Day 2: Soil Infiltration Test Methods and Analyses, as Described in Several Case Studies

Robert Pitt, Ph.D., P.E., BCEE, D.WRE
Emeritus Cudworth Professor of Urban Water Systems
Department of Civil, Construction, and Environmental Engineering
The University of Alabama, Tuscaloosa, AL USA

Plus many other colleagues and students who helped with critical components

1

Initial Research on Compacted Urban Soils and Infiltration Rates

- Research has identified significant reductions in infiltration rates in disturbed urban soils.
- More than 150 initial tests were conducted in predominately sandy and clayey urban soils in the Birmingham and Mobile, Alabama, areas.
- Infiltration in clayey soils was found to be affected by an interaction of soil moisture and compaction, while infiltration in sandy soils was affected by soil compaction alone.

2

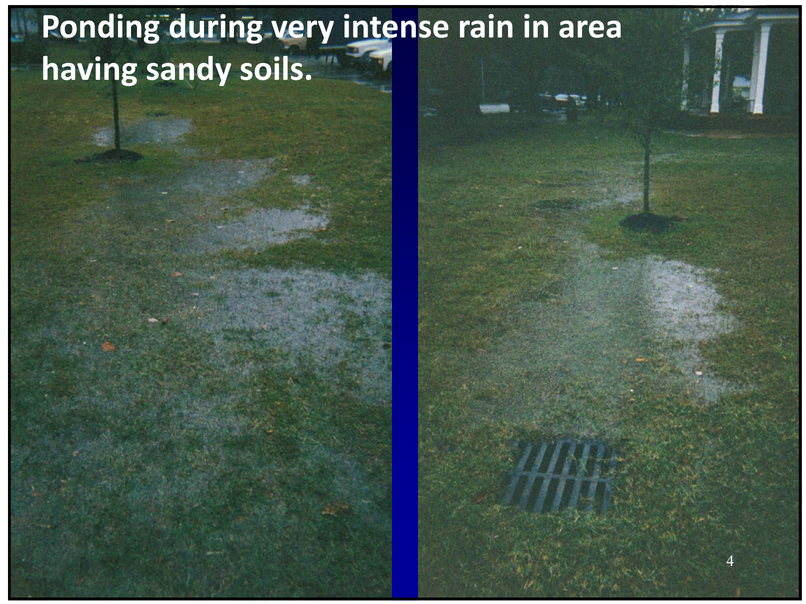
2

Applications of These Data

- Further tests were conducted under more controlled laboratory conditions and represent a wider range of soil textures and specific soil density values.
- The high head conditions during these tests make these results suitable for bioretention/infiltration devices that have 1 to 2 ft of head, but are likely too high for normal infiltration rates through urban soils.

3

3



4

Disturbed Urban Soils during Land Development

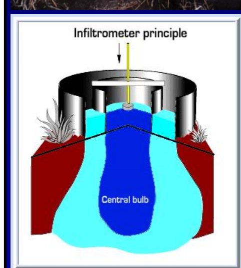
5

5

Road shoulder soil compaction due to parked cars along road.

6

6



Double-Ring Infiltrometer – ASTM D3385 (we typically have used clusters of small Turf-Tec double-ring infiltrometers to measure local variability for surface infiltration conditions)

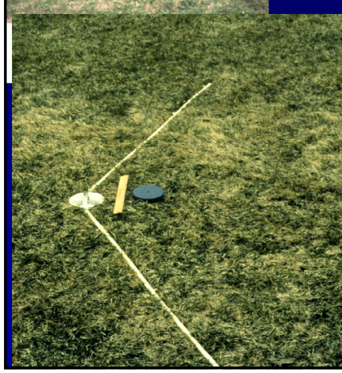
Currently we rely more on larger trench and borehole tests that have less edge effects and better correspond to conditions that occur during actual rains, especially for "deep" stormwater controls.

7

7

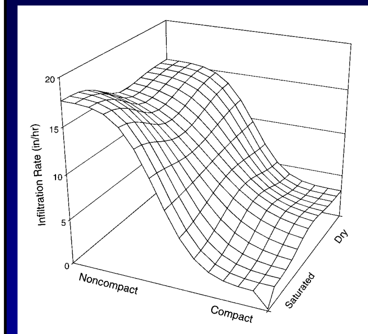
Direct measurements of turf runoff for different soil conditions during rains.

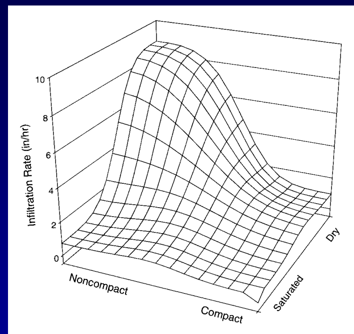
Lawn Sheet Flow Sampler: Tipping bucket for flow measurements and water collection



8

Infiltration Rates in Disturbed Urban Soils (AL tests)





Sandy Soils **Clayey Soils**

Infiltration rates of urban soils are more strongly influenced by compaction than by moisture for sandy soils and by both compaction and moisture in clayey soils.

9

9

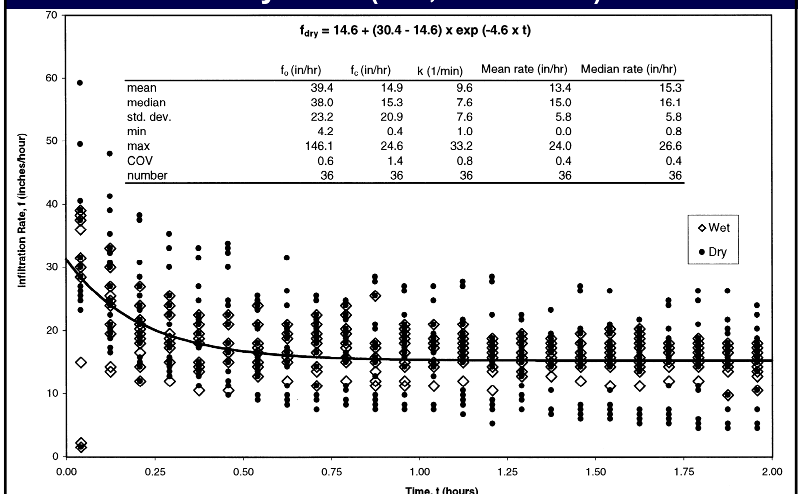
Infiltration Rates during Initial Tests of Disturbed Urban Soils

	Number of tests	Average infiltration rate (in/hr)	COV
Noncompacted sandy soils	36	13	0.4
Compacted 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

10

10

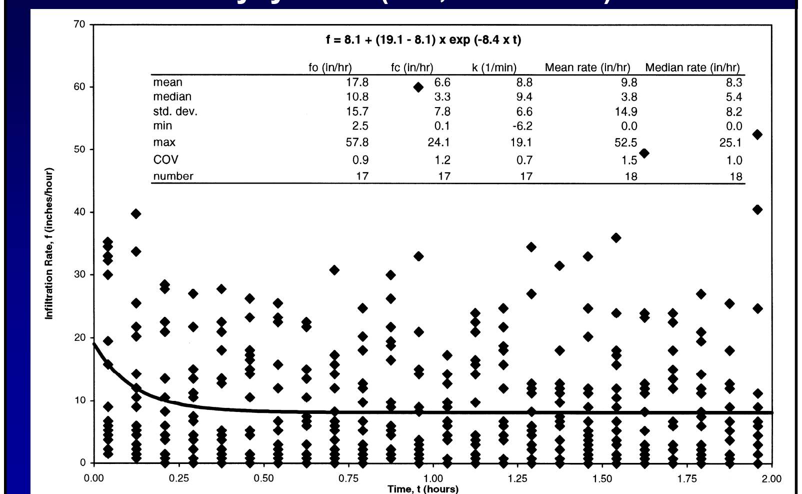
Infiltration Measurements for Noncompacted, Sandy Soils (Pitt, *et al.* 1999)



	f_o (in/hr)	f_c (in/hr)	k (1/min)	Mean rate (in/hr)	Median rate (in/hr)
mean	39.4	14.9	9.6	13.4	15.3
median	38.0	15.3	7.6	15.0	16.1
std. dev.	23.2	20.9	7.6	5.8	5.8
min	4.2	0.4	1.0	0.0	0.8
max	146.1	24.6	33.2	24.0	26.6
COV	0.6	1.4	0.8	0.4	0.4
number	36	36	36	36	36

