Small Storm Hydrology and Why it is Important for the Design of Stormwater Control Practices[1]

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Abstract
Different drainage design criteria and receiving water use objectives often require the examination of different types of rains for the design of urban drainage systems. These different (and often conflicting) objectives of a stormwater drainage system can be addressed by using distinct portions of the long-term rainfall record. Several historical examinations (including Heaney, *et al.* 1977) have also considered the need for the examination of a wide range of rain events for drainage design. However, the lack of efficient computer resources severely restricted long-term analyses in the past. Currently, computer resources are much more available and are capable of much more

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comprehensive investigations (Gregory and James 1996). In addition to having more efficient computational resources, it is also necessary to re-examine some of the fundamental urban hydrology modeling assumptions (Pitt 1987). Most of the urban hydrology methods currently used for drainage design have been successfully used for large "design" storms. Obviously, this approach (providing urban areas safe from excessive flooding and associated flood related damages) is the most critical objective of urban drainage. However, it is now possible (and legally required in many areas) to provide urban drainage systems that also minimizes other problems associated with urban stormwater. This broader set of urban drainage objectives requires a broader approach to drainage design, and the use of hydrology methods with different assumptions and simplifications.

This paper reviews actual monitored rainfall and runoff distributions for Milwaukee, WI (data from Bannerman, *et al.* 1983), and examines long-term rainfall histories and predicted runoff from 24 locations throughout the U.S. The Milwaukee observations show that southeastern Wisconsin rainfall distributions can be divided into the following categories, with possible management approaches relevant for each category of rain:

- Common rains having relatively low pollutant discharges are associated with rains less than about 0.5 in. (12 mm) in depth. These are key rains when runoff-associated water quality violations, such as for bacteria, are of concern. In most areas, runoff from these rains should be totally captured and either re-used for on-site beneficial uses or infiltrated in upland areas. For most areas, the runoff from these rains can be relatively easily removed from the surface drainage system.

- Rains between 0.5 and 1.5 in. (12 and 38 mm) are responsible for about 75% of the runoff pollutant discharges and are key rains when addressing mass pollutant discharges. The small rains in this category can also be removed from the drainage system and the runoff re-used on site for beneficial uses or infiltrated to replenish the lost groundwater infiltration associated with urbanization. The runoff from the larger rains should be treated to prevent pollutant discharges from entering the receiving waters.

- Rains greater than 1.5 in. (38 mm) are associated with drainage design and are only responsible for relatively small portions of the annual pollutant discharges. Typical storm drainage design events fall in the upper portion of this category. Extensive pollution control designed for these events would be very costly, especially considering the relatively small portion of the annual runoff associated with the events. However, discharge rate reductions are important to reduce habitat problems in the receiving waters. The infiltration and other treatment controls used to handle the smaller storms in the above categories would have some benefit in reducing pollutant discharges during these larger, rarer storms.

- In addition, extremely large rains also infrequently occur that exceed the capacity of the drainage system and cause local flooding. Two of these extreme events were monitored in Milwaukee during the Nationwide Urban Runoff Program (NURP) project (EPA 1983). These storms, while very destructive, are sufficiently rare that the resulting environmental problems do not justify the massive stormwater quality controls that would be necessary for their reduction. The problem during these events is massive property damage and possible loss of life. These rains typically greatly exceed the capacities of the storm drainage systems, causing extensive flooding. It is critical that these excessive flows be conveyed in "secondary" drainage systems. These secondary systems would normally be graded large depressions between buildings that would direct the water away from the buildings and critical transportation routes and to possible infrequent/temporary detention areas (such as large playing fields or parking lots). Because these events are so rare, institutional memory often fails and development is allowed in areas that are not indicated on conventional flood maps, but would suffer critical flood damage.

Obviously, the critical values defining these rain categories are highly dependent on local rain and development conditions. Computer modeling analyses from several representative urban locations from throughout the U.S. are presented in this paper. These modeled plots indicate how these rainfall and runoff probability distributions can be used for more effective storm drainage design in the future. In all cases, better integration of stormwater quality and drainage design objectives will require the use of long-term continuous simulations of alternative drainage designs in conjunction with upland and end-of-pipe stormwater quality controls. The complexity of most receiving water quality problems prevents a simple analysis. The use of simple design storms, which was a major breakthrough in effective drainage design more than 100 years ago, is not adequate when receiving water quality issues must also be addressed.

This paper also reviews typical urban hydrology methods and discusses common problems in their use in predicting flows from these important small and moderate sized storms. A general model is then described, and validation data presented, showing better runoff volume predictions possible for a wide range of rain conditions.

Runoff and Pollutant Yields for Different Rain Categories

Figure 1 includes cumulative probability density functions (CDFs) of measured rain and runoff distributions for Milwaukee during the 1981 NURP monitored rain year (data from Bannerman, *et al.* 1983). CDFs are used for plotting because they clearly show the ranges of rain depths responsible for most of the runoff. Rains between 0.05 and 5 in. were monitored during this period, with two very large events (greater than 3 inches) occurred during this monitoring period which greatly distort these curves, compared to typical rain years. The following observations are evident:

- The median rain depth was about 0.3 in.
- 66% of all Milwaukee rains are less than 0.5 in. in depth.
- For medium density residential areas, 50% of runoff was associated with rains less than 0.75 in.
- A 100-yr., 24-hr rain of 5.6 in. for Milwaukee could produce about 15% of the typical annual runoff volume, but it only contributes about 0.15% of the average annual runoff volume, when amortized over 100 yrs.
- Similarly, a 25-yr., 24-hr rain of 4.4 in. for Milwaukee could produce about 12.5% of the typical annual runoff volume, but it only contributes about 0.5% of the average annual runoff volume, when amortized over 25 yrs.

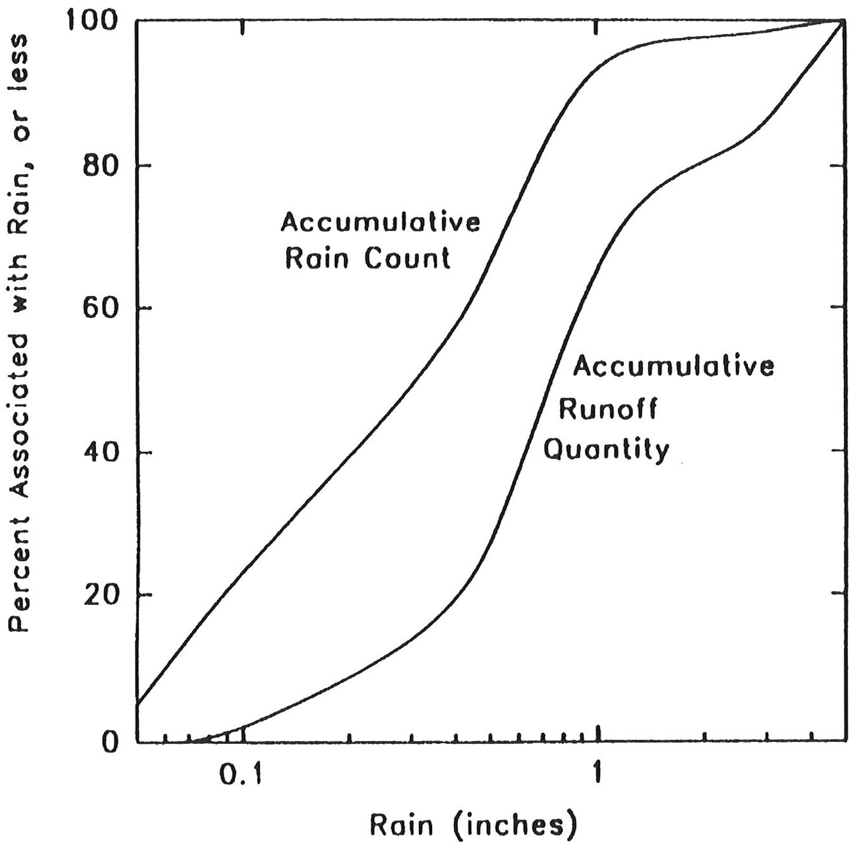


Figure 1. Milwaukee rain and runoff cumulative probability density functions (CDFs).

Figure 2 shows CDFs of measured Milwaukee pollutant loads associated with different rain depths for a medium density residential area. Suspended solids, COD, lead, and phosphate loads are seen to closely follow the runoff volume CDF shown in Figure 1, as expected. Since load is the product of concentration and runoff volume, some of the high correlation shown between load and rain depth is obviously spurious. However, these overlays illustrate the range of rains associated with the greatest pollutant discharges.

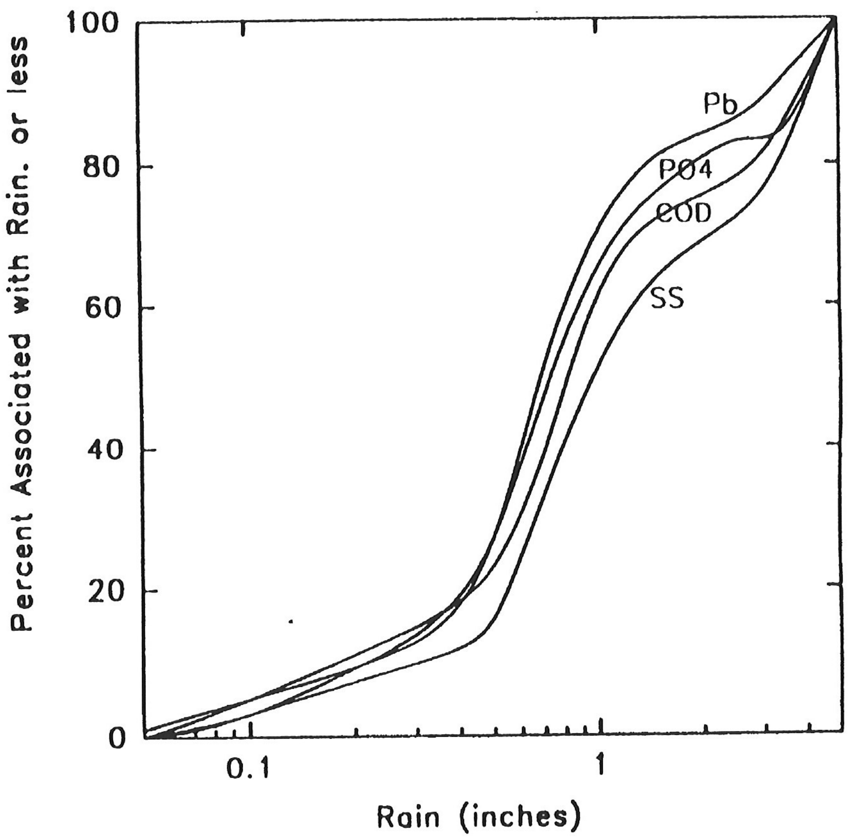


Figure 2. Milwaukee stormwater pollutant cumulative probability density functions (CDFs).

The monitored rainfall and runoff distributions for Milwaukee show the following distinct rain categories:

- <0.5 inch. These rains account for most of the events, but little of the runoff volume, and are therefore easiest to control. They produce much less pollutant mass discharges and probably have less receiving water effects than other rains. However, the runoff pollutant concentrations likely exceed regulatory standards for several categories of critical pollutants, especially bacteria and some total recoverable metals. They also cause large numbers of overflow events in uncontrolled combined sewers. These rains are very common, occurring once or twice a week (accounting for about 60% of the total rainfall events and about 45% of the total runoff events that occurred), but they only account for about 20% of the annual runoff and pollutant discharges. Rains less than about 0.05 inches did not produce noticeable runoff.

- 0.5 to 1.5 inches. These rains account for the majority of the runoff volume (about 50% of the annual volume for this Milwaukee example) and produce moderate to high flows. They account for about 35% of the annual rain events, and about 20% of the annual runoff events. These rains occur on the average about every two weeks during the spring to fall seasons and subject the receiving waters to frequent high pollutant loads and moderate to high flows.

- 1.5 to 3 inches. These rains produce the most damaging flows, from a habitat destruction standpoint, and occur every several months (at least once or twice a year). These recurring high flows, which were historically associated with much less frequent rains, establish the energy gradient of the stream and cause unstable streambanks. Only about 2 percent of the rains are in this category and they are responsible for about 10 percent of the annual runoff and pollutant discharges.

• >3 inches. This category is rarely represented in field studies due to the rarity of these large events and the typically short duration of most field observations. The smallest rains in this category are included in design storms used for drainage systems in Milwaukee. These rains occur only rarely (once every several years to once every several decades, or less frequently) and produce extremely large flows. The 3-year monitoring period during the Milwaukee NURP program (1980 through 1983) was unusual in that two of these events occurred. Less than 2 percent of the rains were in this category (typically <<1% would be), and they produced about 15% of the annual runoff quantity and pollutant discharges. During a "normal" period, these rains would only produce a very small fraction of the annual average discharges. However, when they do occur, great property and receiving water damage results. The receiving water damage (mostly associated with habitat destruction, sediment scouring, and the flushing of organisms great distances downstream and out of the system) can conceivably naturally recover to before-storm conditions within a few years.

Similar rain categories can be determined for other areas, besides Milwaukee. Long-term continuous simulations were made using SLAMM, the Source Loading and Management Model (Pitt 1986; Pitt and Voorhees 1995) for 24 representative locations from throughout the U.S. These locations represent most of the major river basins and much of the rainfall variations in the country. These analyses are intended to show the importance of smaller rains for many different regions and conditions in the U.S.

These simulations were based on 5 to 10 years of rainfall records, usually containing about 500 individual rains. The rainfall records were from certified NOAA weather stations and were obtained from CD-ROMs distributed by EarthInfo of Boulder, CO. Hourly rainfall depths for the indicated periods were downloaded from the CD-ROMs into an Excel spreadsheet. This file was then read by an utility program included in the SLAMM software package. This rainfall file utility combined adjacent hourly rainfall values into individual rains, based on user selections (at least 6 hrs of no rain was used to separate adjacent rain events and all rain depths were used, with the exception of the "trace" values: similar analyses were made using inter-event definitions ranging from 3 to 24 hours, with little differences in the conclusions.). These rain files for each city were then used in SLAMM for typical medium density and strip commercial developments. The outputs of these computer runs were then plotted as shown on Figures 3a through 3f.

