil moisture (%)
average	9.99	2.77	0.39	1.47	13.41
min	1.57	0.34	0.00	1.21	10.80
max	25.00	7.39	1.00	1.66	17.00
standard deviation	5.76	1.95	0.23	0.14	1.99
COV	0.57	0.70	0.61	0.09	0.15

Sample ID	Sand (%)	Silt (%)	Clay (%)	Textural Class	H_2O avail (cm/cm)	Organic Matter (%)	Volatile Solids (g/kg)
Site 1	21.25	76.25	2.5	Silt Loam	0.19	5.5	153.7
Site 2	18.75	76.25	5	Silt Loam	0.20	4.1	99.0
Site 3	23.75	71.25	5	Silt Loam	0.19	5.9	112.5
Site 4	25	70	5	Silt Loam	0.18	5.5	145.9
Site 5	26.25	71.25	2.5	Silt Loam	0.18	5.9	73.8
Site 7	21.25	73.75	5	Silt Loam	0.19	7.0	162.5
Site 8	26.25	66.25	7.5	Silt Loam	0.18	6.9	91.4
Site 9	23.75	66.25	10	Silt Loam	0.19	2.4	67.4
Site 10	22.5	72.5	5	Silt Loam	0.19	4.6	117.1
Site 11	21.25	73.75	5	Silt Loam	0.19	6.3	237.6
Site 12	26.25	71.25	2.5	Silt Loam	0.18	7.3	178.6
average	23.30	71.70	5.0		0.19	5.6	130.9
min	18.75	66.25	2.5		0.18	2.4	67.4
max	26.25	76.25	10.0		0.20	7.3	237.6
standard deviation	2.52	3.37	2.2		0.01	1.4	50.8
COV	0.11	0.05	0.4		0.03	0.3	0.4

Sample Name	pH	Phosphorus (lbs/acre)	Potassium (lbs/acre)	Magnesium (lbs/acre)	Calcium (lbs/acre)	Recommended Limestone (tons/acre)	CEC ($cmol_c kg^{-1}$)
Site 1	6.1	17	16	35	478	0.0	5.84
Site 2	5.9	21	10	25	358	1.5	4.93
Site 3	6.2	10	13	33	497	0.0	5.55
Site 4	6.3	7	14	31	453	0.0	5.2
Site 5	6.2	12	16	47	453	0.0	5.75
Site 7	6.2	11	24	34	583	0.0	5.07
Site 8	5.6	7	18	38	381	2.0	5.69
Site 9	5.1	45	45	17	267	3.0	5.6
Site 10	5.4	8	31	26	249	3.0	6.69
Site 11	6	9	23	45	459	0.0	5.6
Site 12	5.4	9	18	31	340	3.5	7.24
average	5.9	14	21	33	411	1	5.74
min	5.1	7	10	17	249	0	4.93
max	6.3	45	45	47	583	3.5	7.24
standard deviation	0.4	11	10	9	102	1.45	0.68
COV	0.07	0.78	0.48	0.26	0.25	1.23	0.12

Loams and Light clays (CEC = 4.6-9.0 $cmol_c kg^{-1}$)

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.

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.

Gregory, J.H.; Dukes, M.D.; Jones, P.H.; Miller, G.L. Effect of urban soil compaction on infiltration rate. *J. Soil Water Conservation*. 61(3), 117-123. 2006.

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. 1994.

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

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. December 1999.

Pitt, R., S. Clark, and R. Field. "Groundwater contamination potential from stormwater infiltration practices." *Urban Water*, 1(3), 217-236. 1999.

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. pp. 1 –22. 2000.

Pitt, R., S. Chen, and S. Clark. "Compacted Urban Soils Effects on Infiltration and Bioretention Stormwater Control Designs." *Global Solutions for Urban Drainage*; 9IUCD. CD-ROM Proceedings of the 9th International Urban Drainage Conference, edited by E.W. Strecker and W.C. Huber., Sept 8-13, 2002, Portland, OR. Sponsored by the ASCE, Reston, VA, and the International Water Association, London.

Pitt, R. E. Shen-En Chen, S. Clark, J. Lantrip, and C.K. Ong. "Infiltration through compacted urban soils and effects on biofiltration design." *Stormwater and Urban Water Systems Modeling*. In: *Models and Applications to Urban Water Systems*, Vol. 11 (edited by W. James). CHI. Guelph, Ontario, pp. 217 – 252. 2003.

Pitt, R., S.-E. Chen, S.E. Clark, J. Lantrip, C.K. Ong. "Compaction's impacts on urban stormwater infiltration." *Journal of Irrigation and Drainage Engineering*. Vol. 134, no. 5, pp. 652-658. October 2008.

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

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.