11

Infiltration Measurements for Dry-Noncompacted, Clayey Soils (Pitt, *et al.* 1999)



	fo (in/hr)	fc (in/hr)	k (1/min)	Mean rate (in/hr)	Median rate (in/hr)
mean	17.8	6.6	8.8	9.8	8.3
median	10.8	3.3	9.4	3.8	5.4
std. dev.	15.7	7.8	6.6	14.9	8.2
min	2.5	0.1	-6.2	0.0	0.0
max	57.8	24.1	19.1	52.5	25.1
COV	0.9	1.2	0.7	1.5	1.0
number	17	17	17	18	18

12

Method

- Controlled laboratory tests were also run for up to 20 days, although most were completed (when steady low rates were observed) within 3 or 4 days.
- Initial soil moisture levels were about 8% (sand was about 3%), while the saturation moisture levels after the tests ranged from about 20 to 45%.
- Three methods were used to compact the test specimens: hand compaction, plus two Proctor test methods.
- Both Modified and Standard Proctor Compactions follow ASTM standard (D 1140-54).

13

13

Method (cont.)

- Hand compaction (gentle hand pressing to force the soil into the mold with as little compaction as possible),
- Standard Proctor Compaction (24.4 kN hammer dropped 25 times form 300 mm on each of 3 soil layers).
- Modified Proctor Compaction (44.5 kN hammer dropped 25 times from 460 mm on each of 5 soil layers).

14

14

Method (cont.)

- A total of 7 soil texture types were tested representing all main areas of the standard soil texture triangle.
- Three levels of compaction were tested for each soil.
- Only 15 of the 21 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 infiltration, even after several days duration.

15

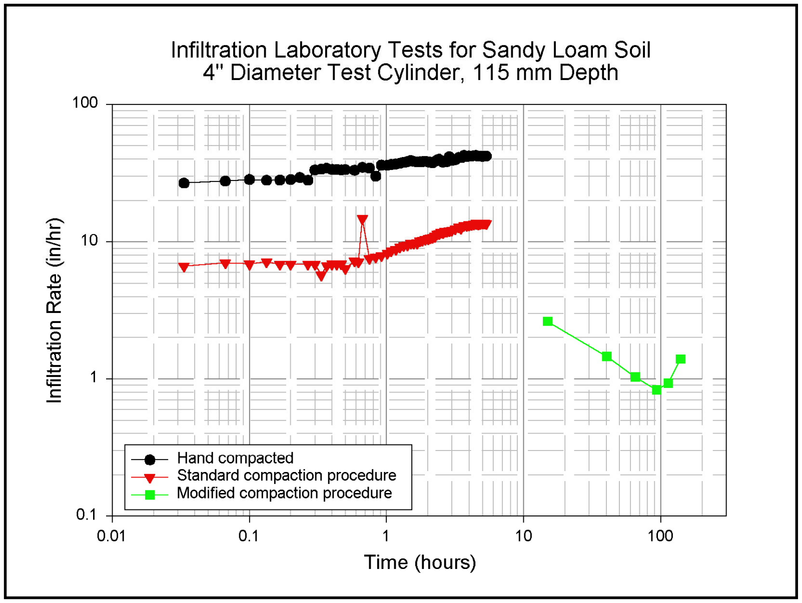
15

Test Mixtures for Laboratory Tests

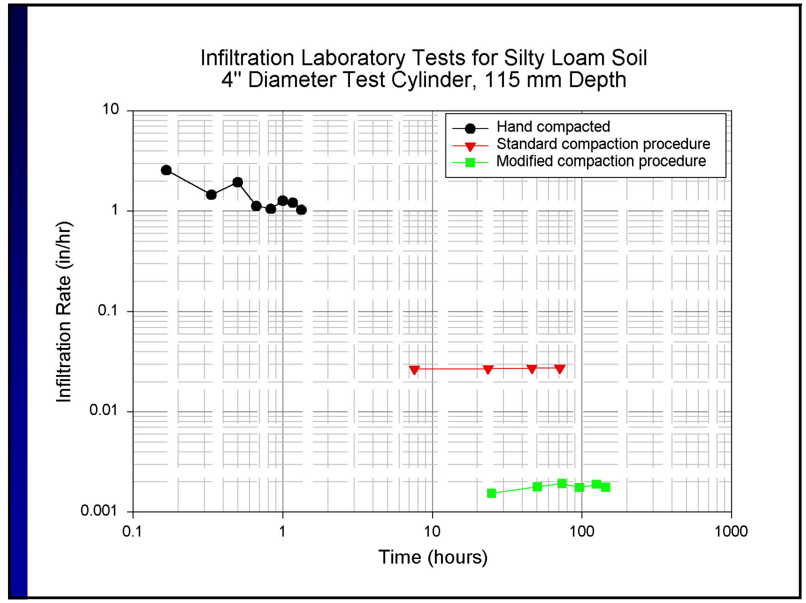
	Sand	Clay	Silt	Sandy loam	Clayey loam	Silty loam	Clay mix
% sand	100			72.1	30.1	19.4	30
% clay		100		9.2	30.0	9.7	50
% silt			100	18.7	39.9	70.9	20

16

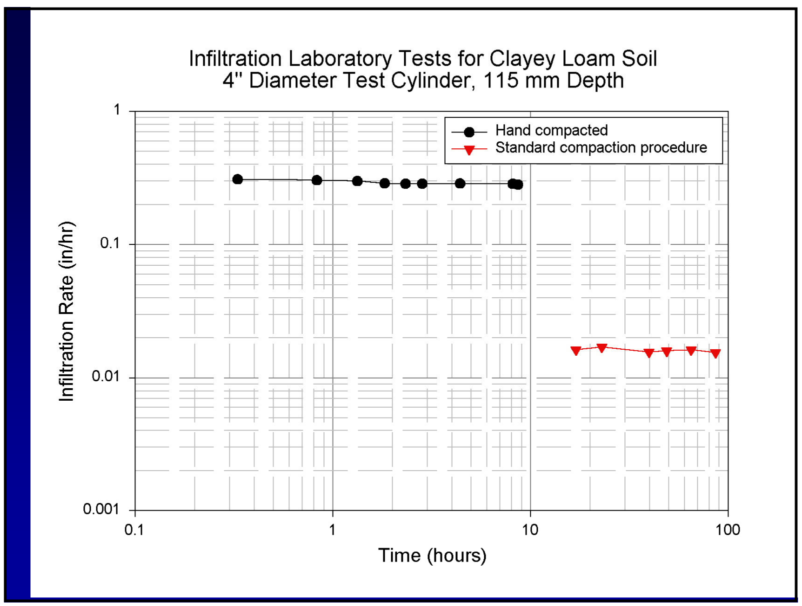
16



17



18



19

Long-Term Sustainable Average Infiltration Rates

Soil Texture	Compaction Method	Dry Bulk Density (g/cc)	Effects on Root Growth (per NRCS)	Long-term Average Infilt. Rate (in/hr)
Sand	Hand	1.451	Ideal	Very high
	Standard	1.494	Ideal	0.5 ?
	Modified	1.620	May affect -	3.2
Silt	Hand	1.508	May affect	0.7
	Standard	1.680	May affect +	0.034
	Modified	1.740	Restrict	0.0030
Clay	Hand	1.241	May affect	0.12
	Standard	n/a	n/a	0
	Modified	n/a	n/a	0

20

20

Natural forces and management attempts to increase infiltration in compacted soils. Nature much better at this than we are.

