

Infiltration Through Disturbed Urban Soils

Robert Pitt and Janice Lantrip

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 stormwater models.

Early unpublished double-ring infiltration tests conducted by the Wisconsin Department of Natural Resources (DNR) in Oconomowoc, Wisconsin, (shown in Table 1.1) indicated highly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/h (3 in/h), but ranged from 0 to 600 mm/h (0 to 25 in/h). The final rates also had a median value of about 75 mm/h (3 in/h) after at least two hours of testing, but ranged from 0 to 400 mm/h (0 to 15 in/h). Many infiltration rates actually increased with time during these tests. In about one third 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.

In an attempt to explain the variations observed in early infiltration tests in disturbed urban soils, tests were conducted in the Birmingham, Alabama, area by the authors, assisted by UAB hydrology students. About 150 individual double-ring

Pitt, R.E. and J. Lantrip. 2000. "Infiltration Through Disturbed Urban Soils." *Journal of Water Management Modeling* R206-01. doi: 10.14796/JWMM.R206-01.

© CHI 2000 www.chijournal.org ISSN: 2292-6062 (Formerly in Applied Modeling of Urban Water Systems. ISBN: 0-9683681-3-1)

Table 1.1 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 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 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 1.2. The data from each individual test were fitted

Table 1.2 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

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 elapsed 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.

1.1 Background

1.1.1 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 infiltrate totally, 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).

1.1.2 Horton Equation

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

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

where:

- f = infiltration capacity (in/h)
- f_o = initial infiltration capacity (in/h)
- f_c = final capacity (in/h)
- k = empirical constant (h⁻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 by many (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, with only a single value used for all conditions (Akan 1993). The k value units is listed as 1/minute instead of 1/h 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. These values will be compared to the measured values obtained during this study by calibrating the Horton equation to the field observations.

1.1.3 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. A component of the current Environmental Protection Agency (EPA) sponsored project that will include these Birmingham tests results is being conducted by the College of Forestry Resources at the University of Washington in the Seattle area to measure the benefits of amending urban soils with compost (Pitt and Harrison 1999). It is hoped that compost-amended soils will improve infiltration characteristics of these soils, along with providing some filtration/sorption benefits to capture stormwater pollutants before they enter the groundwater.

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

30cm (12 in.) deep. A thick sand backfill was used and then the area was capped 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 (10ft.) 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.

1.2 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 2³ 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 Wisconsin Department 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.

1.2.1 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 Infiltrimeters 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 infiltrimeters, but their ease of use allowed many tests under a wide variety of conditions to be conducted. The use of three infiltrimeters 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 in water level in the inner compartment over the five minute time period.

1.2.2 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 thorough 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%.

1.2.3 Soil Texture Measurements

The texture of the samples were determined by ASTM (American Society for Testing and Materials) standard sieve analyses to verify the soil conditions estimated in the field and for comparison to the NRCS (National Resources Conservation Service) 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 hexametaphosphate) 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 μ m) 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.

1.2.4 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.

1.3 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, Alabama, where the rainfall averages about 250 mm (10 in.) more than in Birmingham, and the summers are even hotter and more humid. Table 1.3 briefly describes the test locations and site conditions, while Figure 1.1 is a soil texture diagram showing the distribution of the soil texture classifications at the different test sites.

Table 1.3 Infiltration test site locations and conditions.

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

1.4 Results

This chapter presents the preliminary exploratory analyses of this data. On-going evaluations are examining additional statistical tests (especially factorial evaluations, plus other multivariate analyses to explore other relationships in the data), plus other infiltration models. The first analysis involved the preparation of 3D