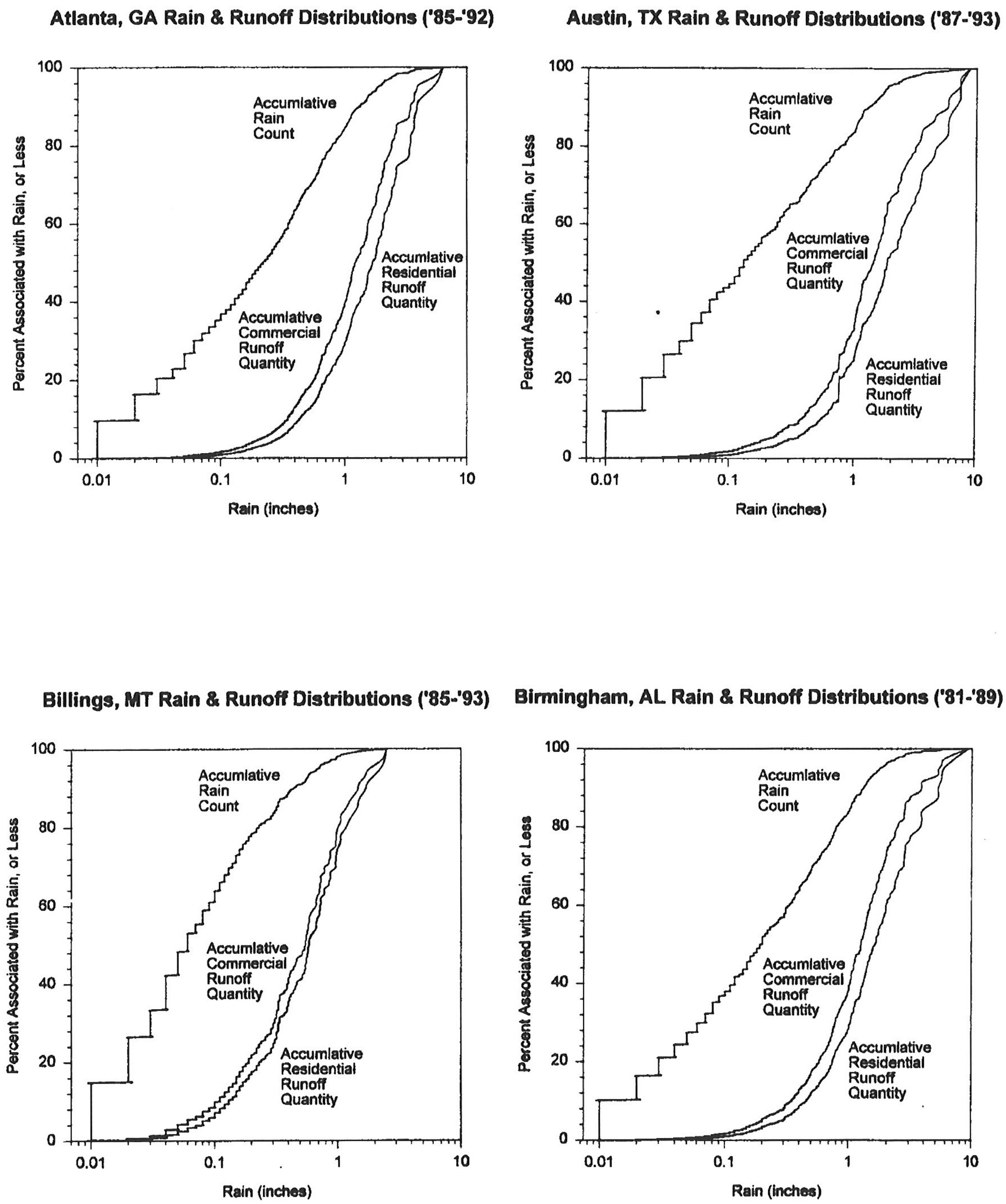


Figure 3a. Modeled rainfall and runoff cumulative probability density functions (CDFs).

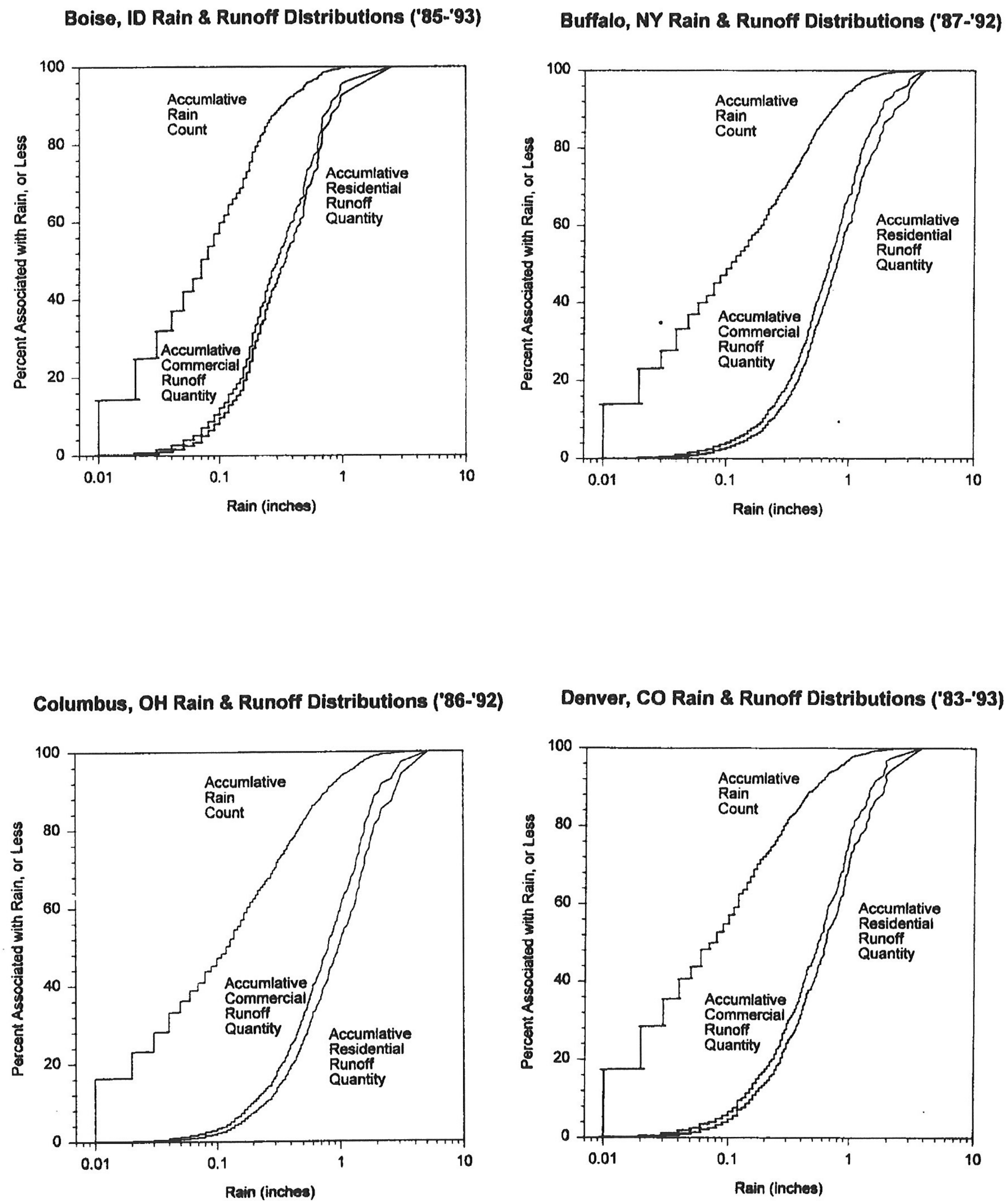


Figure 3b. Modeled rainfall and runoff cumulative probability density functions (CDFs), cont.

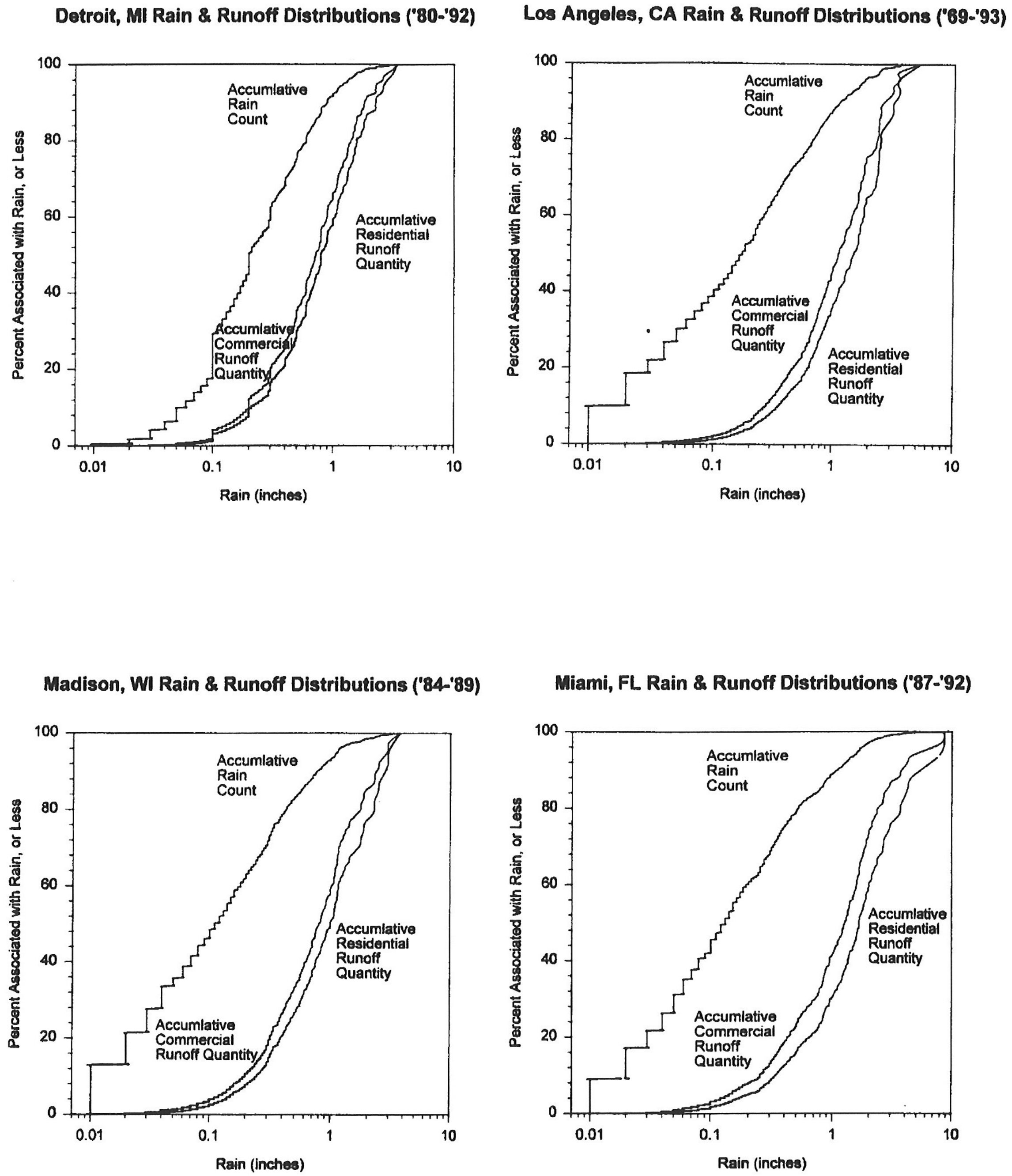
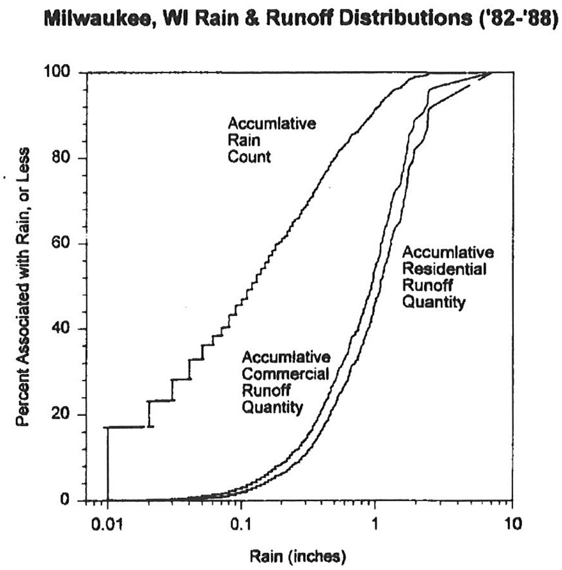
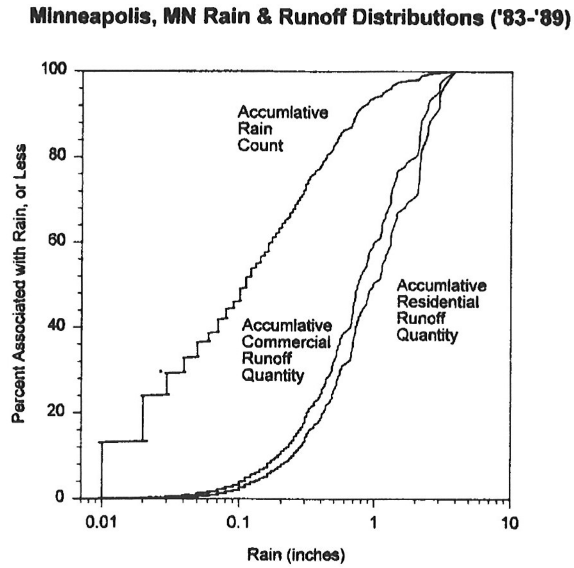
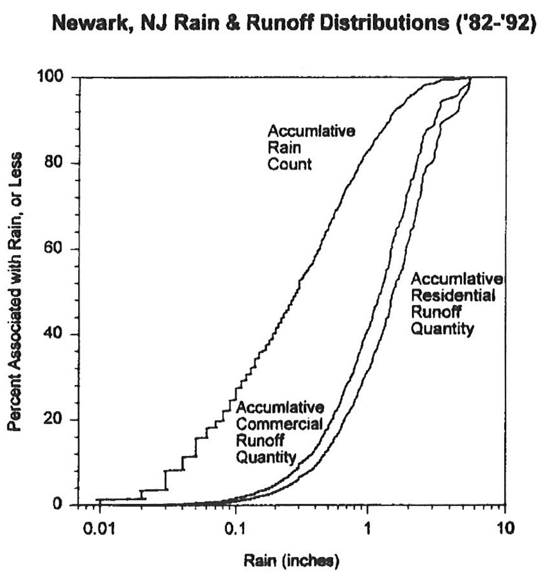


Figure 3c. Modeled rainfall and runoff cumulative probability density functions (CDFs), cont.







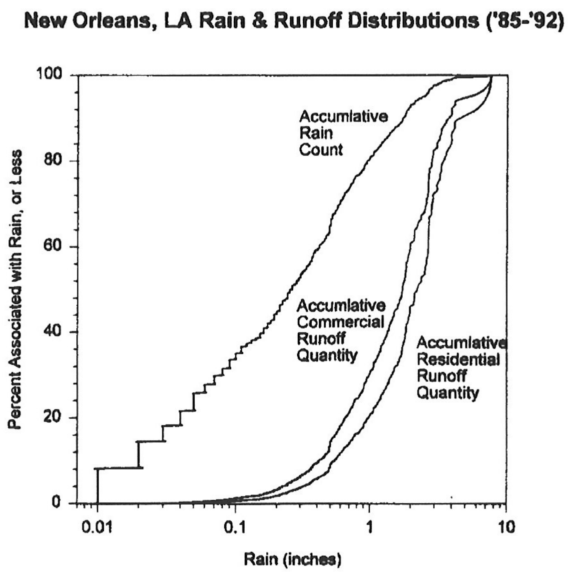


Figure 3d. Modeled rainfall and runoff cumulative probability density functions (CDFs), cont.