21

21

Laboratory and Field Verification Tests

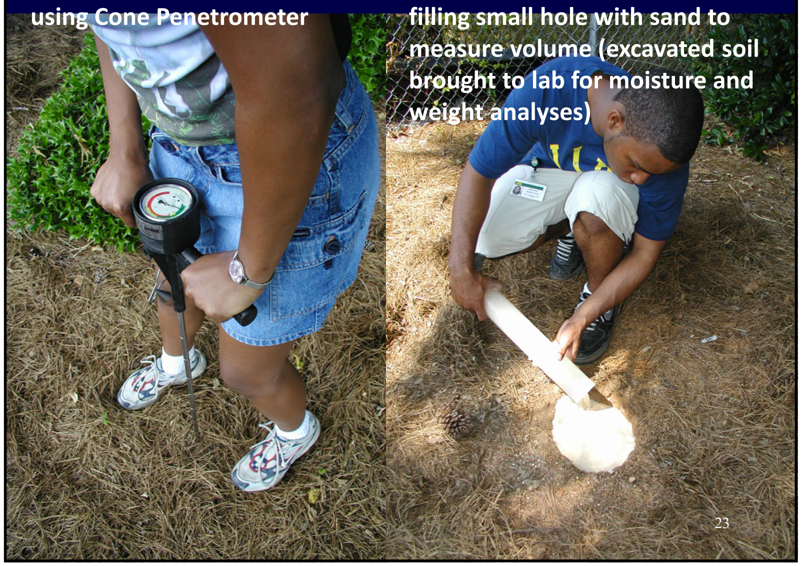
- Conducted high resolution, low-head laboratory tests with soils, each at three compactions.
- Conducted field measurements of soil density and infiltration rates.
- These field soils are then brought to the laboratory for moisture and texture analyses, plus laboratory infiltration will be conducted on these soils at the different compaction conditions.

22

22

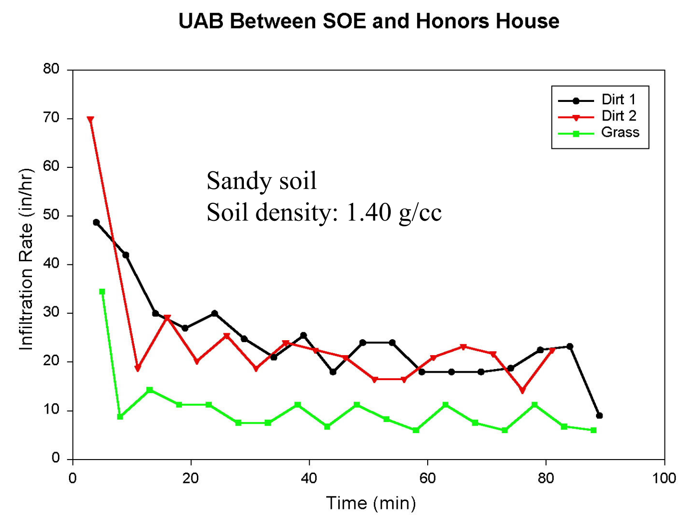
Compaction Measurements using Cone Penetrometer

Soil Density Measurements filling small hole with sand to measure volume (excavated soil brought to lab for moisture and weight analyses)

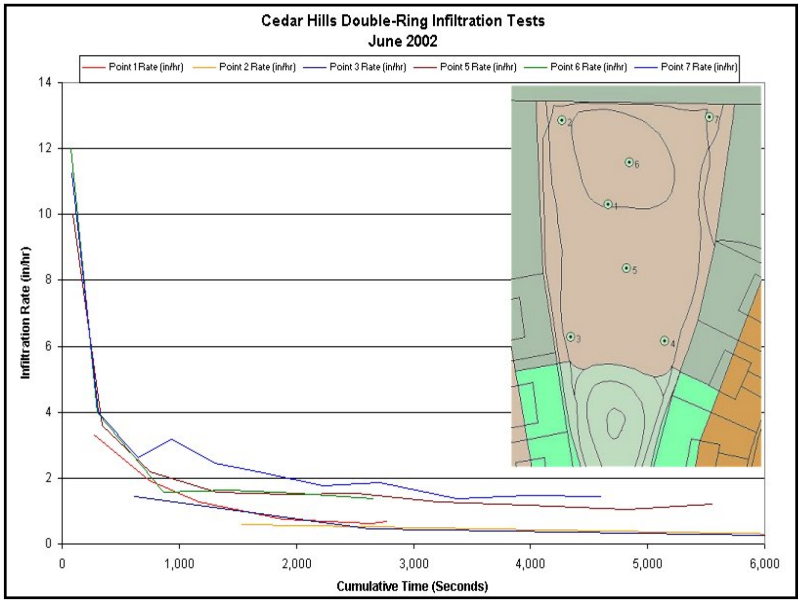


23

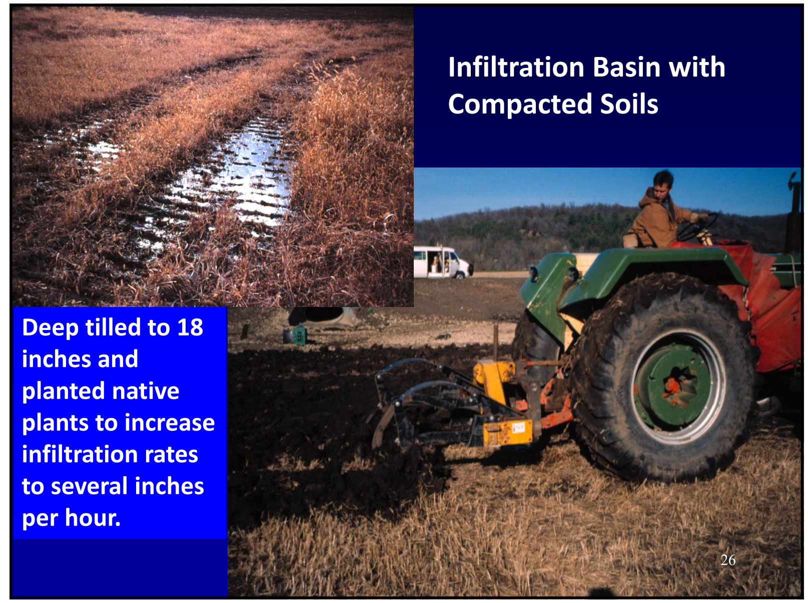
23



24


Cedar Hills Double-Ring Infiltration Tests
June 2002
Point 1 Rate (in/hr)
Point 2 Rate (in/hr)
Point 3 Rate (in/hr)
Point 5 Rate (in/hr)
Point 6 Rate (in/hr)
Point 7 Rate (in/hr)
Infiltration Rate (in/hr)
Cumulative Time (Seconds)
0
2
4
6
8
10
12
14
0
1,000
2,000
3,000
4,000
5,000
6,000

25


Infiltration Basin with Compacted Soils
Deep tilled to 18 inches and planted native plants to increase infiltration rates to several inches per hour.
26

26


Soil modifications can result in greatly enhanced infiltration in marginal soils

27


Soil Modifications and Rain Gardens
28

28

Amended Soil Compared to Unamended Soil (ratios)

Constituent	Surface Runoff Mass Discharges	Subsurface Flow Mass Discharges
Runoff Volume	0.09	0.29
Phosphate	0.62	3.0
Ammonia	0.56	4.4
Nitrate	0.28	1.5
Copper	0.33	1.2
Zinc	0.061	0.18

Water Quality and Quantity Effects of Amending Urban Soils with Compost

- Surface runoff rates and volumes decreased by five to ten times after amending the soils with compost, compared to unamended sites.
- Unfortunately, the concentrations of many pollutants increased in surface runoff from amended soils, especially nutrients which were leached from the fresh compost.
- However, the several year old test sites had less, but still elevated concentrations, compared to unamended soil only test plots.