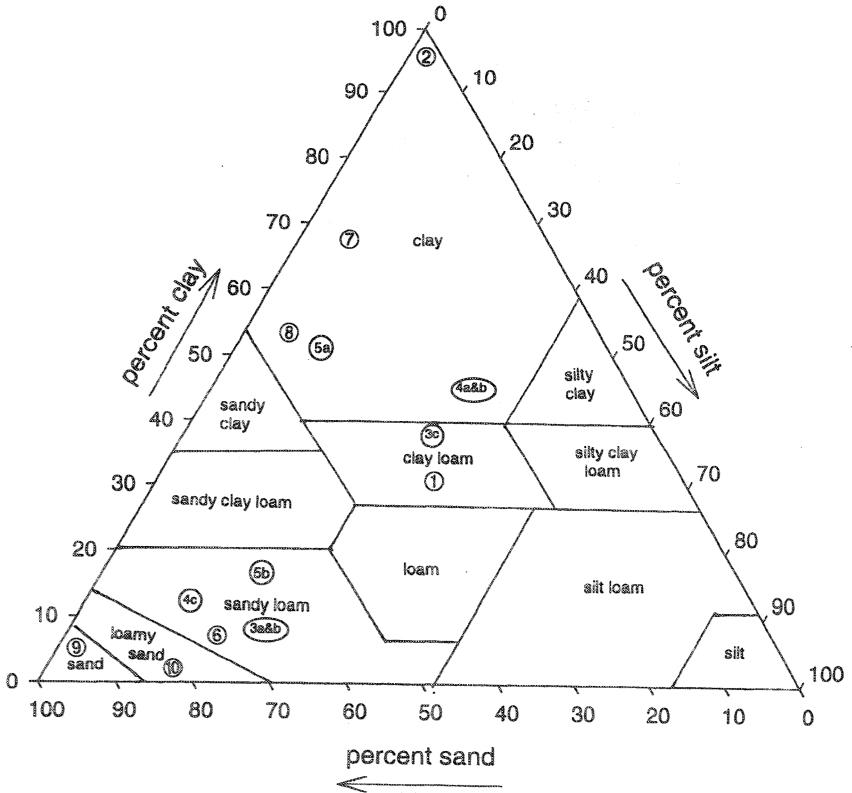


Figure 1.1 Soil texture classifications for test sites.

plots of the infiltration data, illustrating effects of soil-water levels and compaction, for both sand and clay. These plots are shown in Figures 1.2 and 1.3. Four general conditions were observed to be statistically unique, as previously listed on Table 1.2. Compaction has the greatest effect on infiltration rates in sandy soils, with little detrimental effects associated with higher soil-water content. 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 1.4 through 1.7 are the plots showing the observed infiltration rates, and the fitted Horton equation parameters for the four general conditions.

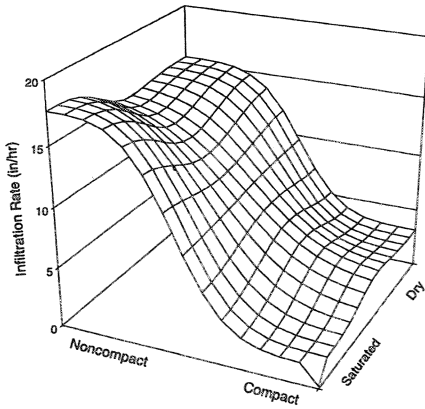


Figure 1.2 Three dimensional plot of infiltration rates for sandy soil conditions.

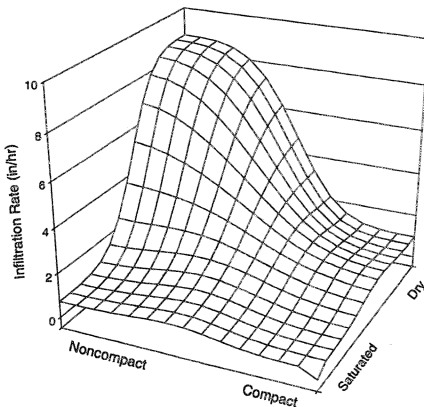


Figure 1.3 Three dimensional plot of infiltration rates for clayey soil conditions.

Figure 1.4 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 1.4 summarizes the observed Horton equation parameter values, compared to the typical published parameter values, for sandy soil conditions.

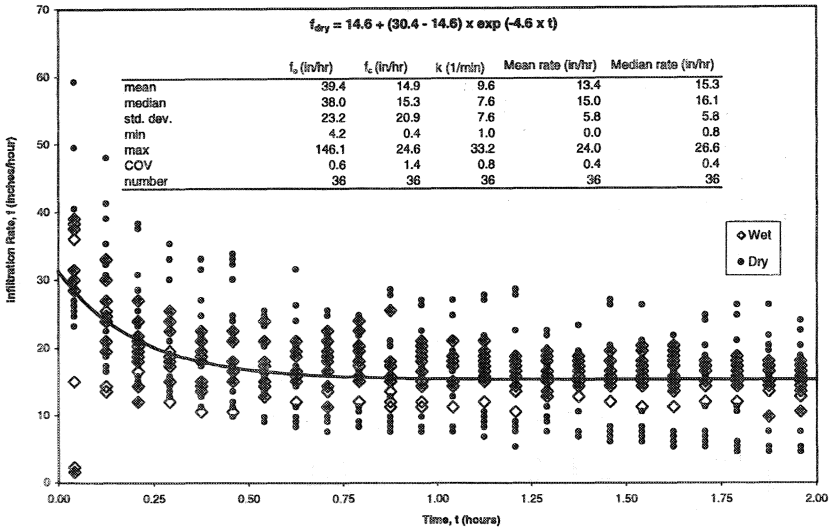


Figure 1.4 Infiltration measurements for noncompacted, sandy soil, conditions.