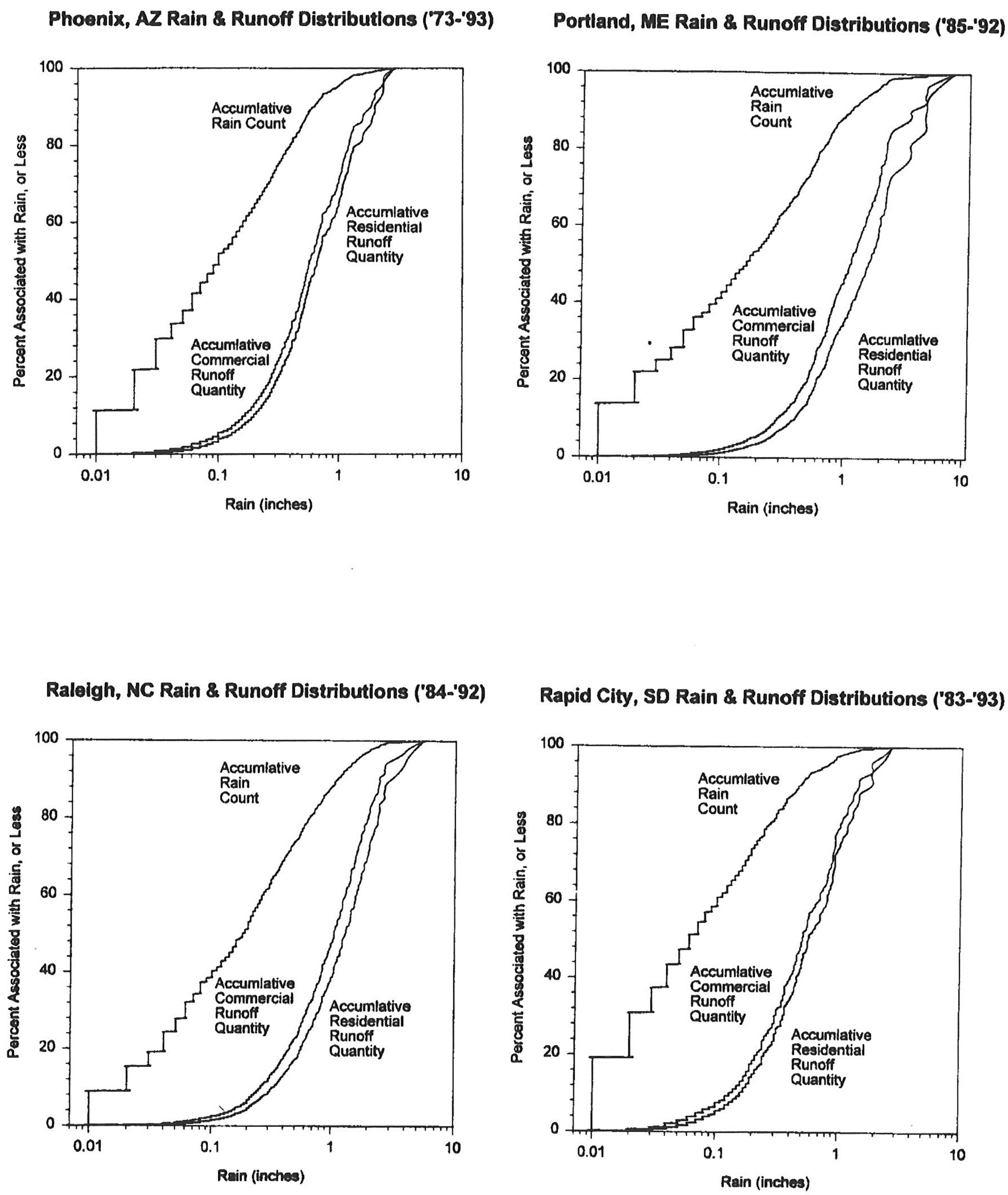


Figure 3e. Modeled rainfall and runoff cumulative probability density functions (CDFs), cont.

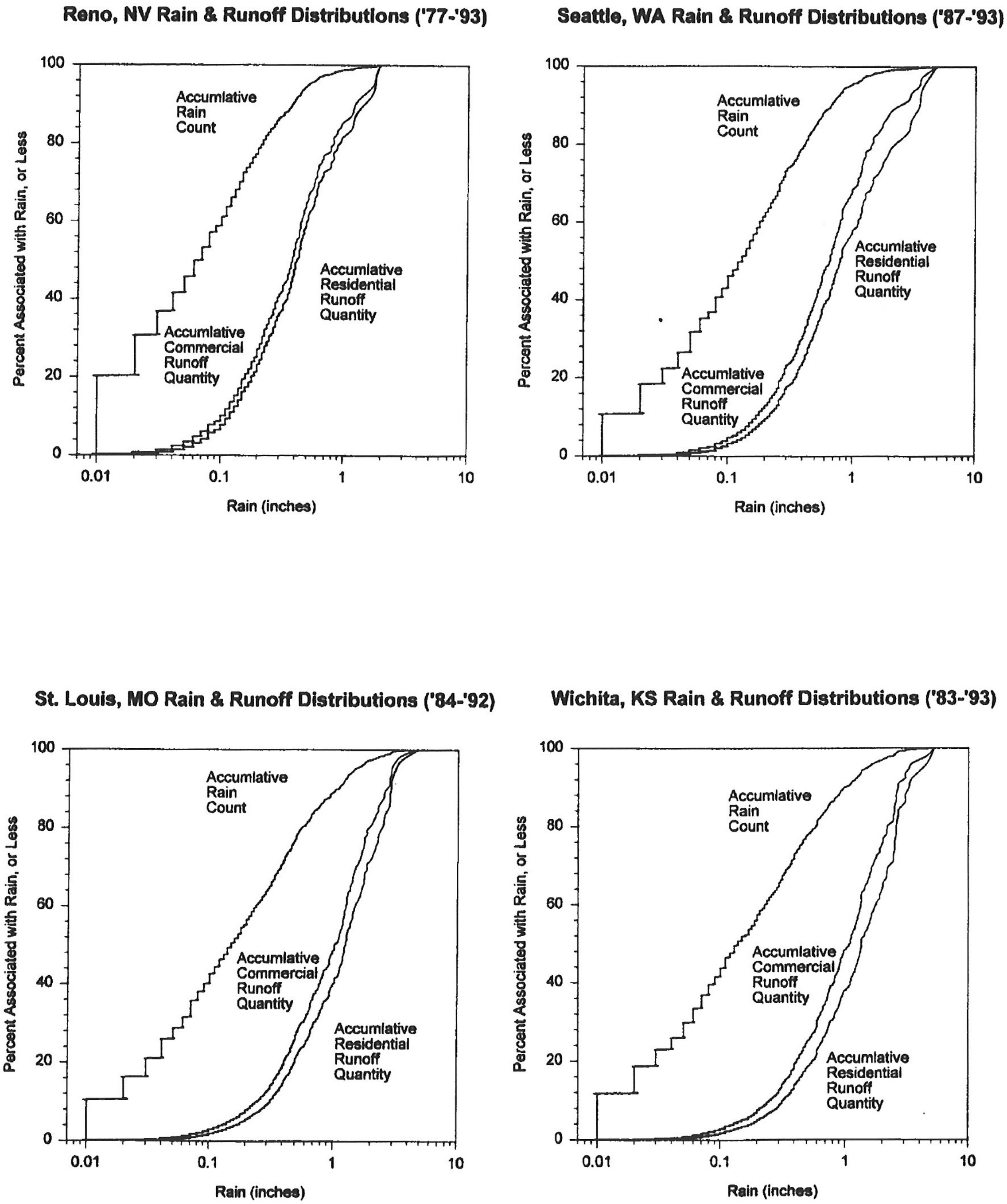


Figure 3f. Modeled rainfall and runoff cumulative probability density functions (CDFs), cont.

Table 1 summarizes these rain and runoff distributions for different U.S. locations. Lower and upper runoff distribution breakpoints were identified on all of the individual distributions. Ranges are given for many of the values, corresponding to different land use conditions (medium density residential and commercial areas). In most cases, the range covers a relatively narrow set of values. The breakpoints separate the distributions into the following three general categories:

• less than lower breakpoint: small, but frequent rains. These generally account for 50 to 70 percent of all rain events (by number), but only produce about 10 to 20 percent of the runoff volume. The rain depth for this breakpoint ranges from about 0.10 in. in the Southwest arid regions of the U.S., to about 0.5 in. in the wet Southeast. These events are most important because of their frequencies, not because of their mass discharges. These rains are therefore of great interest where water quality violations associated with urban stormwater occur. This would be most common for fecal coliform bacteria and for total recoverable heavy metals which typically exceed receiving water numeric criteria during practically every rain event in heavily urbanized drainages having separate stormwater drainage systems.

• between the lower and upper breakpoint: moderate rains. These rains generally account for 30 to 50 percent of all rain events (by number), but produce 75 to 90 percent of all of the runoff volume. The rain depths associated with the upper breakpoint range from about 1 to 2 in. in the arid parts of the U.S. and up to 5 or 6 in. in wetter areas. As shown earlier for actual monitored events in Milwaukee and elsewhere, these runoff volume distributions are approximately the same as the pollutant distributions. Therefore, these intermediate rains also account for most of the pollutant mass discharges and much of the actual receiving water problems associated with stormwater discharges.

• above the upper breakpoint: large, but rare rains. These rains include the typical drainage design events and are therefore quite rare. During the period analyzed, many of the sites only had one or two, if any, events above this breakpoint. These rare events can account for about 5 to 10 percent of the runoff in years when they occur. Obviously, these events must be evaluated to ensure adequate drainage capacity.

Table 1a. Rainfall and Runoff Distribution Characteristics for Different Locations in the U.S.

	Median rain depth, by count (in)	Percentage of runoff occurring during rains less than the median rain depth	Rain depth associated with median runoff depth (in)	Lower breakpoint rain depth (in)	Percentage of rain events less than lower breakpoint	Percentage of runoff volume less than lower breakpoint
Boise, ID	0.07	3 - 5	0.30 - 0.35	0.10	52	9 - 11
Seattle, WA	0.12	4 - 6	0.62 - 0.80	0.18	60	8 - 11
Los Angeles, CA	0.18	3 - 5	1.2 - 1.5	0.29	64	7 - 10
Reno, NV	0.07	3 - 5	0.35 - 0.41	0.10	61	8 - 10
Phoenix, AZ	0.10	4 - 6	0.55 - 0.68	0.19	64	9 - 12
Billings, MT	0.06	2 - 4	0.55 - 0.60	0.12	64	8 - 10
Denver, CO	0.08	2 - 4	0.50 - 0.60	0.19	71	13 - 17
Rapid City, SD	0.06	2 - 4	0.50 - 0.55	0.15	69	10 - 13
Wichita, KS	0.13	2 - 5	1.1 - 1.4	0.31	65	10 - 13
Austin, TX	0.14	2 - 3	1.4 - 1.8	0.50	72	8 - 12
Minneapolis, MN	0.11	3 - 5	0.73 - 1.0	0.22	65	9 - 13
Madison, WI	0.12	3 - 5	0.78 - 0.98	0.23	65	9 - 13
Milwaukee, WI	0.12	2 - 4	0.9 - 1.1	0.25	65	9 - 12
St. Louis, MO	0.14	4 - 6	1.0 - 1.2	0.31	65	10 - 13
Detroit, MI	0.20	7 - 11	0.72 - 0.81	0.20	50	7 - 11
Buffalo, NY	0.11	2 - 4	0.61 - 0.72	0.12	64	8 - 12
Columbus, OH	0.12	3 - 5	0.80 - 1.0	0.22	63	8 - 12
Portland, ME	0.15	2 - 4	1.1 - 1.5	0.30	64	8 - 12
Newark, NJ	0.28	6 - 12	1.2 - 1.5	0.33	54	8 - 12
New Orleans, LA	0.25	3 - 5	1.7 - 2.2	0.45	62	7 - 11
Atlanta, GA	0.22	3 - 5	1.2 - 1.7	0.32	58	5 - 9
Birmingham, AL	0.20	3 - 5	1.2 - 1.5	0.40	64	8 - 13
Raleigh, NC	0.18	4 - 6	1.0 - 1.2	0.26	60	7 - 11
Miami, FL	0.13	3 - 5	1.2 - 1.6	0.30	67	9 - 13

Table 1b. Rainfall and Runoff Distribution Characteristics for Different Locations in the U.S.

	Upper breakpoint rain depth (in)	Percentage of rain events less than upper breakpoint	Percentage of runoff volume less than upper breakpoint	Percentage of runoff volume between breakpoints	Percentage of rain events between breakpoints
Boise, ID	0.91	99	89 - 93	80 - 82	47
Seattle, WA	3.4	99	92 - 96	84 - 85	39
Los Angeles, CA	3.5	99	92 - 98	85 - 88	35
Reno, NV	1.7	99	93 - 95	85	38
Phoenix, AZ	2.3	99	94 - 98	85 - 87	35
Billings, MT	1.6	99	89 - 93	81 - 83	35
Denver, CO	1.8	99	91 - 95	78	28
Rapid City, SD	1.9	99	92 - 96	82 - 83	30
Wichita, KS	3.0	99	88 - 93	78 - 80	34
Austin, TX	6.0	99	88 - 94	80 - 82	27
Minneapolis, MN	2.8	99	94 - 96	83 - 85	34
Madison, WI	3.5	99	97 - 99	86 - 88	34
Milwaukee, WI	2.5	99	89 - 95	80 - 83	34
St. Louis, MO	2.8	99	90 - 95	80 - 82	34
Detroit, MI	2.4	99	92 - 95	85 - 84	49
Buffalo, NY	2.1	99	88 - 93	80 - 81	35
Columbus, OH	2.2	99	85 - 91	77 - 79	36
Portland, ME	4.5	99	90 - 96	82 - 84	35
Newark, NJ	3.3	99	89 - 94	81 - 82	45
New Orleans, LA	4.0	99	88 - 93	81 - 82	37
Atlanta, GA	4.0	99	91 - 95	86	41
Birmingham, AL	5.0	99	90 - 96	82 - 83	35
Raleigh, NC	2.5	99	87 - 93	80 - 82	39
Miami, FL	4.0	99	87 - 93	78 - 80	32

Because of the importance of these small and moderate rains, it is important to review typically used urban hydrology methods that have been commonly used to predict runoff from urban areas. These tools have been reasonably successful when evaluating drainage capacity for large "design storm" events. However, the following paragraphs will indicate their short-comings when used for evaluating the common smaller events. A general urban runoff model is also presented that has been shown to be useful to predict runoff volumes for a wide range of rain events, especially the small and moderate rains of greatest interest in water quality evaluations.