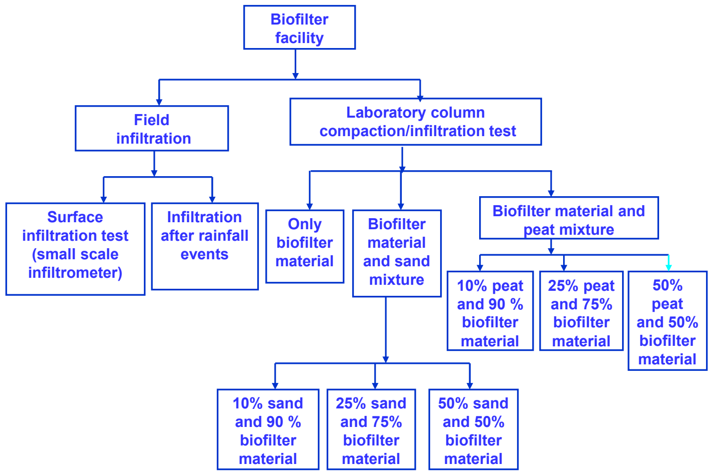
Conclusions for Compaction and Infiltration Tests

- The laboratory tests indicated that both texture and compaction were important in determining the infiltration rates, with time since the beginning of rain only important for less than half of the conditions tested.
- These tests were conducted using a standard 1.1 m head and are most appropriate for bioretention and infiltration designs where ponded water may occur.
- A series of tests were also conducted for sandy loam using 0.1 m head and the resulting infiltration rates were substantially less. Other tests examined other soils.

In-situ infiltration tests at a poorly operating existing biofilter (Sileshi 2013)

- The poorly functioning biofilter facility is located in Shelby Park, adjacent to The Univ. of Alabama rental car parking lot from which it receives flow.
- It had standing water for extended periods and poor vegetation
- The biofilter is about 100 m long and 10 m wide (0. 1 ha) and is about 11% of the paved and roofed source area (very large for a biofilter installation).

Field and Lab Infiltration Study of Existing Biofilter



33

Field Infiltration Tests at Biofilter

- Four locations using a cluster of three infiltrometers were conducted to examine variations along the biofilter length.
- The infiltrometers were gently driven into the surface of the biofilter soil until the “saturn” ring was against the soil surface.
- Relatively flat areas were selected in the biofilter to install the Turf-Tec infiltrometers.

Very little “bio” in this biofilter, indicating compacted media having adverse affects on plant growth. This biofilter also had long periods of standing water.

34

34

Field Infiltration Tests at Biofilter (Cont’d)

- After the soil was inspected and sealed around each ring to make sure that it was even and smooth, clean water was poured into the inner ring and allowed to overflow and fill up the outer ring.
- The rate of decline in the water level was measured by starting the timer immediately when the pointer reached the beginning of the depth scale.
- The tests were conducted for a period of 1-2.5 hr, until the infiltration rate become relatively constant.

A Close Up of Turf-Tec Infiltrometer (Turf-Tec International)

35

35

Infiltration after Rainfall Events

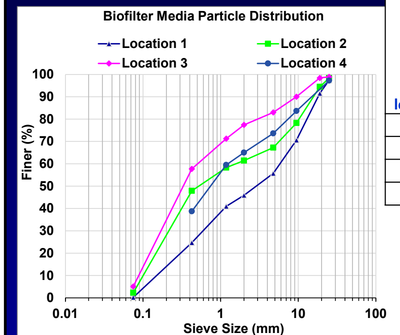
- Extended periods of surface ponding of water on the biofilter was often observed following heavy rainfall events.
- Infiltration rate measurements were manually recorded from biofilter ponded areas after five rainfall events.
- Depth indicator rules were placed at 3 to 5 different locations along the biofilter at surface ponding areas.
- The decrease in the depth of water was measured every 30 min at the beginning of the observations and less frequently as the test progressed, until the water completely infiltrated (or evaporated).

The Vegetation Cover Is Very Poor Indicating Likely Serious Compaction).

36

36

Soil Media Characteristics



Test locations	median size D_{50} (mm)	uniformity coefficient (C_u)	dry density (g/cm³)	moisture content (%)
1	3.0	38	2.18	9.2
2	0.5	17	2.32	5.6
3	0.3	5.6	1.80	8.0
4	0.7	12.5	2.05	8.2

Density and uniformity coefficients are high, indicating poor infiltration potential.

37

37

Laboratory Column Infiltration Tests of Biofilter Media

- The effects of different compaction levels on the infiltration rates through the biofilter media in controlled laboratory column tests, along with benefits associated with adding sand, to the media mixture were examined.
- Four-inch (100 mm) diameter PVC pipes (Charlotte Pipe TrueFit 4 in. PVC Schedule 40 Foam-Core Pipe) 3 ft (0.9 m) long, were used for these test.

38

38

Lab Column Tests (Cont'd)

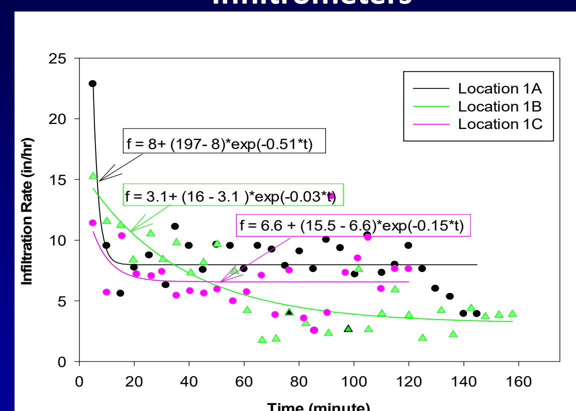
- To separate the gravel layer from the media layer, a permeable fiberglass screen was placed over the gravel layer.
- The columns were then filled with the biofilter media imported from the biofilter, with varying amounts of added filter sand mixed with the media. The media layer was about 1.5 ft thick.
- The infiltration rates were measured in each column using clean tap water.
- The surface ponding depths in the columns ranged between 11 in. and 14 in.

Data series	Compaction	percent (%) sand	percent (%) media
1	hand	0	100
2	standard proctor	0	100
3	modified proctor	0	100
4	hand	10	90
5	standard proctor	10	90
6	modified proctor	10	90
7	hand	25	75
8	standard proctor	25	75
9	modified proctor	25	75
10	hand	50	50
11	standard proctor	50	50
12	modified proctor	50	50

39

39

In Situ Biofilter Media Infiltration Using Turf-Tec Infiltrometers

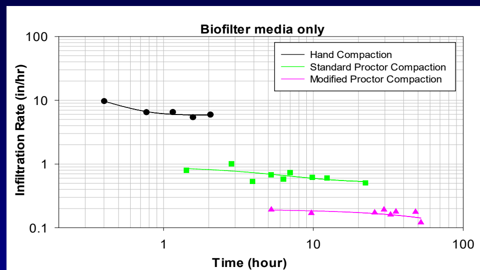


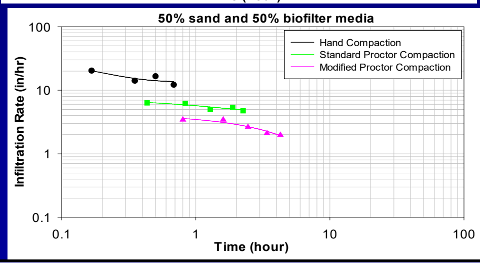
These rates are much greater than indicated based on the standing water observations and therefore likely do not represent the full-depth conditions in the biofilter.