Table 1.4 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/h (14 in/h), ranging from about 125 to 635 mm/h (5 to 25 in/h) during the tests. The comparable published rates were less than 25 mm/h (1 in/h). The infiltration rates leveled-off to the constant final values after about 30 to 45 minutes.

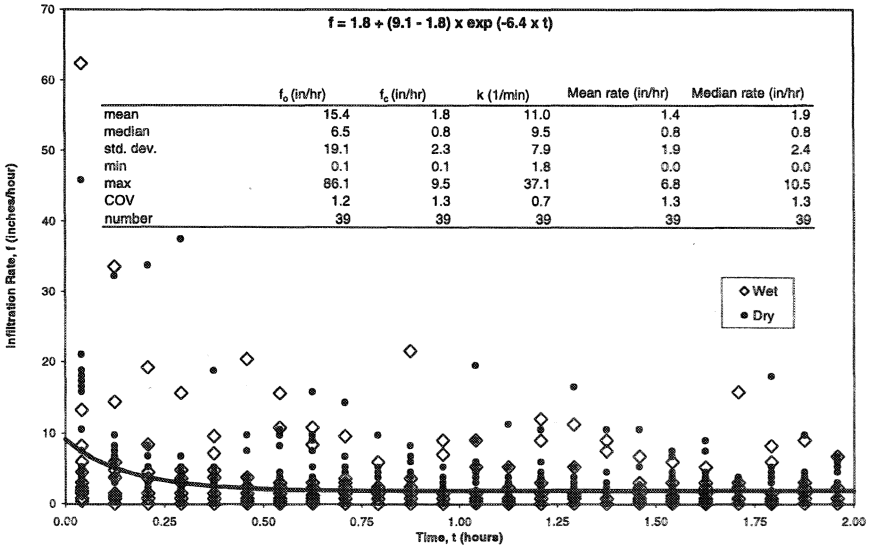


Figure 1.5 Infiltration measurements for compacted, sandy soil, conditions.

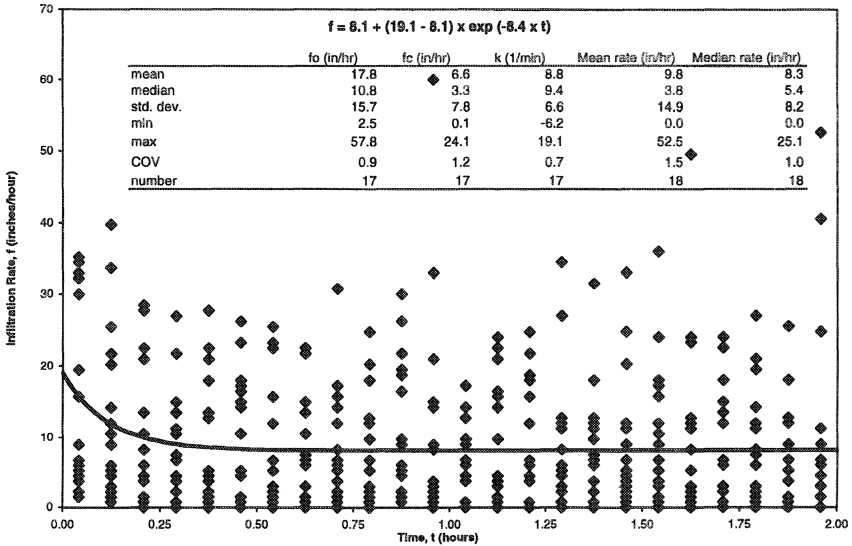


Figure 1.6 Infiltration measurements for dry-noncompacted, clayey soil, conditions.

Figure 1.5 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 five and ten 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/h (0 to 20 in/h), with most of the 39 observations less than 125 mm/h (5 in/h).

Figure 1.6 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/h (0.3 to 20 in/h), with a mean rate of about 230 mm/h (9 in/h) for all eighteen tests combined. Figure 1.7 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/h (5 in/h). Table 1.5 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.