Observed Runoff Volumes Do Not Compare Well With Commonly Used Urban Runoff Prediction Methods

Some of the most commonly used stormwater design methods utilizes the NRCS curve number (CN) method, especially TR-20 and TR-55 (SCS 1986). The NRCS recommends against the use of the curve number procedure for rains less than one-half inch. Unfortunately, this warning is ignored in many urban runoff models that have been developed. As shown previously, small rains are very significant when analyzing urban runoff. In addition, the NRCS recommends that the curve number method should be used for individual components of the drainage area, if CN values differ by more than 5, instead of using a composite CN for the complete area. Unfortunately, many users of the CN method ignore these two basic warnings, and many urban stormwater models use composite CN values for all storms. The CN method is a suitable tool if properly used, unfortunately, it is frequently used for small storms and for water quality evaluations, well beyond its intended use addressing drainage design for conveyance objectives for large rains.

An example of typical errors associated with the misuse of the CN method is illustrated using commonly available rainfall and runoff data. Observed CN (from monitored rain and runoff events) versus rain depth plots were prepared by Pitt, *et al.* (1997) for: 2 locations in Broward County, FL; 1 site in Dade County, FL; 2 sites in Salt Lake City, UT; and 2 sites in Seattle, WA (from the rainfall-runoff-quality data base, Huber 1981), plus 4 sites in Champaign, IL; 5 sites in Irondequoit Bay, NY; 2 sites in Austin, TX; and 1 site in Rapid City, SD (from the NURP data, EPA 1983). All of the test watersheds are typical for these land uses and do not contain any unusual drainage designs or stormwater controls. Figure 4 contains plots for medium density residential areas and mixed common urban areas, while Figure 5 contains plots for high density and commercial areas.

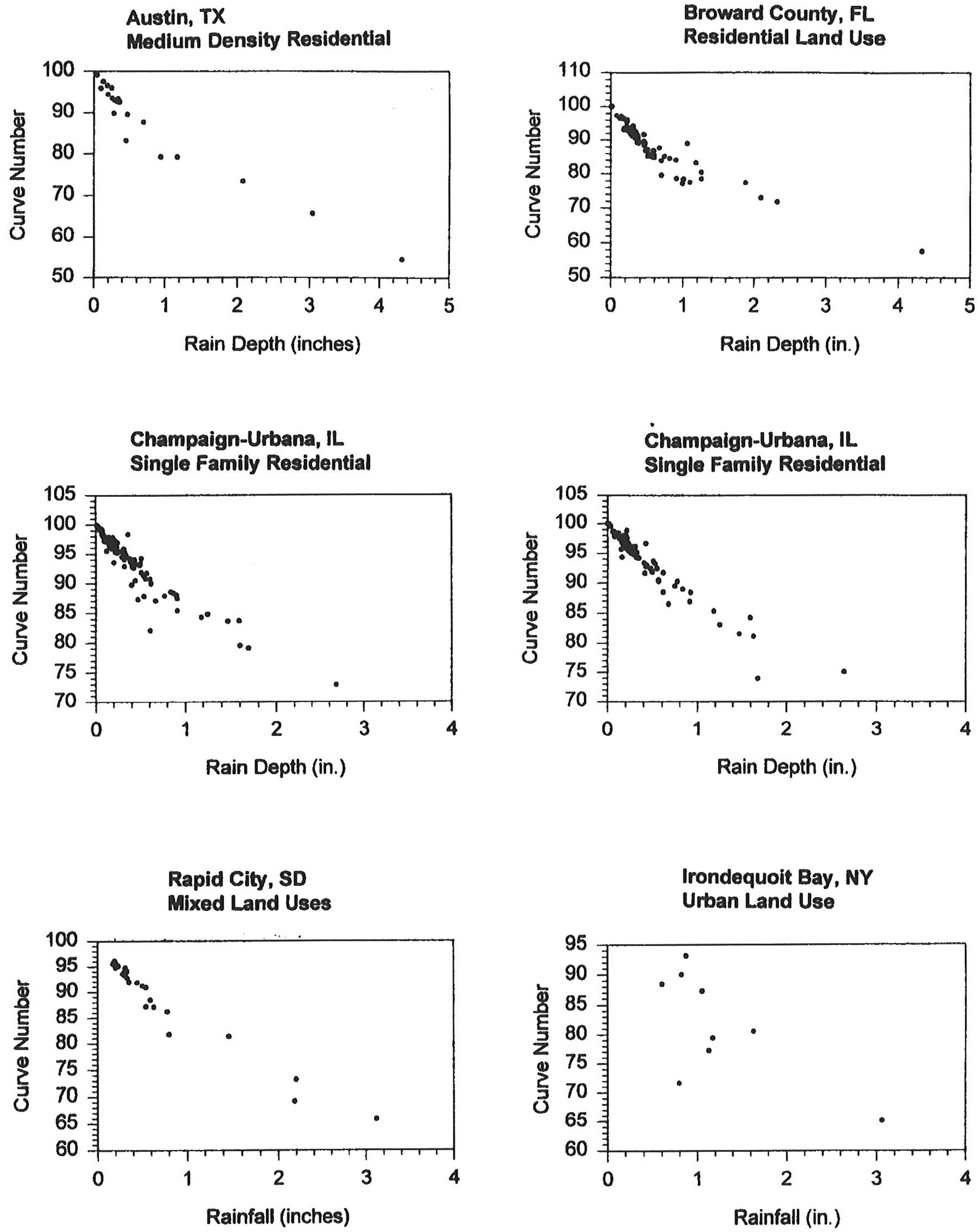


Figure 4. Medium density land use area observed CN vs. rain depth plots.

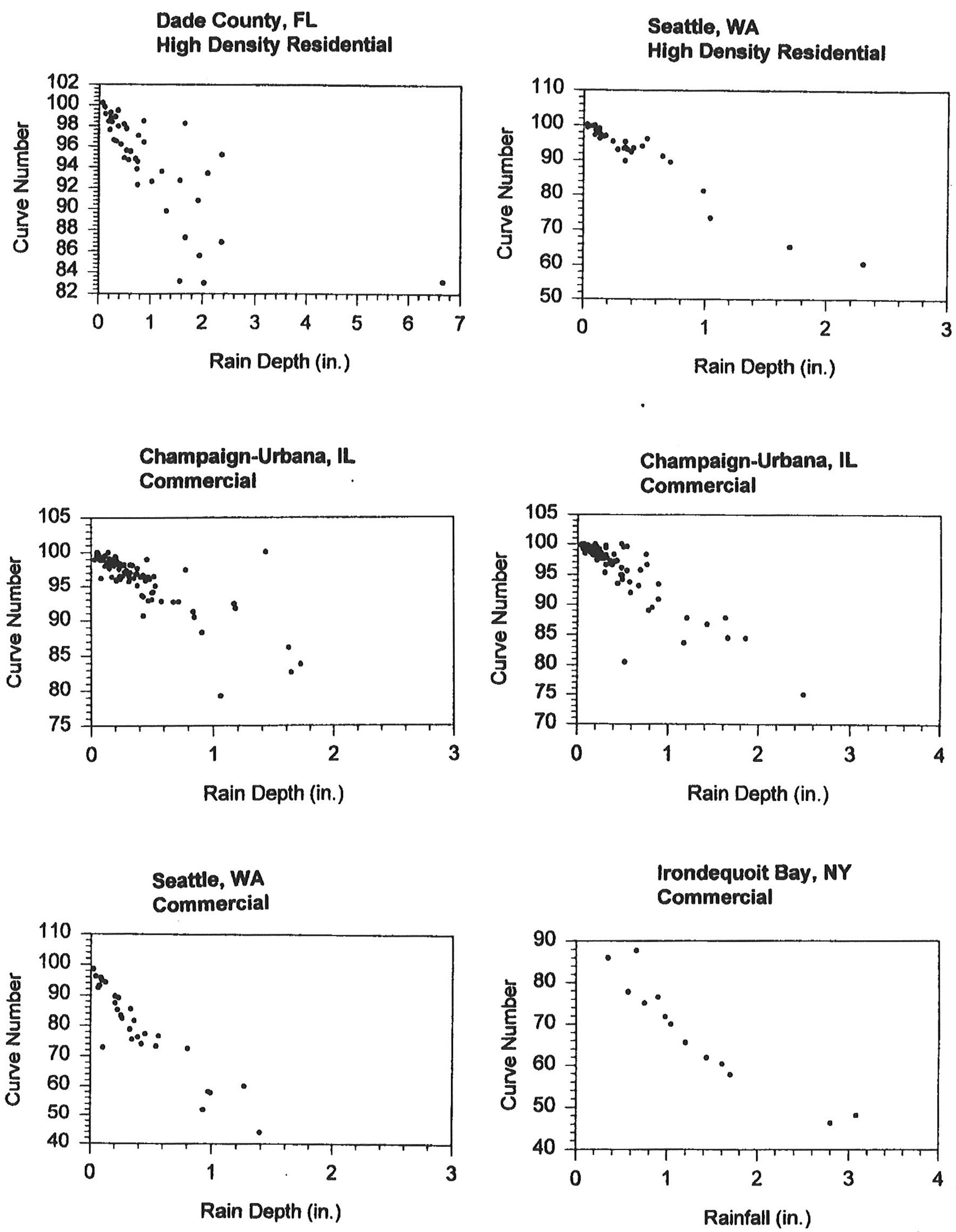


Figure 5. High density and commercial land use area observed CN vs. rain depth plots.

In all cases, the general pattern is the same: observed curve numbers are all very high for small rains, tapering off as the rains become large. The NRCS CN procedure assumes that the curve numbers are constant for all rains greater than 0.5 inch. However, it may be best to only use the CN method for rains greater than several inches in depth, in the range of drainage design for conveyance, the purpose of the CN method when it was developed. The reason for the behavior of these plots is based on the simplifications inherent in the CN method, especially the assumption that initial abstractions are always equal to 20% of the total abstractions. This assumption may be valid for large rains, resulting in relatively small errors, but the associated errors during small rains become very large.

Table 2 is a summary of these observed curve numbers at several different rain depths, compared to typical curve numbers presented by the NRCS (SCS 1986) for these land uses. Several of the sites had adequate descriptions to enable curve numbers to be estimated, based on their directly connected impervious areas and soil texture. The following list shows these sites, with the NRCS recommended curve numbers, and the approximate rain depth where these curve numbers were observed:

- Broward Co., FL, residential land use (40% imperv., with sandy soils). NRCS CN = 61, observed at about 3.5 in. of rain.
- Champaign-Urbana, IL, single family residential land use (18% imperv., with silty, poorly drained soils). NRCS CN = 84, observed at about 1.2 in. of rain.
- Champaign-Urbana, IL, single family residential land use (19% imperv., with silty, poorly drained soils). NRCS CN = 84, observed at about 1.2 in. of rain.
- Dade Co., FL, high density residential land use (almost all impervious, "D" soils). NRCS CN = 92, observed at about 1.3 in. of rain.
- Champaign-Urbana, IL, commercial land use (40% imperv., with silty and poorly drained soils). NRCS CN = 87, observed at about 1.1 in. of rain.
- Champaign-Urbana, IL, commercial land use (55% imperv., with silty and poorly drained soils). NRCS CN = 91, observed at about 0.8 in. of rain.
- Broward Co., FL, transportation catchment (54% imperv., with sandy soils). NRCS CN = 73, observed at about 1.7 in. of rain.
- Salt Lake City, UT, roadway land use (mostly paved, sandy loam). NRCS CN = 89, observed at about 0.3 in. of rain.
- Salt Lake City, UT, transportation catchment (imperv. roads, clay loam). NRCS CN = 95, observed at about 0.15 in. of rain.

Table 2a. Observed Curve Numbers During Actual Rainfall-Runoff Monitoring

Land Use and Location	Directly connected imperviousness	0.2 in. rain	0.5 in. rain	1 in. rain	3 in. rain	For max. rain observed
Low Density/Suburban						
Austin, TX	21%	94	84	72	53	42 (5 in.)
Irondequoit Bay, NY	Rv = 0.1	95	88	76	55	52 (4 in.)
Irondequoit Bay, NY	Rv = 0.2	94	86	77	57	52 (4 in.)
Irondequoit Bay, NY	Rv = 0.2	94	89	84	69	67 (4 in.)
Medium Density Residential						
Austin, TX	39%	96	89	82	66	52 (5 in.)
Broward County, FL	40% (sandy soils)	96	89	81	65	54 (5 in.)
Champaign-Urbana, IL	18% (silty, poorly drained soils)	96	94	87	72	71 (4 in.)
Champaign-Urbana, IL	19 % (silty, poorly drained soils)	98	93	86	74	72 (4 in.)
Rapid City, SD	mixed	95	92	84	67	63 (4 in.)
High Density Residential						
Dade County, FL	"Almost all imperv." (D soils)	99	97	94	87	82 (7 in.)
Seattle, WA	?	94	89	80	56 (max.)	
Commercial						
Champaign-Urbana	40% (silty, poorly drained soils)	97	95	89	81 (max.)	
Champaign-Urbana	55% (silty, poorly drained soils)	99	95	89	74	73 (4 in.)
Seattle, WA	?	90	76	61	44 (max.)	
Irondequoit Bay, NY	?	92	82	72	46	46 (4 in.)
Transportation						
Broward County, FL	54% (sandy soils)	96	93	86	62	53 (5 in.)
Salt Lake City, UT	Mostly paved (sandy loam)	91	81	67	na	na
Salt Lake City, UT	"imperv. roads" (clay loam)	95	84	73	na	na

Table 2b. Typically Used Curve Number Values

Land Use and Location	Estimated CN from NRCS tables for different soil conditions (if possible, most likely CN highlighted, based on available site description):			
Low Density/Suburban	A (sandy to sandy loam)	B (silt loam or loam)	C (sandy clay loam)	D (silty to clayey)
Austin, TX	51	68	79	84
Irondequoit Bay, NY	46	65	77	82
Irondequoit Bay, NY	51	68	79	84
Irondequoit Bay, NY	51	68	79	84
Medium Density Residential				
Austin, TX	61	75	83	87
Broward County, FL	**61**	75	83	87
Champaign-Urbana, IL	51	68	79	**84**
Champaign-Urbana, IL	51	68	79	**84**
Rapid City, SD	?	?	?	?
High Density Residential				
Dade County, FL	77	85	90	**92**
Seattle, WA	77	85	90	92
Commercial				
Champaign-Urbana	61	75	83	**87**
Champaign-Urbana	73	82	88	**91**
Seattle, WA	?	?	?	?
Irondequoit Bay, NY	?	?	?	?
Transportation				
Broward County, FL	**73**	82	88	91
Salt Lake City, UT	**89**	92	94	95
Salt Lake City, UT	89	92	94	**95**

For the rains less than the matching point (rain depth where the NRCS recommended CN was observed), the actual CN is larger than the recommended CN and the predicted runoff using the NRCS methods would be less than actually occurred. Similarly, for rains larger than the matching point, the actual CN is smaller than the recommended CN and the predicted runoff using the NRCS CN method would be greater than actually occurred. The magnitude of the runoff differences varies greatly, depending on the CN values and the rain depth. As an example, if the recommended NRCS CN was 84, but the actual CN was really 98 for a 0.2 in. rain (similar to the Champaign, IL, medium density residential sites), the percentage error is infinite. For a 1 in. rain, the actual CN at this site was about 86 and the recommended NRCS remains at 84. The difference now is much smaller, as the rain depth being examined is close to the matching point depth of 1.2 inches. If the rain depth of concern was much larger, say 3 inches, the errors would be in the other direction, as summarized below:

	0.2 in. rain (matching point of 1.2 in)	1 in. rain (matching point of 1.2 in)	3 in. rain (matching point of 1.2 in)
Predicted runoff using CN of 84 (recommended by NRCS)	0 in. of runoff predicted by NRCS method	0.15 in. of runoff predicted by NRCS method	1.52 in. of runoff predicted by NRCS method
Actual runoff and calculated CN	0.10 in. of runoff observed (actual CN of 98)	0.20 in. of runoff observed (actual CN of 86)	0.91 in. of runoff observed (actual CN of 74)
Errors	Actual runoff is infinitely larger, predicted runoff is infinitely less.	Actual runoff is larger, predicted runoff is less. Error of 25%.	Actual runoff is less, predicted runoff is larger. Error of -67%.