40

40

Biofilter Media Infiltration Characteristics using Lab Columns

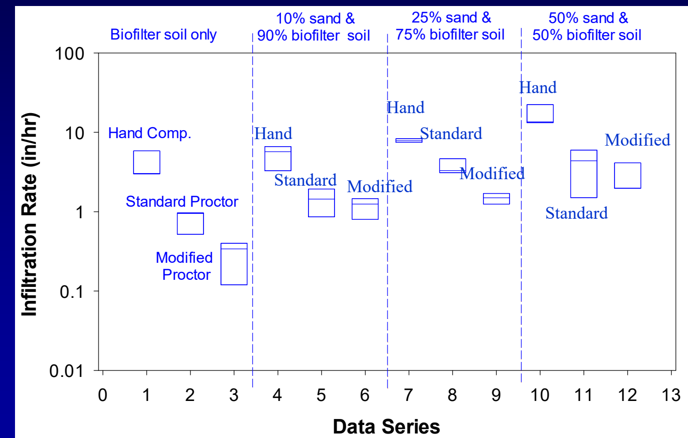




41

41

Summary of Lab Biofilter Media Infiltration Rates Comparing Different Compaction Conditions with Varying Amounts of Sand Amendments



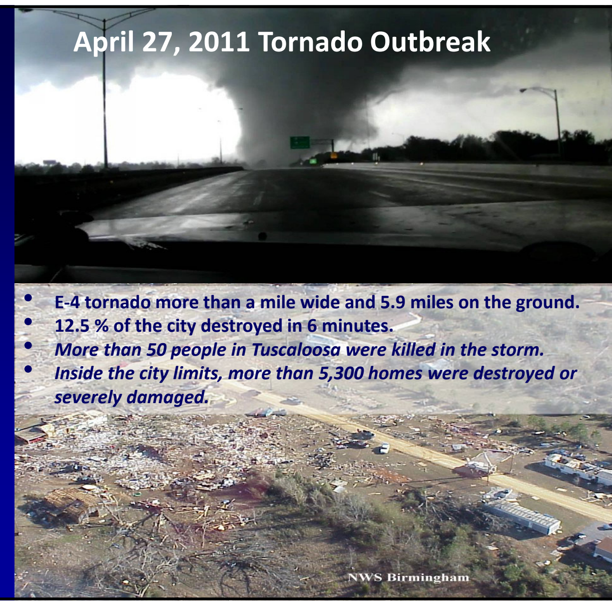
42

Soil Media Characteristics of Stormwater Construction Sites

- Additional research by Sileshi (2005) included both laboratory and field-scale studies that was conducted to provide insight into the existing soil characteristics at stormwater bioinfiltration study sites.
- Surface and subsurface soil characteristic studies were conducted to assist in the design of new stormwater management practices in the city of Tuscaloosa, AL.
- The test sites are located in four areas which were severely affected by the April 27, 2011 tornado that devastated the city of Tuscaloosa.

43

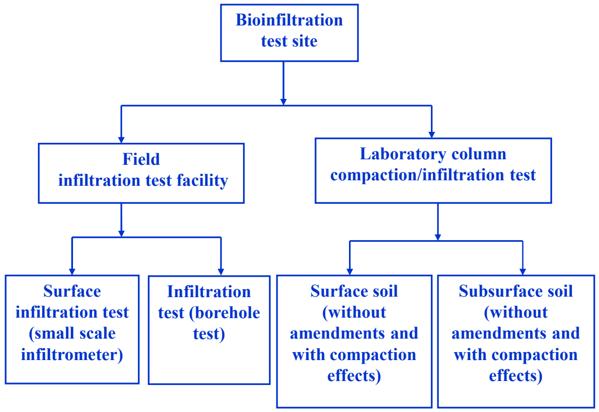
43



44

44

Field and Lab Infiltration Study of Stormwater Bioinfiltration Site Studies



45

Introduction

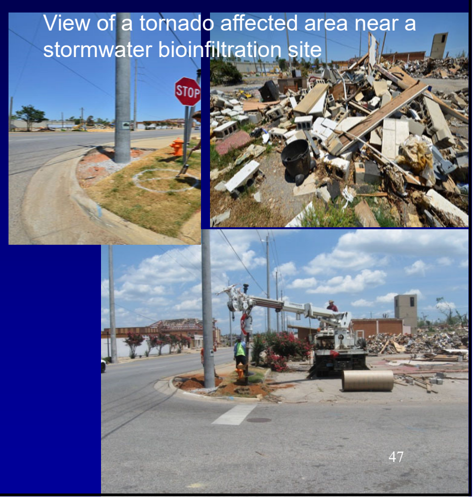
- Small scale, rapid, tests are needed to quickly inventory soil conditions in areas undergoing planning following natural disasters, or to meet short schedules associated with accelerated construction goals.
- The performance of bioinfiltration facilities and other infiltration devices can be affected by factors such as texture, structure and degree of compaction of the media used during construction and the underlying soils.
- Large borehole infiltration tests were conducted in the Tuscaloosa area to compare with small surface infiltration measurements.

46

46

Soil media characteristics of stormwater bioinfiltration construction sites

Laboratory and field-scale studies were conducted to provide information of the existing soil in areas which were severely affected by the April 27, 2011 tornado that devastated the city of Tuscaloosa, AL.



View of a tornado affected area near a stormwater bioinfiltration site

47

47

We worked with the City of Tuscaloosa to develop soils data that can be used for stormwater management designs that meet the city and state regulations for commercial sites that require re-building. Emphasizing runoff volume reductions; most destroyed commercial areas were not in compliance with current City regulations and they were not allowed to duplicate what was there before the tornadoes.

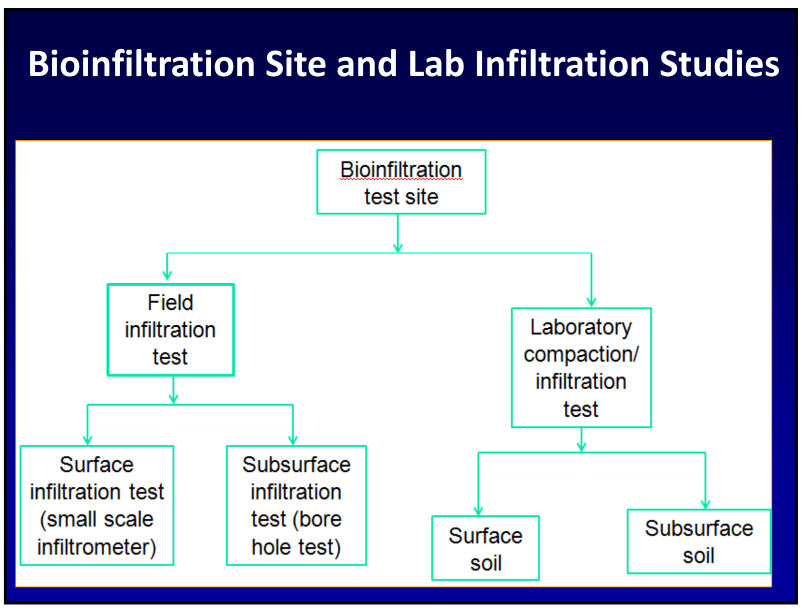
48


View of a tornado affected area near a proposed stormwater bioinfiltration site
A clean slate at the Krispy Crème location… total destruction of building, was totally impervious and will now have to meet current stormwater regulations with volume reductions. Surrounding destroyed neighborhoods also is being rebuilt to meet current regulations.
49