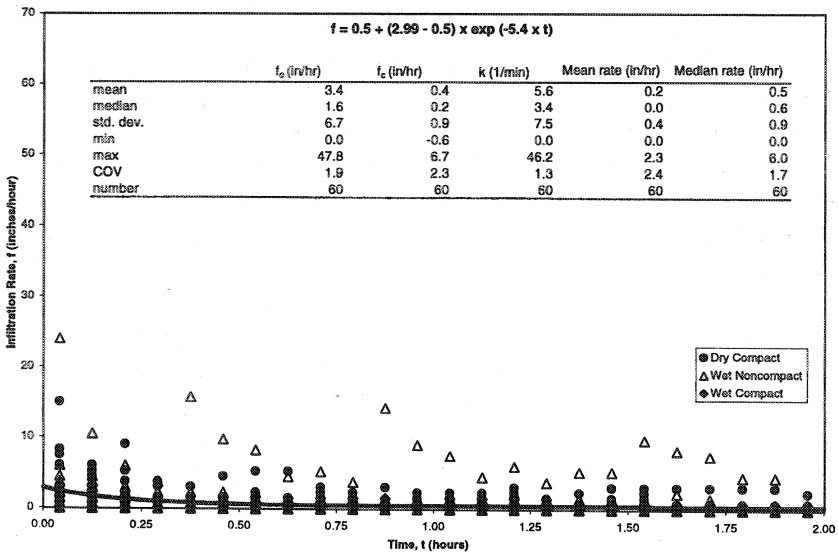


Figure 1.7 Infiltration measurements for wet-noncompacted, dry-compacted, and wet-compacted, clayey soil conditions.

Table 1.5 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 conds.)	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	

Because of the wide range in observed rates for each of the major categories, it may not matter much 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.

As one example of an approach, Table 1.6 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 coefficient of variation (COV) 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 1.8 through 1.11 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 in 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.

Table 1.6 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

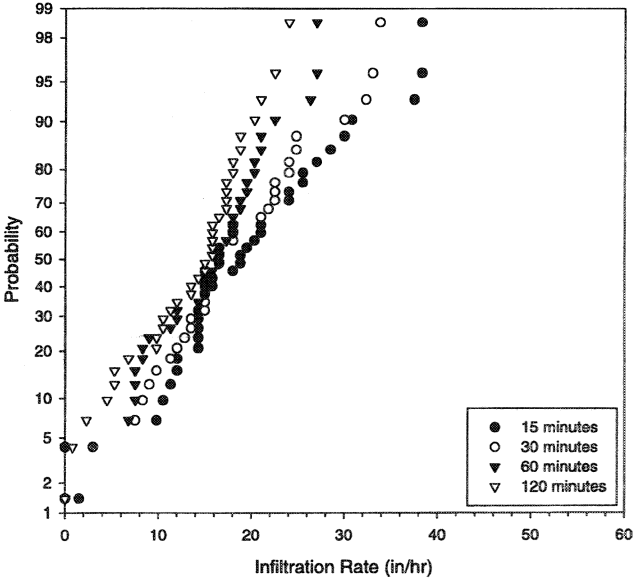


Figure 1.8 Probability plots for infiltration measurements for noncompacted, sandy soil, conditions.

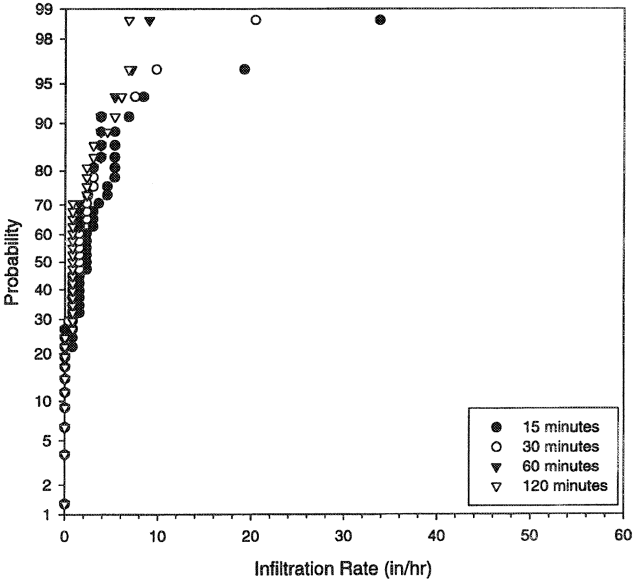


Figure 1.9 Probability plots for infiltration measurements for compacted, sandy soil, conditions.