The overall annual runoff depth error associated with using the NRCS recommended CN method depends on the frequency of rains having the different errors. Because the matching point rainfall depths are close to the rain depth associated with the median runoff depth, the annual errors may be within reason. However, the errors associated with individual events, and for the different categories of rains described earlier, are likely very large. This is a significant problem with stormwater quality management where accurate representations of the sources of the runoff are needed in order to evaluate control practices and development options. If the relative sources of the runoff flows are in great error, inappropriate and wasteful expenditures are likely. It is very obvious that the curve number method should not be used for the small events, as warned by NRCS, but only for the larger "drainage design" classes of storms for which the method was intended.

General Urban Hydrology Model

Runoff Process for Paved Surfaces

Initial abstractions are dependent on pavement texture and slope, while infiltration is dependent on pavement porosity and pavement cracks. Typical urban street pavements are relatively porous, in contrast to the much thicker and denser pavements used for freeways and airport runways which are much more impervious. It is the pavement base course that is much more resistant to percolation for urban streets. Infiltrated water is therefore forced to flow laterally towards the pavement edges. If the flow path is long (such as for large parking areas), then the resulting infiltration is limited. Figure 6 is an example from a typical pavement runoff test (Pitt 1987). This plot is similar to the SCS plot of rainfall vs. runoff, except it does not have the Ia/S ratio assumption of 0.2 (it is 0.13 in this plot), or other restraints on the curvature of the plot. This and other tests showed that initial abstractions may be about 1 mm for pavement, while the total infiltration may be between 5 and 10 mm. The maximum losses may occur after about 20 mm of rain. These abstractions are not very important for large drainage events, where simplifications are appropriate. However, they are very important for small storms, especially in their pattern of variability.

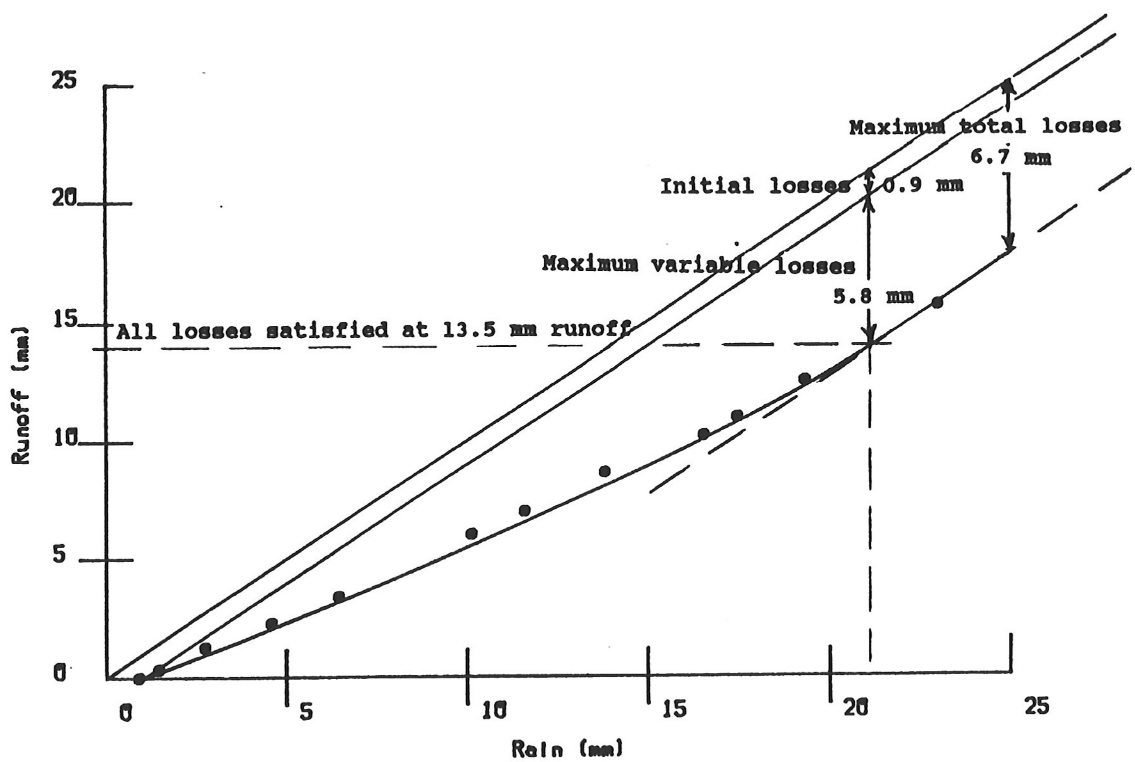


Figure 6. Example pavement rainfall-runoff test plot (Pitt 1987).

Figure 7a shows that high infiltration rates are associated with high rainfall intensities. The Horton equation predicts a single infiltration relationship as a function of time, irrespective of rain intensity. When variable runoff losses (infiltration losses) are plotted against total rain depth (Figure 7b) a single relationship is seen (rain intensity multiplied by time duration gives rain depth). Horton actually recommended infiltration as a function of rain depth, but current practice of using double-ring infiltrometers to calibrate the Horton equation does not allow infiltration measurements to be made as a function of rain depth, only as a function of time for the ponded test conditions. SWMM uses an integrated Horton equation where infiltration capacity is a function of cumulative infiltration depth, not time.

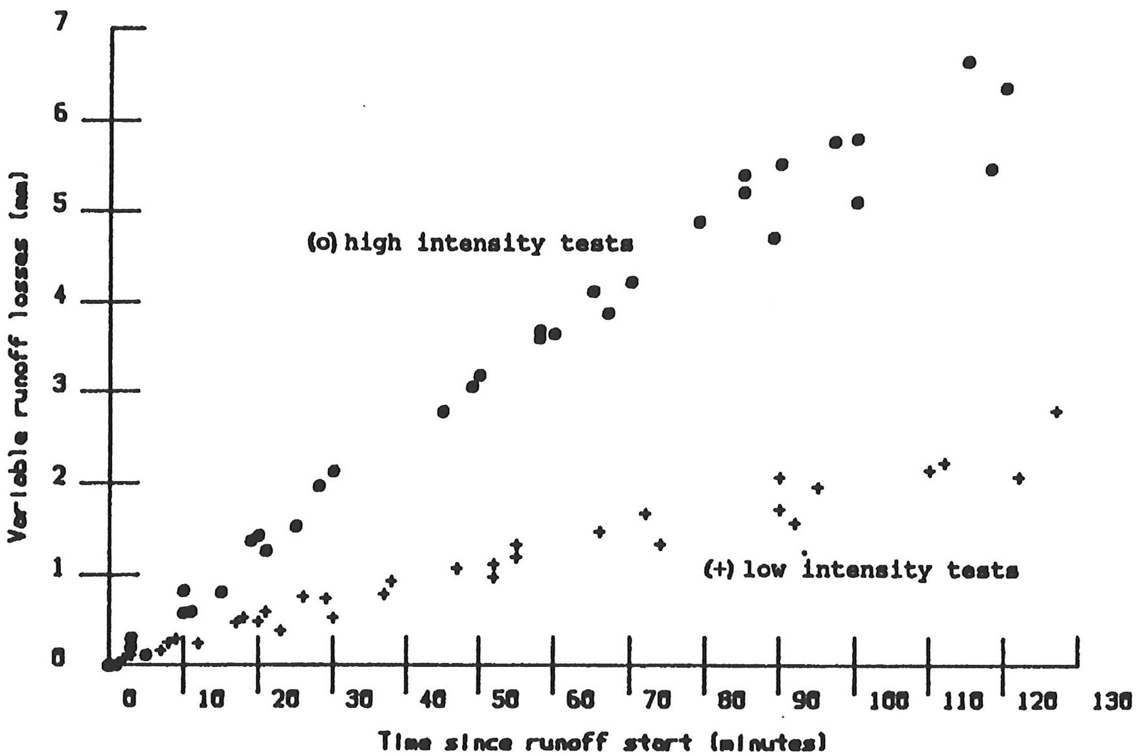


Figure 7a. Pavement infiltration rates for time since start of rain (Pitt 1987).

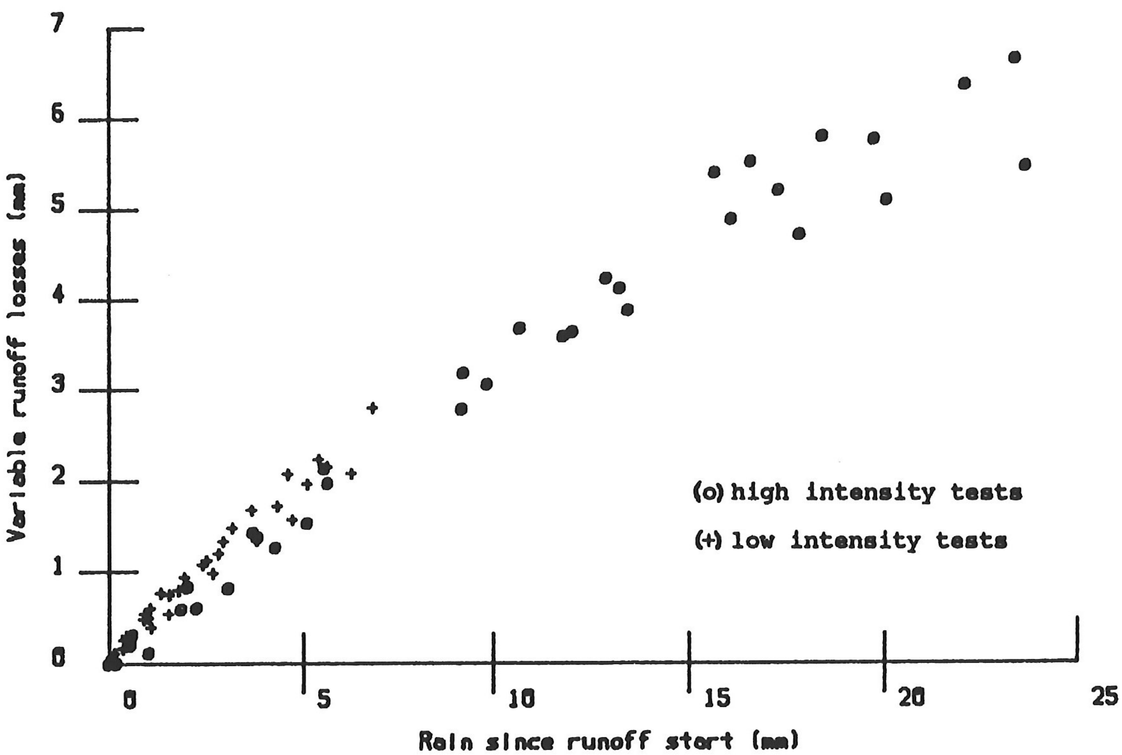


Figure 7b. Pavement infiltration rates for rain depth since start of rain (Pitt 1987).

Infiltration in Disturbed Urban Soils

Disturbed urban soils do not behave as indicated by typically used models. More rain infiltrates through pavement surfaces and less rain infiltrates through soils than typically assumed. Double-ring infiltrometer test results from Oconomowoc, WI, urban soils (Table 3) indicated highly variable infiltration rates for soils that were generally sandy (NRCS A/B hydrologic group soils). The median initial rate was about 3 in/hr, but ranged from 0 to 25 in/hr. The final rates also had a median value of about 3 in/hr after at least two hours of testing, but ranged from 0 to 15 in/hr. Many infiltration rates actually increased with time during these tests. In about 1/3 of the cases, the observed infiltration rates remained very close to zero, even for these sandy soils. Areas that experienced substantial disturbances or traffic (such as school playing fields) had the lowest infiltration rates, typically even lower than concrete or asphalt! These values indicate the large variability in infiltration rates that may occur in areas having supposedly similar soils. Obviously, these variations can significantly affect site specific runoff predictions. The lowest infiltration rates were observed in areas having heavy foot traffic and in areas obviously impacted by silt, while the highest rates were in relatively undisturbed areas. The following discussion is a brief summary of these important issues. The appendix attached to the end of this paper contains a more detailed discussion on compacted urban soils.

Table 3. Ranked Oconomowoc, WI, Double Ring Infiltration Test Results

	Observed urban soil Infiltration rates (in/hr):	
Initial Rate	Final Rate (after 2 hours)	Total Observed Rate Range
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

In an attempt to explain much of the variation shown in the above early tests, recent tests of infiltration through disturbed urban soils were conducted in the Birmingham, AL, area by the author and UAB students (Pitt, *et al.* 1999). Eight categories of soils were tested, with about 15 to 20 individual tests conducted in each of eight categories (comprising a full factorial experiment). Numerous replicates were needed in each category because of the expected high variation in infiltration rates. The eight categories tested were as follows:

Category	Soil Texture	Compaction	Moisture
1	Sand	Compact	Saturated
2	Sand	Compact	Dry
3	Sand	Non-compact	Saturated
4	Sand	Non-compact	Dry
5	Clay	Compact	Saturated
6	Clay	Compact	Dry
7	Clay	Non-compact	Saturated
8	Clay	Non-compact	Dry

Figure 8 contains plots showing the interactions of moisture and compaction on infiltration for both soil texture conditions. Four general conditions were observed to be statistically unique:

- noncompact sandy soils
- compact sandy soils
- noncompact and dry clayey soils
- all other clayey soils

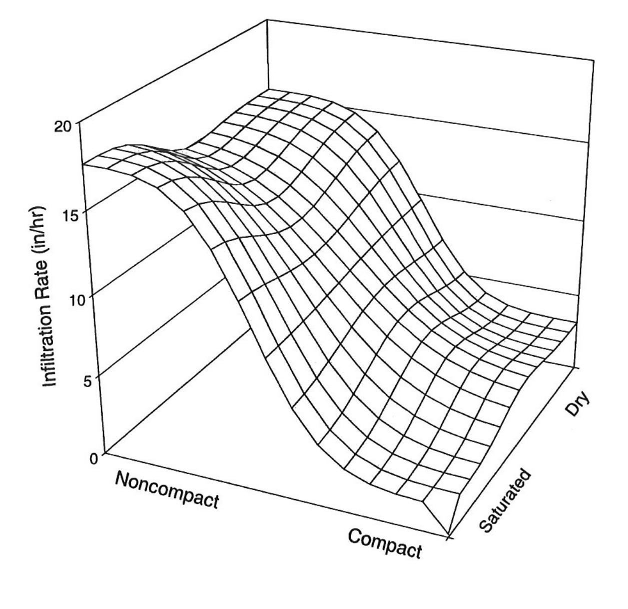


Figure 8a. Interactions of soil moisture and compaction on infiltration rates for sandy urban soils (Pitt, *et al.* 1999).