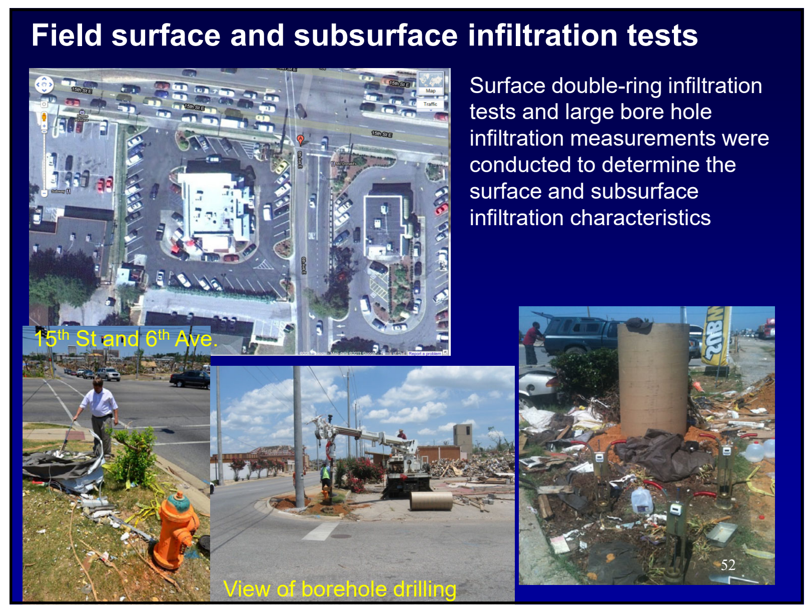
49


By 2016, much re-building had occurred. According to Office of the Tuscaloosa city engineer the City has permitted over 200 LID sites since April 27th, 2011. The City of Tuscaloosa has been recognized as a leader in the state for LID implementation. The City of Tuscaloosa will require and promote the use of Low Impact Development/Green Infrastructure techniques for both new development and redevelopment.
(Ben Flanagan AL.com)
50

50


Bioinfiltration Site and Lab Infiltration Studies
Bioinfiltration test site
Field infiltration test
Laboratory compaction/ infiltration test
Surface infiltration test (small scale infiltrometer)
Subsurface infiltration test (bore hole test)
Surface soil
Subsurface soil

51


Field surface and subsurface infiltration tests
Surface double-ring infiltration tests and large bore hole infiltration measurements were conducted to determine the surface and subsurface infiltration characteristics
15th St and 6th Ave.
View of borehole drilling
52

52

Borehole installation

University Blvd. and 17th Ave.

borehole installation at test site

53

53

Field surface and subsurface infiltration tests

21st Ave. and University Blvd.

54

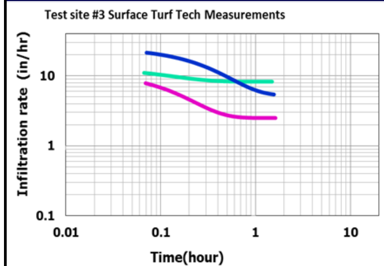
Double ring infiltration measurement installations at test site

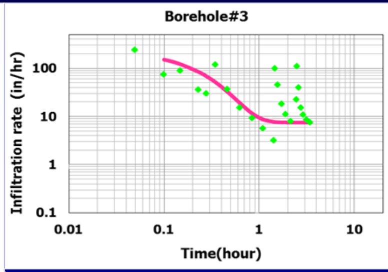
25th Ave. and University Blvd.

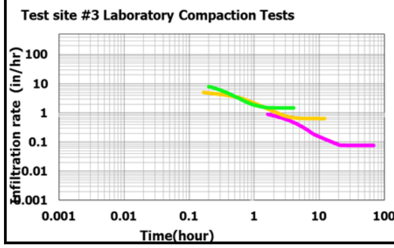
55

55

Comparison of surface turf tech, borehole, and lab infiltration data fitted to Horton's equation.







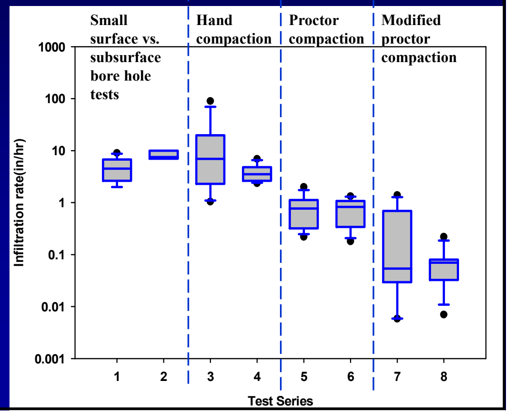
Test methods resulted in varying results; in this case, the soil at the bottom of the borehole was little compacted and had much higher infiltration rates than the surface soil.

56

Summary of surface, subsurface, and lab infiltration data for the bioinfiltration sites

Box and whisker plots comparing saturated soil infiltration rates (in/hr). Test series descriptions (12 replicates in each test series except for the borehole tests which only included 3 observations):

1. Tur-Tec small double ring infiltrometer
2. Pilot-scale borehole infiltration tests
3. Surface soil composite sample with hand compaction
4. Subsurface soil composite sample with hand compaction
5. Surface soil composite sample with standard proctor compaction
6. Subsurface soil composite sample with standard proctor compaction
7. Surface soil composite sample with modified proctor compaction
8. Subsurface soil composite sample with modified proctor compaction



57

Summary of *in-situ* soil density measurements at the bioinfiltration sites

	Horton infiltration equation parameters				
Location	f_o (in/hr) mean	f_c (in/hr) mean	k (1/min) mean	Dry density (g/cc)	Texture class
Test site #1	10	4	0.15	1.88	Clay Loam
Test site #2	7.2	4	0.12	1.66	Loam
Test site #3	16.5	5.3	0.1	1.61	Sandy Clay Loam
Test site #4	24	7	0.06	1.66	Sandy Clay Loam

General relationship of soil bulk density to root growth on soil texture (USDA Natural Resources Conservation Service)

Soil Texture	Ideal bulk densities for plant growth (g/cm^3)	Bulk densities that restrict root growth (g/cm^3)
Sandy	<1.60	>1.80
Silty	<1.40	>1.65
Clayey	<1.10	>1.47

58

58

Laboratory column tests

- Controlled laboratory column tests were conducted to examine the effects of different compaction levels (hand compaction, standard proctor compaction, and modified proctor compaction) on the infiltration rates through the soil media obtained from the surface and subsurface of bioinfiltration test sites, along with benefits associated with mixing sand with the media mixture.
- Four-inch (100 mm) diameter PVC pipes 3 ft (0.9 m) long, were used for these tests

59

59

Lab column tests for predicting changes in flow with changes in various biofilter mixtures

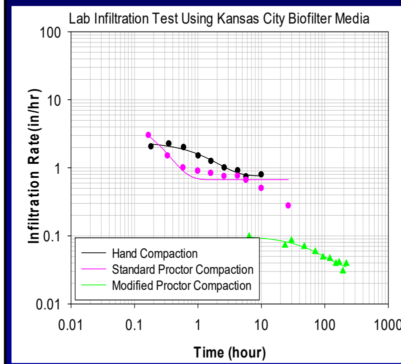
- A series of controlled lab column tests conducted using various mixtures of sand and peat to predict changes in flow with changes in the mixture, focusing on media density associated with compaction, particle size distribution (and uniformity), and amount of organic material.
- The results of the predicted performance of these mixtures were also verified using column tests (for different compaction conditions) of surface and subsurface soil samples obtained from Tuscaloosa, AL, infiltration test areas, along with bioretention media obtained from actual Kansas City biofilters, Wisconsin biofilters, and samples of North Carolina biofilter media.