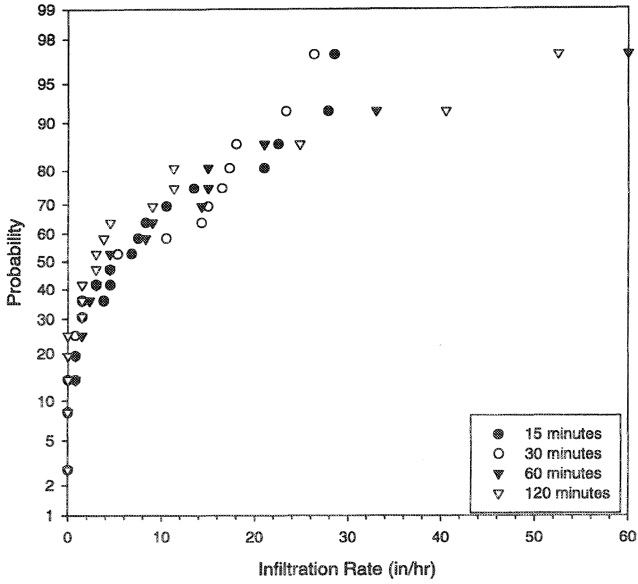


Figure 1.10 Probability plots for infiltration measurements for dry-noncompacted, clayey soil, conditions.

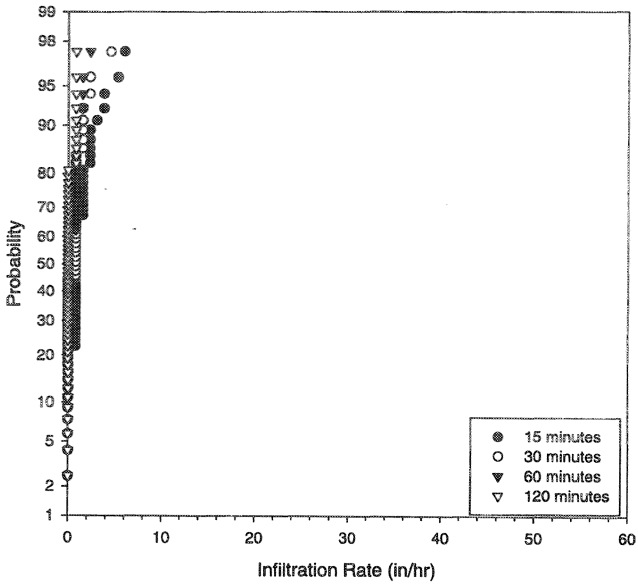


Figure 1.11 Probability plots for infiltration measurements for wet-noncompacted, dry-compacted, and wet-compacted, clayey soil conditions.

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 US Department of Agriculture (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 1.7 (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.

Table 1.7 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

1.5 Conclusions

Very large errors in soil infiltration rates can easily be made if published soil maps are used in conjunction with the recommended parameters for 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) can be used to more accurately estimate 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 1.2 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 are being 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 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 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, plus the measured values can be directly used to estimate the infiltration rates that may be expected from stormwater infiltration controls that utilize ponding. Additional research is needed in other urban areas to measure site specific effects of these soil conditions on infiltration rates.

Acknowledgments

This research was carried out mostly as class projects by University of Alabama at Birmingham hydrology and experimental design students. Specific thanks are given to Rebecca Martin, Stacey Sprayberry, Muhammad Salman, Wade Burcham, Brian Adkins, Sarah Braswell, Scott Lee, and Jennifer Harper. Additional tests conducted by Janice Lantrip, as part of her research for her MSCE degree, and the associated data evaluation, were supported by the Urban Watershed Management Branch, U.S. Environmental Protection Agency, Edison, NJ. Thomas O'Connor was the EPA project officer and provided project guidance. Additional thanks are also given to the anonymous reviewers of this chapter whose suggestions helped clarify several topics.

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.
- Gilbert, R.O., *Statistical Methods for Environmental Pollution Monitoring* New York: Van Nostrand Reinhold Publishing Co., 1987.
- Turf Tec International. *Turf Tec Instructions*. Oakland Park, Florida. 1989.
- Dickey-John Corporation. *Installation Instructions Soil Compaction Tester*. Auburn, Illinois:, 1987.
- 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.
- 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. and S.R. Durrans. *Drainage of Water from Pavement Structures*. Alabama Dept. of Transportation. 253 pgs. September 1995.
- Pitt, R. and R. Harrison. *Infiltration Through Disturbed Soils and Compost-Amended Soil Effects on Runoff*. U.S. Environmental Protection Agency. Urban Watershed Management Branch. Cincinnati, Ohio. To be published in 1999.
- 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.