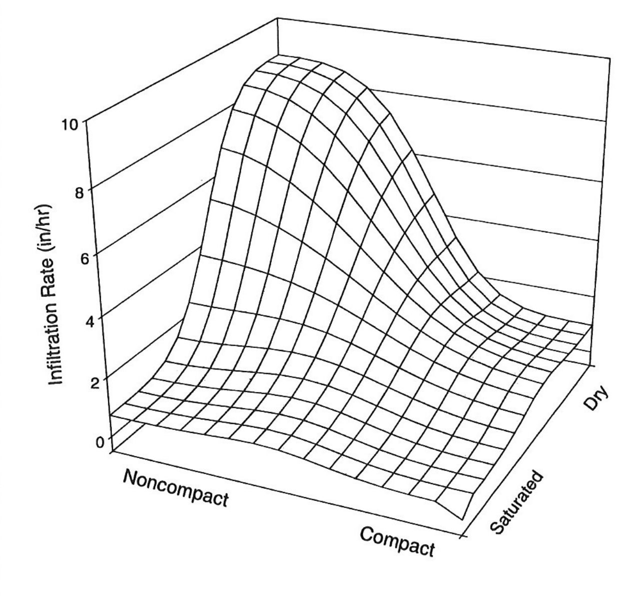


Figure 8b. Interactions of soil moisture and compaction on infiltration rates for clayey urban soils (Pitt, *et al.* 1999).

Compaction has the greatest effect on infiltration rates in sandy soils, with little detrimental effects associated with soil moisture. Clay soils, however, are affected by both compaction and moisture. Compaction is seen to have about the same effect as moisture on these soils, with saturated and compacted clayey soils having very little effective infiltration. In most cases, the mapped soils were similar to what was actually measured in the field. However, significant differences were found at many of the 146 test locations. Table 4 shows that the 2-hour averaged infiltration rates and their COVs in each of the four major categories were about 0.5 to 2. Although these COV values are generally high, 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 the four main 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 be considered using Monte Carlo components in runoff models. More detailed analyses of these data will be presented in the Toronto stormwater modeling conference next year.

Table 4. Infiltration Rates for Different Soil Texture, Moisture, and Compaction Conditions

	Number of tests	Average infiltration rate (in/hr)	COV
noncompact sandy soils	29	17	0.43
compact sandy soils	39	2.7	1.8
noncompact and dry clayey soils	18	8.8	1.1
all other clayey soils	60	0.69	2.1

Very large errors in soil infiltration rates can easily be made if published soil maps and typical models are used for typically disturbed urban soils. Knowledge of compaction (which can be mapped using a cone pentrometer, or estimated based on expected activity on grassed areas) can be used to much more accurately predict stormwater runoff quantity.

General Runoff Loss Model

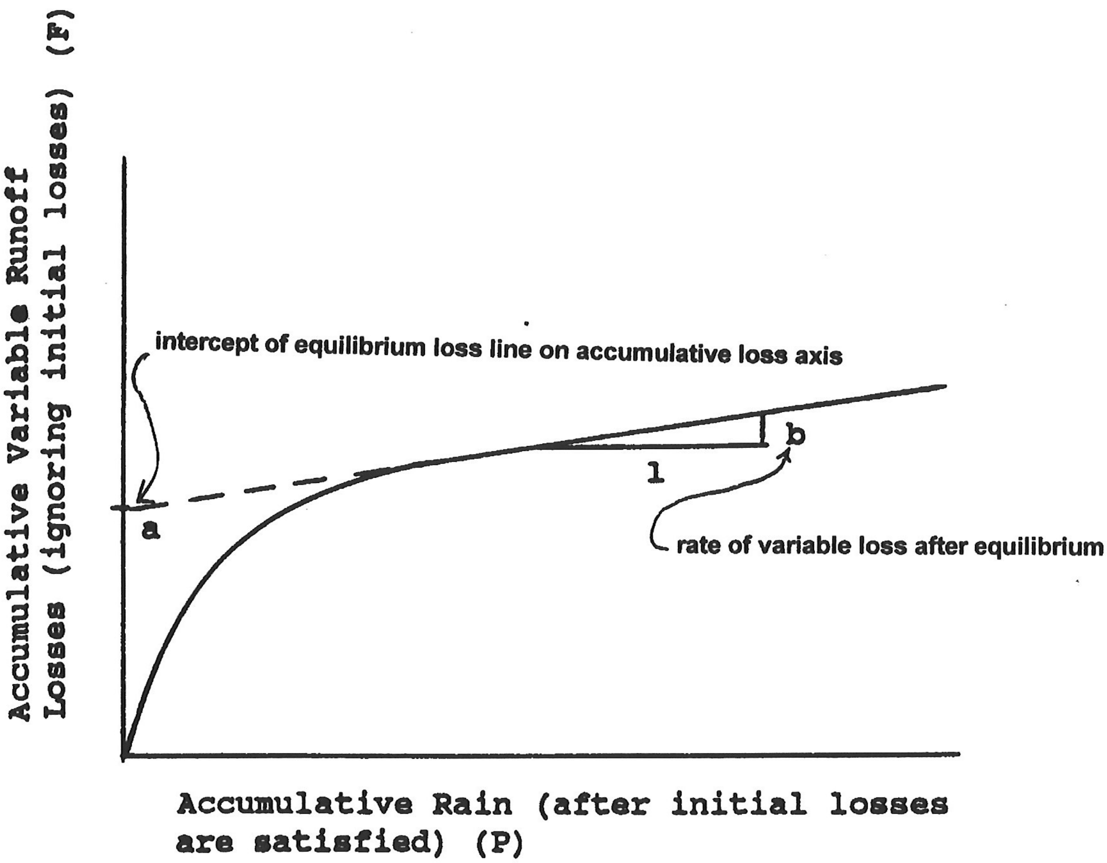
As shown in the above two discussions, more rain typically infiltrates through pavement surfaces and less rain infiltrates through soils than usually expected. This dramatically affects the predictions of relative contributions of runoff and pollutants from different source areas, and in turn, results in erroneous designs and predictions of stormwater pollutant control benefits associated with runoff control practices. The following discussion outlines the general runoff loss model used by Pitt (1987) to more accurately describe urban runoff processes over a wide range of rains.

When rain falls on an impervious surface, much of it will flow off the surface and contribute to the total urban runoff. With the exception of infiltration, rainfall abstractions are mostly associated with the initial portions of the rain and are termed initial abstractions. Water may also infiltrate through pavement, or through cracks or seams in the pavement. For small rains, a much greater portion of the rain will be lost to these runoff loss processes than for large rains.

Paved surfaces are usually considered impervious, implying no infiltration. However, numerous researchers have long concluded that paved surfaces do indeed experience infiltration losses (such as Willeke 1966; Cedergren 1974; Falk and Niemczynowicz 1978; Pratt and Henderson 1981; Davies and Hollis 1981; and Pitt 1987).

Both small-scale and large-scale tests, described by Pitt (1987), obtained data to calibrate and verify a model for homogeneous impervious and pervious areas (similar to the plot shown in Figure 6). The runoff response curve departs from the x-axis at the rainfall depth when runoff begins. This depth lag corresponds to initial runoff losses (detention storage, evaporation losses due to pavement cooling, and dirt and debris absorbing moisture for pavements). After some rain depth, infiltration into the ground (or pavement or through cracks) slows practically to nothing, and each additional increment of rainfall results in a similar increment of runoff. Between these two rain depths, infiltration losses occur. Figure 9 shows the model describing these infiltration losses. This figure plots cumulative variable runoff losses (F, inches or mm), ignoring the initial losses, versus cumulative rain (P, inches or mm), after runoff begins. The slope of this line is the instantaneous variable runoff loss (infiltration) occurring at a specific rain depth after runoff starts. A simple nonlinear model can be used to describe this relationship which is similar to many other infiltration models. For a constant rain intensity (i), total rain depth since the start of runoff (P), equals intensity times the time since the start of runoff (t). The general nonlinear model for this variable runoff loss (F) is therefore:

$$F = bit + a(1 - e^{-git}) \qquad \text{or} \qquad F = bP + a(1 - e^{-gP})$$



$$F = bP + a(1 - e^{-gP})$$

where F = accumulative variable losses

g = exponential coefficient

P = accumulated rainfall

If b = 0, then a = total losses and no steady state losses occur (equivalent to SCS model)

Note: time since runoff started is not a factor (as implied by most users of Horton equation).

Figure 9. Cumulative variable runoff loss model for pavement (Pitt 1987).

Three basic model parameters were used to define the model behavior, in addition to initial runoff losses and rain depth: "a", the intercept of the equilibrium loss line on the cumulative variable loss axis; "b", the rate of the variable losses after equilibrium; and "g", an exponential coefficient. If variable losses are zero at equilibrium, then "b" would be zero. Because this plot does not consider initial runoff losses, the variable loss line must pass through the origin. This model reduces to the SCS model when the "b" value is zero and "a" is S', and when Ia is 0.16 (80% of 0.2) of "a". This general model also reduces to the Horton equation when cumulative rain depth since the start of the event is used instead of just time since the start of rain.

Observed runoff data from both small- and large-scale tests were fitted to this equation to determine the values for a, b, and g for observed i and t (or P), and F values. In addition, outfall runoff observations from many different heterogeneous land uses were used to verify the calibrated model (Pitt 1987).

Volumetric Runoff Coefficients

Table 5 is a summary of the volumetric runoff coefficients (Rv, the ratio of runoff to rainfall volume) for different urban surfaces and rain depths from detailed source area runoff tests and through calibrating the general runoff model (Pitt 1987). Flat roofs and unpaved parking areas behave strangely similar because of similar detention storage volumes and no infiltration. Large impervious areas have the largest runoff yields because of very poor pavement under-drainage. The drainage path through the pavement base is relatively thin and very long, making it very difficult for infiltrated water to drain from the base. Street widths are much narrower than the widths of large impervious areas and the base water can drain much more effectively. Pitched roofs have no infiltration rates, but do experience limited initial losses associated with flash evaporation and sorption of moisture in leaves and other roof or gutter debris. After three inches (no longer a "small" rain) the runoff yields from all impervious surfaces are similar (within 10%), but the differences can be very large for the small rains of most concern in water quality evaluations.

Table 5. Summary of Volumetric Runoff Coefficients for Urban Runoff Flow Calculations (Pitt 1987).

Runoff Coefficients for Directly Connected Areas:

Rain Depth mm	Rain Depth inches	Flat roofs* (or large unpaved parking areas)	Pitched roofs*	Large impervious areas*	Small impervious areas and streets	Sandy soils	Typical urban soils	Clayey soils
1	0.04	0.00	0.25	0.93	0.26	0.00	0.00	0.00
3	0.12	0.30	0.75	0.96	0.49	0.00	0.00	0.00
5	0.20	0.54	0.85	0.97	0.55	0.00	0.05	0.10
10	0.39	0.72	0.93	0.97	0.60	0.01	0.08	0.15
15	0.59	0.79	0.95	0.97	0.64	0.02	0.10	0.19
20	0.79	0.83	0.96	0.97	0.67	0.02	0.11	0.20
30	1.2	0.86	0.98	0.98	0.73	0.03	0.12	0.22
50	2.0	0.90	0.99	0.99	0.84	0.07	0.17	0.26
80	3.2	0.94	0.99	0.99	0.90	0.15	0.24	0.33
125	4.9	0.96	0.99	0.99	0.93	0.25	0.35	0.45

*If these "impervious" areas drain for a significant length across sandy soils, the sandy soil runoff coefficients will usually be applied to these areas, however, if these areas drain across clayey soils, the runoff coefficients will be reduced, depending on the land use and rain depth, according to the following table:

Reduction factors for different rain depths (mm):

	1	3	5	10	15	20	30	50	80	125
Strip commercial and shopping centers:	0.00	0.00	0.47	0.90	0.99	0.99	0.99	0.99	0.99	0.99
Other medium to high density land uses, with alleys:	0.00	0.08	0.11	0.16	0.20	0.29	0.46	0.81	0.99	0.99
Other medium to high density land uses, without alleys:	0.00	0.00	0.11	0.16	0.20	0.21	0.22	0.27	0.34	0.46

If low density land uses, use clayey soil runoff coefficients.

The impervious and roof area values are for directly connected surfaces. If runoff is allowed to drain across grass areas, then the runoff yield may significantly decrease. However, sufficient length of drainage across the pervious surface in good condition is needed. For a relatively small paved surface, short pervious drainage paths are all that are needed. If the paved area is large, or if the pervious area has clayey or compacted soils, then much longer drainage paths are needed before significant infiltration occurs.

Table 5 does not accurately incorporate the effects of disturbed urban soils presented earlier, but the runoff coefficients shown generally bracket the range of likely conditions expected. Some users have had good success using an intermediate soil Rv value, half way between the clayey and sandy soil conditions shown, and only using the extreme values for more unusual cases. The four urban soil categories identified earlier better represent the conditions encountered, and appropriate coefficients are currently being developed.

The runoff coefficients and indirect connection correction values were determined from calibrating the small storm hydrology model for large urban watersheds having variable complexities in Toronto and in Milwaukee (Pitt 1987). The first calibrations were conducted for simple areas. The first area was the large parking area of a commercial shopping area. The runoff coefficients for this area were used to determine the runoff relationships from large flat roofs from another shopping area that was made of mostly paved large parking and roof areas in order to determine runoff characteristics for flat roofs. The next step was to evaluate runoff data for two high density residential areas that had very little pervious areas and had all of the impervious areas directly connected. The street runoff was subtracted from the total area runoff observations to obtain information solely for pitched roofs. Finally, two medium density residential areas were studied in areas that had clayey soils and all of the impervious areas were directly connected. Roof, street and other impervious area runoff information was subtracted to obtain clayey soil runoff coefficients. Similarly, a medium density residential area was studied in an area having sandy soils to obtain sandy soil runoff coefficients. Finally, two medium density residential areas having unconnected impervious areas were studied to obtain correction coefficients.

Example Validation of General Small Storm Hydrology Model

The final runoff coefficients were validated using additional runoff data from these same areas (that were not used in the calibration efforts) and from areas located elsewhere. Figures 10 through 13 show how well the small storm hydrology model works over a wide range of rain depths and for two very different land uses. The "Post Office" site was a commercial shopping center, the "Burbank" site was a medium density residential area. These sites were monitored as part of the EPA's NURP project in Milwaukee (Bannerman, *et al.* 1983). Figures 12 and 13 are for two residential sites monitored by the WI DNR in Superior, WI, and in Marquette, MI, during 1993 and 1994. These last two sites were compared to the small storm hydrology component of SLAMM with no local calibration, demonstrating the excellent fit of observed and predicted flows. The model was subsequently calibrated for these two sites to enable better fits for the larger events (due to inaccurate initial estimates of soil conditions). It was originally expected that this model would not work very well for very large storms, especially in areas having appreciable pervious areas, where rain intensity was expected to have a more significant effect on infiltration than for small rains. The largest rains observed for the two Milwaukee sites were greater than three inches, very large rains that would not be expected to commonly occur. Even these rains had runoff quantities that were well predicted by this general runoff model.