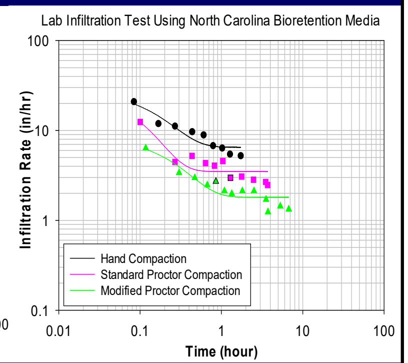
60

60

Lab Infiltration Data Fitted to Horton's Equation

- Infiltration data for different test trials were fitted to Horton's equation to estimate f_c (final infiltration) based on the observed data





61

Rain Gardens for Roof and Paved Area Runoff

- Simple rain gardens with extensive excavations or underdrains can be used near buildings for the control of roof runoff, or can be placed in or around the edges of parking areas for the control of runoff from parking areas.
- Rain gardens provide greater groundwater contamination protection compared to porous pavements as the engineered soil fill material should contain significant organic material that hinders migration of many stormwater pollutants. This material also provides much better control of fine sediment found in the stormwater.
- Rain gardens can be sized to control large fractions of the runoff, but maintenance to prevent clogging and to remove contaminated soils is also necessary.

62

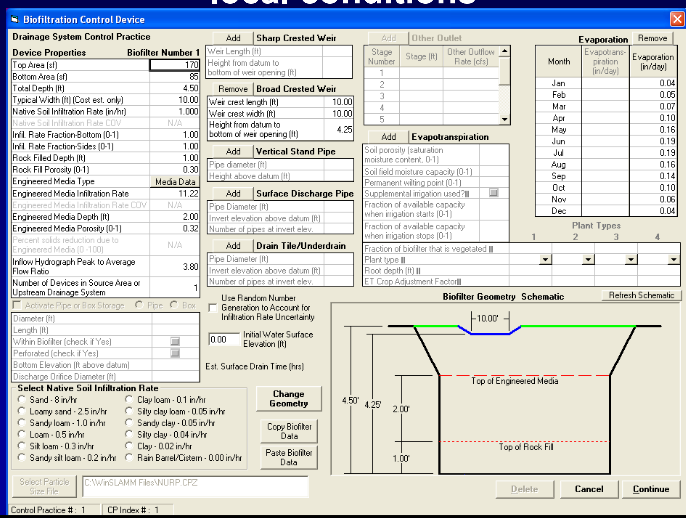
62

Different types of rain gardens for a residential roof, a commercial parking lot, and a curb-cut biofilter.

63

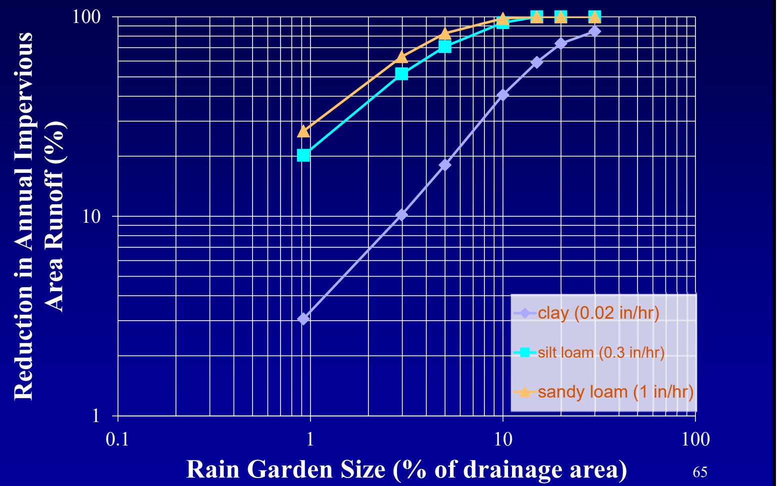
63

WinSLAMM used to model rain gardens for local conditions



64

Annual Runoff Reductions from Paved Areas or Roofs for Different Sized Rain Gardens



65

Conclusions on Infiltration Measurements

- Small-scale infiltrometers work well if surface characteristics are of the greatest interest. Large-scale (deep) infiltration tests would be appropriate when subsurface conditions are of importance (as in bioinfiltration systems and deep rain gardens).
- Soil compaction has dramatic effects on the infiltration rates; therefore care needs to be taken during stormwater treatment facilities construction to reduce detrimental compaction effects.
- The results of the four factor factorial analysis indicated that media texture and the interaction of the texture and uniformity of the media mixtures have the highest effect on the measured infiltration rate when the compaction is controlled.
- It is important that stormwater practice designers determine the subsoil characteristics before designing stormwater treatment facilities and consider the use of added amendments (sand and peat) to the soils.

66

66

Modeling Groundwater Recharge at Stormwater Drywell Installations in Millburn Township, New Jersey (from Pitt and Talebi 2012 EPA report)

67

Millburn, NJ

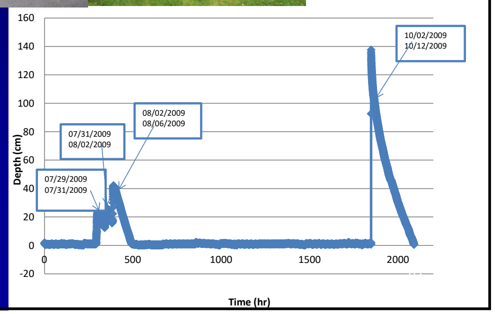
Dry well disposal of stormwater for groundwater recharge in conjunction with irrigation beneficial use

- For the past several years, the city of Millburn has required dry wells to infiltrate increased flows from newly developed areas.
- There are some underground water storage tanks now being installed to use stormwater for irrigation.
- Project supported by the U.S. EPA investigated the performance of this shallow groundwater recharge, including groundwater contamination potential, in conjunction with irrigation beneficial uses of the stormwater.

68

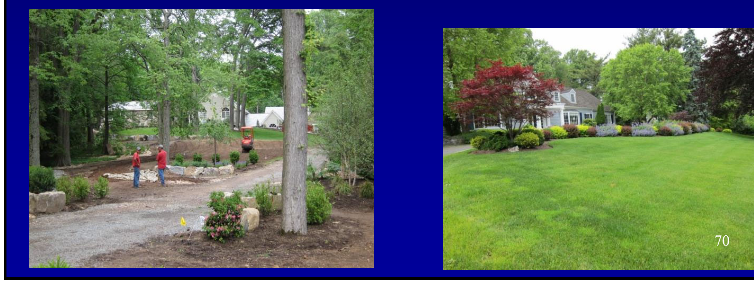
68

Nine dry wells were monitored in Millburn, NJ, as part of EPA project for long-term hydraulic performance, and six were monitored to examine surface and subsurface water quality conditions.



69

This major home restoration project included the installation of underground water storage tanks instead of dry wells. Homes in this neighborhood have summer water bills approaching $1k/month for landscape irrigation, so the economic benefits of irrigation using stormwater are very good.



70

70

Millburn, NJ (Background)

- For the past several years, the city of Millburn has required dry wells/cisterns to infiltrate the increased flows from newly developed areas.
- There are some water storage tanks being installed to use the increased stormwater for irrigation.
- The project was supported by the Wet Weather Flow Research Program of the US EPA and investigated whether increased beneficial uses of the runoff would be a more efficient use of the water instead of infiltrating into the shallow groundwaters.
- There are substantial data available for this community, and we supplemented these data with more detailed site information to allow a comprehensive review of beneficial stormwater uses.