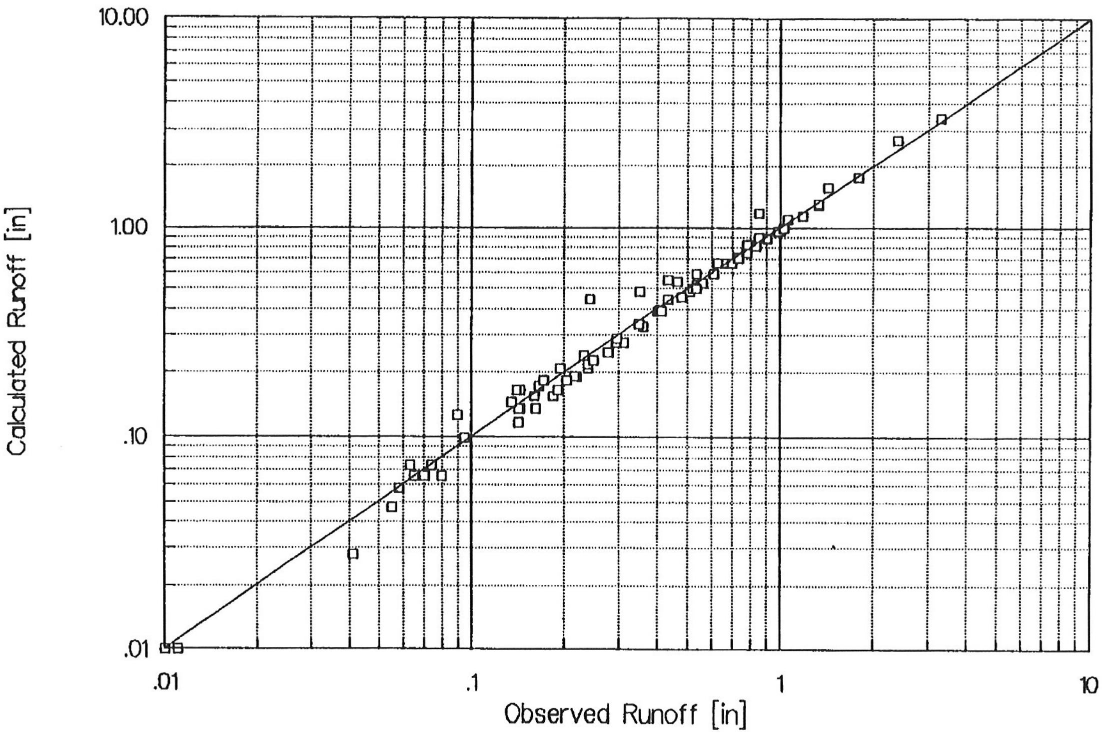


Figure 10. General hydrology model validation plot for Post Office commercial site (Milwaukee) (Pitt 1987).

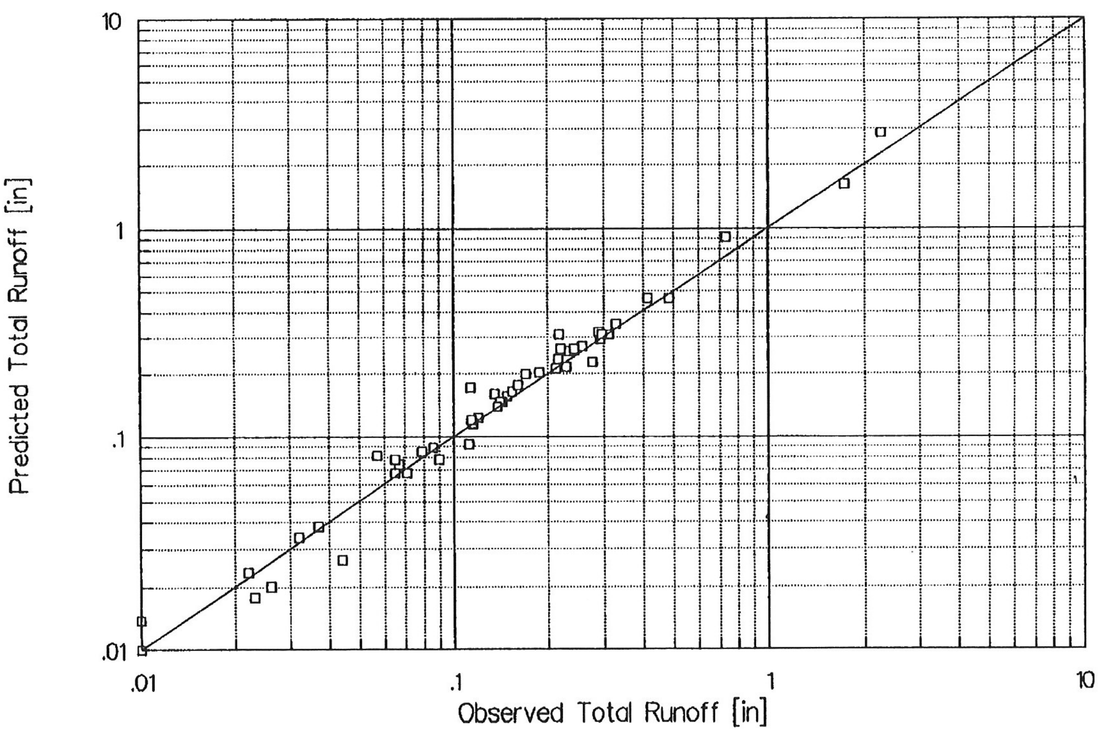


Figure 11. General hydrology model validation plot for Burbank residential site (Milwaukee) (Pitt 1987).

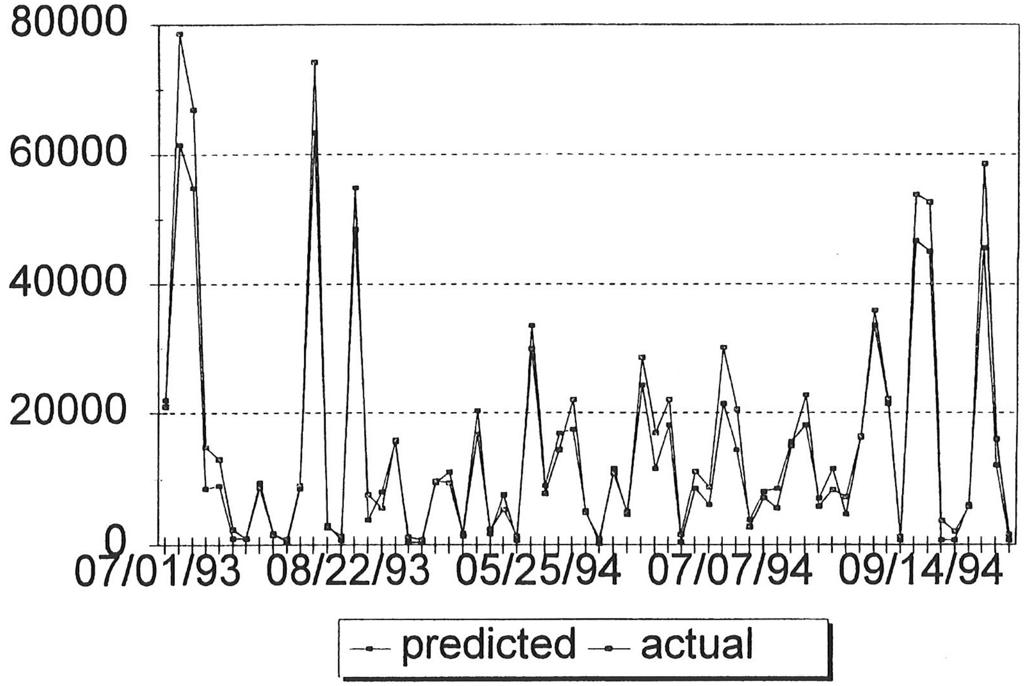


Figure 12. SLAMM validation plot for Superior, WI, ft^3 of runoff (personal communication, Jeff Prey, WI DNR).

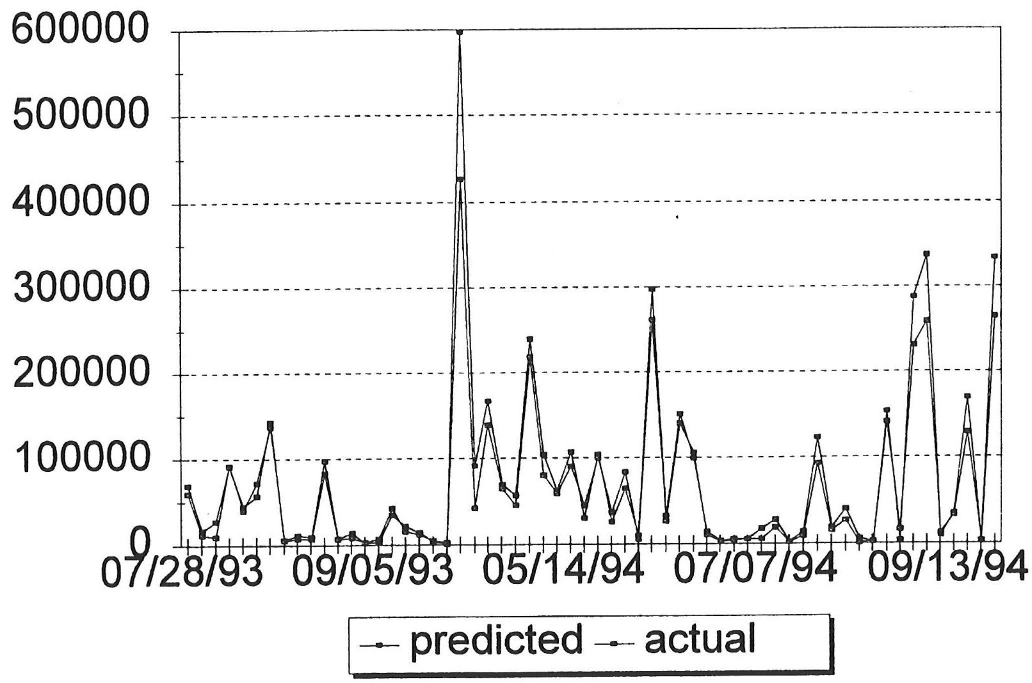


Figure 13. SLAMM validation plot for Marquette, MI, ft^3 of runoff (personal communication, Jeff Prey, WI DNR).

Conclusions

Runoff volume is the most important hydraulic parameter needed for most water quality studies, while peak flow rate and time of concentration are the most important parameters for most flooding and drainage studies. Common small rains account for much more of the annual runoff volume than rare flooding events. Pitt (1987) showed that estimates of runoff volume could be made with only rain depth information. Other rain characteristics (including antecedent conditions, durations, intensities, etc.) did not substantially improve runoff volume predictions, but are likely needed for peak flow rate predictions.

The literature indicates that both initial runoff abstractions (mostly detention/storage) and continuous runoff losses (infiltration) are important for impervious surfaces. Recent work with disturbed urban soils has also shown that care must be taken when using soil maps for developed conditions. The general model successfully predicts runoff from several types of paved, roofed, and disturbed soil urban surfaces. This model was shown to accurately predict runoff volumes for a wide range of rain conditions.

This model was used to examine long-term rain conditions at many locations throughout the U.S. to indicate the significance of small and moderate sized rains in stormwater management. These smaller rains, compared to the typical "design storm" rains used for drainage system design, contribute the vast majority of stormwater pollutants. Stormwater control practices must therefore effectively address these smaller storms to provide effective pollutant and flow reduction schemes.

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Appendix: Infiltration through Compacted Urban Soils and Effects on Biofiltration Design

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 biofiltration devices can be jeopardized. This paper is a compilation of results from several recent and on-going research projects that have examined some of these problems, plus possible solutions. Basic infiltration measurements in disturbed urban soils were conducted during the EPA-sponsored project by Pitt, *et al* (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 information and it is hoped that it will prove useful to both stormwater practice designers and to modelers.

Introduction and Summary

This paper is a compilation of information from previous chapters in this book series (specifically in Monographs 7 and 8), plus our on-going work. 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. This paper therefore includes a short summary of our past work on investigating the potential of groundwater contamination through stormwater infiltration. This material is summarized from prior EPA-funded research, an updated book, and a more recent review paper (Pitt, *et al.* 1994, 1996 and 1999b). This material shows that is possible to incorporate many stormwater infiltration options in urban areas, as long as suitable care is taken. These 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.

The bulk of this paper reviews our past and current investigations of the infiltration characteristics of disturbed urban soils. Several sets of tests have been conducted, 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. Sandy soils are better able to withstand compaction, although their infiltration rates are still significantly reduced.

This paper also 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). Our 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 our work 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.

Alternative stormwater management options are also examined using the Source Loading and Management Model (SLAMM) and this soil information. The use of biofiltration controls, such as roof gardens for example, can result in almost complete removal of roof runoff from the surface runoff component.

Much of our prior work has been previously reported in Monographs 7 and 8 of this series (Pitt 1999 and Pitt and Lantrip 2000). The following paragraphs briefly summarize this earlier work to better indicate how our more recent tests integrate with this earlier information to provide a more through understanding of the role of urban soils in stormwater management.

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, "biofiltration" 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 biofiltration 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.

Relative Risks Associated with Stormwater Infiltration of Various Contaminants

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.

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

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

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.

- 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

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

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

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

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

More recently, 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 2^3 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 3. 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.

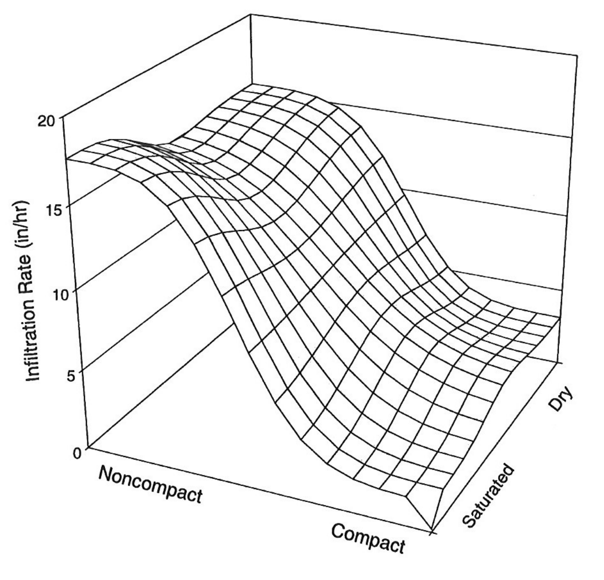

Figure 1. Three dimensional plot of infiltration rates for sandy soil conditions.

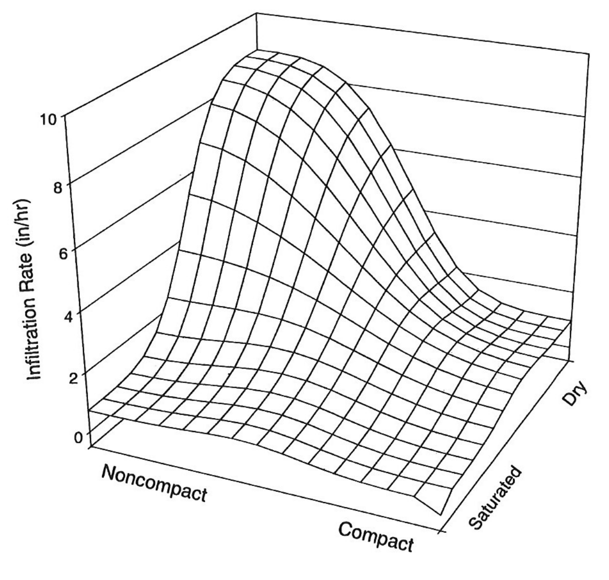

Figure 2. Three dimensional plot of infiltration rates for clayey soil conditions.

Table 3. 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 4 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.

Table 4. 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

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.

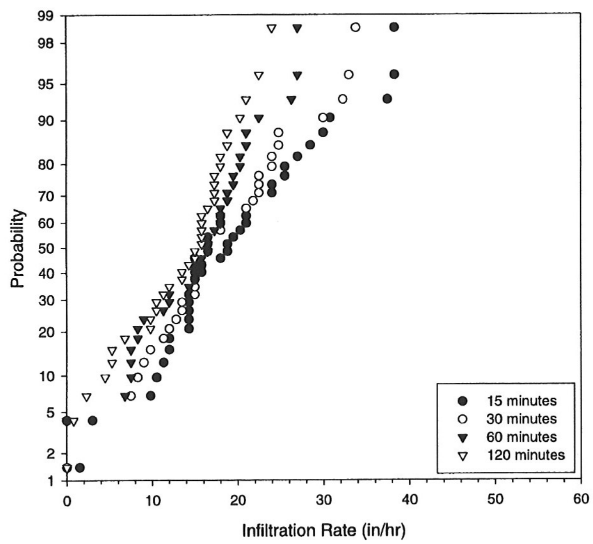

Figure 3. Probability plots for infiltration measurements for noncompacted, sandy soil, conditions.

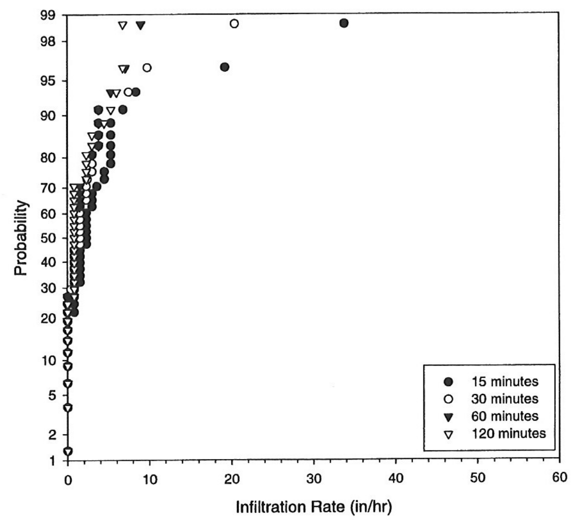

Figure 4. Probability plots for infiltration measurements for compacted, sandy soil, conditions.

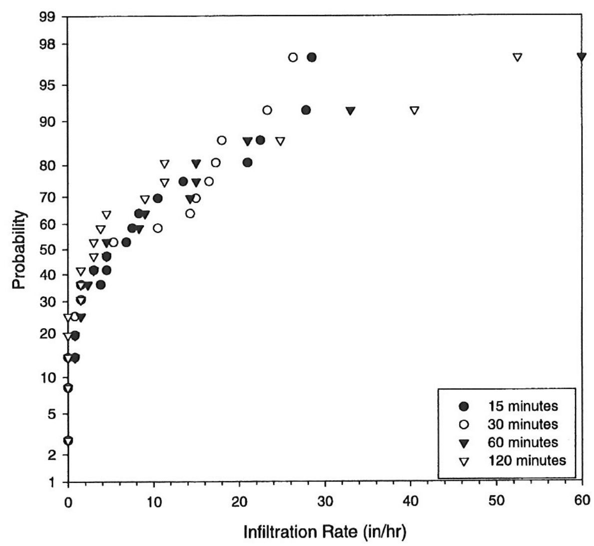

Figure 5. Probability plots for infiltration measurements for dry-noncompacted, clayey soil, conditions.

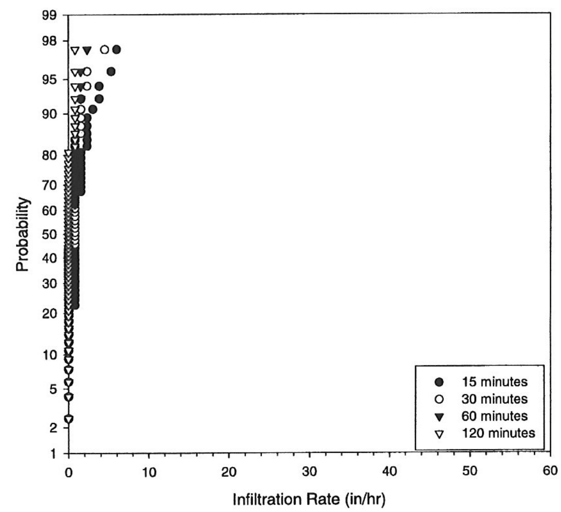

Figure 6. Probability plots for infiltration measurements for wet-noncompacted, dry-compacted, and wet-compacted, clayey soil conditions.

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

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

McCuen (1998) presents Table 5 (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 5. 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 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 6. 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 7 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.

Table 6. 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 7. 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

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.

As shown on Table 7, 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 7 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 biofiltration 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.

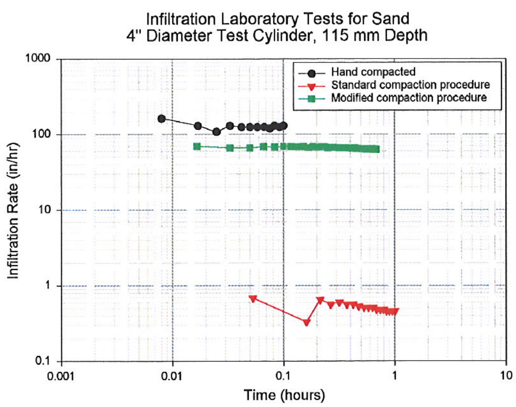

Figure 7. Sandy soil laboratory infiltration test results.

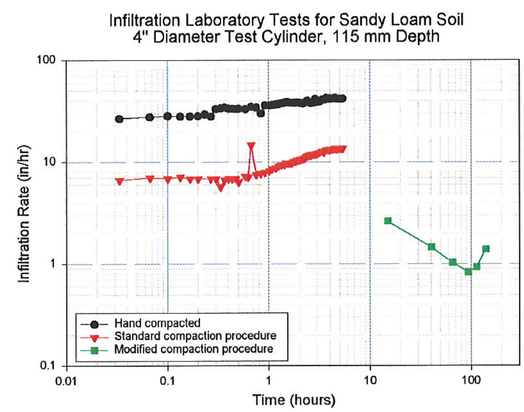

Figure 8. Sandy loam soil laboratory infiltration test results.

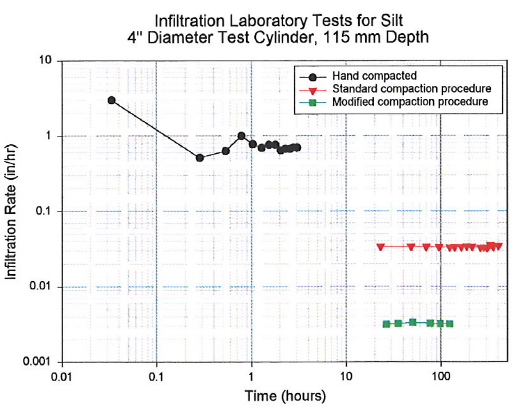

Figure 9. Silty soil laboratory infiltration test results.

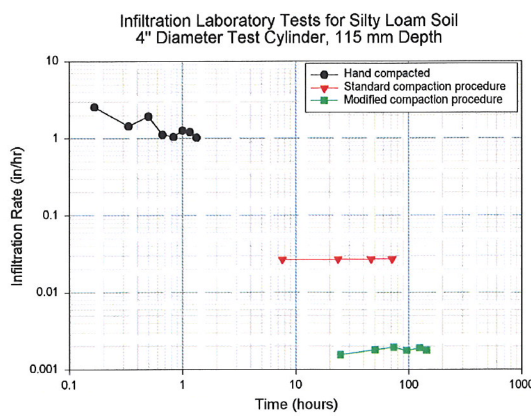

Figure 10. Silty loam soil laboratory infiltration test results.

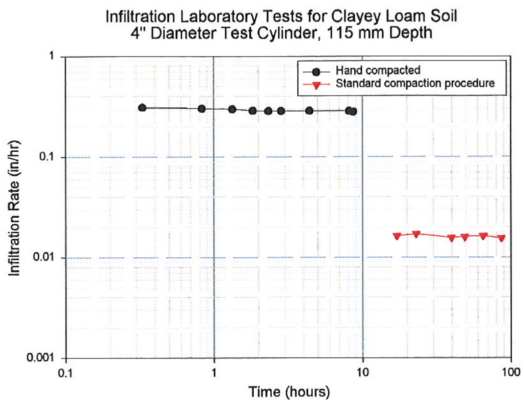

Figure 11. Clayey loam soil laboratory infiltration test results.

Another series of controlled laboratory tests were conducted to better simulate field conditions and standard double-ring infiltration tests, as shown in Table 8. 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.

Table 8. 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

Soil Amendments to Improve Urban Soil Performance

A growing area of research is the investigation of the use of soil amendments to improve the infiltration performance of urban soils, and to provide additional protection against groundwater contamination.

Soil Modifications to Enhance Infiltration

Turf scientists have been designing turf areas with rapid infiltration capabilities for playing fields for many years. It is thought that some of these design approaches could be used in other typical urban areas to enhance infiltration and reduce surface runoff. Several golf course and athletic field test sites were examined in Alabama during our study to document how turf areas can be constructed to enhance infiltration (Pitt, *et al.* 1999a). These areas were designed to rapidly dry-off following a rain to minimize downtime due to excessive soil-water levels. Turf construction techniques were reviewed at three sites: an intramural playing field at the University of Alabama at Birmingham (UAB), the UAB practice football field, and a local golf course. The UAB intramural field has a simple drainage design of parallel 100 mm (4in.) wide trenches with a filter fabric wrapped pipe laid 30 cm (12 in.) deep. A thick sand backfill was used and then the area was recapped with sod. The drainage pipe was directed to the storm drainage system. The drainage for the UAB practice field was done by a local engineering firm that chose a fishbone drainage design. A trunk line of 100 mm (4 in.) corrugated pipe is the "spine" of the system with smaller 75 mm (3 in.) pipes stemming off from the main line. All the pipes rest on a gravel base with a sand backfill. This system feeds to a larger basin that collects the stormwater and takes it to the existing storm drainage system. The golf course used the same basic fishbone design noted above, but differed in the sizes of the individual pipes. The drainpipes are 3 m (10 ft.) apart in trenches filled with 75 mm (3 in.) of gravel. The pipes are then covered with 30 cm (12 in.) of sand with the top 50 mm (2 in.) of the sand consisting of a blend of sand and peat moss. This particular mixture is known as the USGA greens sand mix and is readily available because of its popularity in golf course drainage design. If the backfill sand particles are too large, clay is added to the mixture to slow the drainage. However, if the sand particles are too small, the soil will compact too tightly and will not give the desired results. In all of these cases, standing water is rare after rain has stopped, even considering the generally flat playing fields and very high rainfall intensities occurring in the Birmingham area.

Other modifications include amending the soil with other materials. The following discussion summarizes the results of tests of amended soils and the effects on infiltration and groundwater protection.

Water Quality and Quantity Effects of Amending Soils with Compost

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

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

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

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

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

Compost-amended soils caused increases in concentrations of many constituents in the surface runoff. However, the compost amendments also significantly decreased the amount of surface runoff leaving the test plots. Table 9 summarizes these expected changes in surface runoff and subsurface flow mass pollutant discharges associated with newly placed compost-amended soils. All of the surface runoff mass discharges from the amended soil test plots were reduced from 2 to 50 percent compared to the unamended discharges. However, many of the subsurface flow mass discharges increased, especially for ammonia (340% increase), phosphate (200% increase), plus total phosphorus, nitrates, and total nitrogen (all with 50% increases). Most of the other constituent mass discharges in the subsurface flows decreased. During later field pilot-scale tests, Clark and Pitt (1999) also found that bacteria was reduced by about 50% for every foot of travel through columns having different soils and filtration media.

Table 9. Changes in Pollutant Discharges from Surface Runoff and Subsurface Flows at New Compost-Amended Sites, Compared to Soil-Only Sites

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

Selection of Material for use as Soil Amendments

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

The University of Washington and other Seattle amended soil test plots (Pitt, *et al.* 1999a and Harrison 1997) examined GroCo compost-amended soil (a sawdust/municipal waste mixture) and Cedar Grove compost-amended soil (yard waste compost). In addition, an older GroCo compost test plot was also compared to the new installations. These were both used at a 2:1 soil:compost rate. As noted previously, these compost-amended soils produced significant increases in the infiltration rates of the soils, but the new compost test sites showed large increases in nutrient concentrations in surface runoff and the subsurface percolating water. However, most metals showed major concentration and mass reductions and toxicity measurements were also decreased at the amended soil sites. The older compost-amended test plots still indicated significant infiltration benefits, along with much reduced nutrient concentrations. Table 10 shows the measured infiltration rates at the old and new compost-amended test sites in the Seattle area (all Alderwood glacial till soil).

Table 10. Measured Infiltration Rates at Compost-Amended Test Sites in Seattle (Pitt, *et al.* 1999a)

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

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

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

- Activated carbon-sand mixture (very good removals with minimal to no degradation of effluent)
- Peat-sand mixture (very good removals, but with some degradation of effluent with higher turbidity, color, and COD)
- Zeolite-sand mixture and sand alone (some removals with minimal degradation of effluent)
- Enretech (a cotton processing mill waste)-sand mixture (some removals with minimal degradation of effluent)
- Compost-sand mixture (some removals but with degradation of effluent with higher color, COD, and solids)

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

Conclusions

Very large errors in soil infiltration rates can easily be made if published soil maps are used in conjunction with most available models for typically disturbed urban soils, as these tools ignore compaction. Knowledge of compaction (which can be measured using a cone penetrometer, or estimated based on expected activity on grassed areas, or directly measured) can be used to more accurately predict stormwater runoff quantity, and to better design biofiltration 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 3 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. However, the measured values can be directly used to predict the infiltration rates that may be expected from stormwater infiltration controls that utilize ponding (most infiltration and biofiltration devices).

Table 11 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 month to examine some of these issues again. 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.

Table 11. 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

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

This information can be effectively used in the modeling of small-scale stormwater controls, such as biofiltration 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 12 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 12. 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. Biofiltration 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.

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