71

71

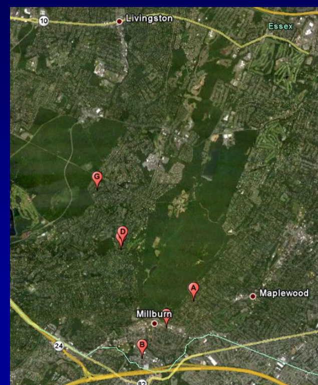
- This EPA project in Millburn included monitoring the water levels in several dry wells and concurrent rainfall conditions. This information was also used to calibrate WinSLAMM for detailed evaluations of alternative stormwater management options, including beneficial water use (irrigation and groundwater recharge).
- This information, along with the rainfall and evapotranspiration data, was used to calculate the amount of stormwater that can be beneficially used for local groundwater recharge and site irrigation and to show how landscaping irrigation needs integrates with the available rainfall.

72

72

Location of monitored dry wells

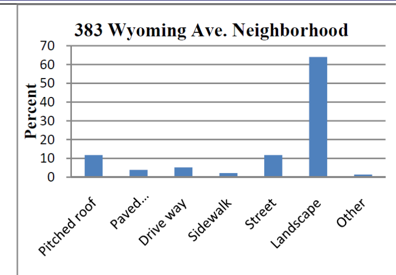
	Address
A	383 Wyoming Avenue, Millburn, NJ.
B	258 Main St., Millburn, NJ.
C	11 Fox Hill Ln, Millburn, NJ.
D	8 South Beechcroft Rd., Millburn, NJ.
E	2 Undercliff Rd. , Millburn, NJ.
F	Linda's Flower, Millburn, NJ.
G	9 Lancer, Millburn, NJ.



73

73

Land Development Characteristics (a sample site)



Most of areas covered by landscape (grass + trees)

74

74

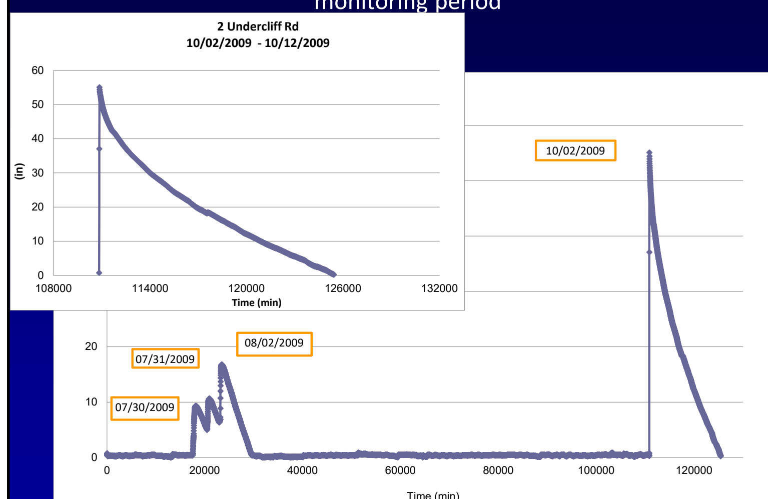
Soil Characteristics (from Online Soil Survey, USDA)

Address	Soil Name	Soil Group	Slope (%)	K_{sat}	Drainage class	Typical profile
383 Wyoming Ave.	Boonton-Urban land, Boonton substratum complex, red sandstone	C	3-8	Moderately low to moderately high (0.06 to 0.20 in/hr)	Well drained	0 to1 in: Slightly decomposed plant 1-3 in: Silt loam 3-10 in: Loam 10-27 in: Gravelly loam 27-67 in: Gravelly fine sandy loam 67-83 in: Gravelly sandy loam
258 Main St.	Dunellen sandy loam	A	3-8	High (1.98 to 5.95 in/hr)	Well drained	0-42 in: Sandy loam 42-70 in: Stratified gravelly sand to sand to loamy sand
11 Fox Hill Ln 8 South Beechcroft 2 Undercliff Rd Linda's Flower	Boonton - Urban land, Boonton substratum complex, terminal moraine	C	3-8	Moderately low to moderately high (0.06 to 0.20 in/hr)	Well drained	0-1 in: Highly decomposed plant 1-24 in: Sandy loam 24-42 in: Gravelly sandy loam 42-60 in: Fine sandy loam
9 Lancer	Boonton - Urban land, Boonton substratum complex	C	8-15	Moderately low to moderately high (0.06 to 0.20 in/hr)	Well drained	0-5 in: Loam 5-30 in: Silt loam 30-40 in: Gravelly fine sandy loam 40-47 in: Fine sandy loam 47-72 in: Loamy sand

75

75

Example site infiltration measurements during a two month monitoring period



76

Classical Infiltration Equations

- Horton (1940)

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

f: the infiltration rate at time t (in/hr),
f_o: the initial infiltration rate (in/hr),
f_c: the final infiltration rate (in/hr),
k: first-order rate constant (hr^{-1}).

This equation assumes that the rainfall intensity is greater than the infiltration capacity at all times and that the infiltration rate decreases with time

- Green–Ampt (1911)

$$f_t = K\left(\frac{\psi \Delta\theta}{F_t} + 1\right)$$

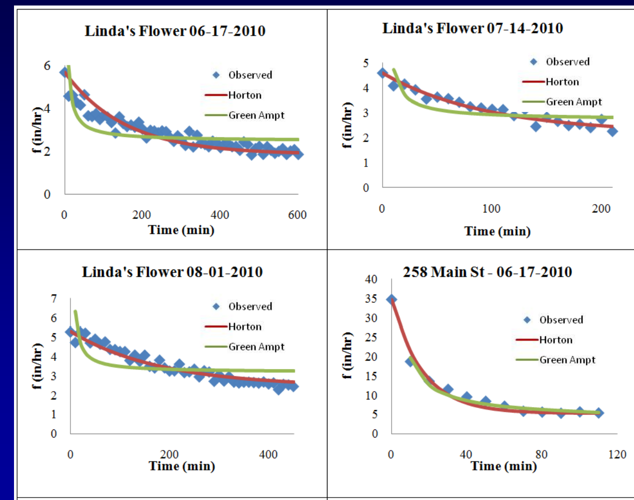
f_t : infiltration rate at time t (in/hr),
ψ : the suction head of the soil (in),
Δθ: the difference of soil water content after infiltration with initial water content (in^3/in^3),
K: hydraulic conductivity (in/hr),
F_t is the cumulative infiltration at time t (in).

This equation requires a linear relationship between f_t and ($1/F_t$)

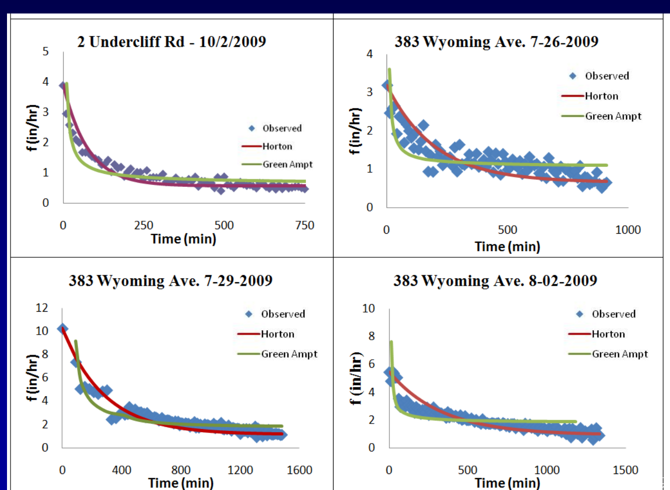
77

77

Horton equation has better agreement with observed data

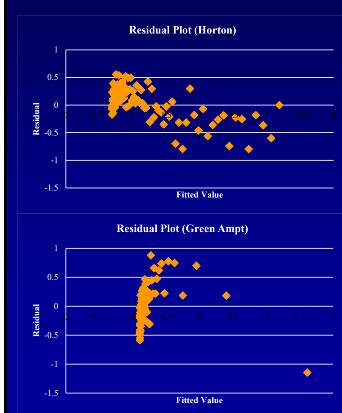


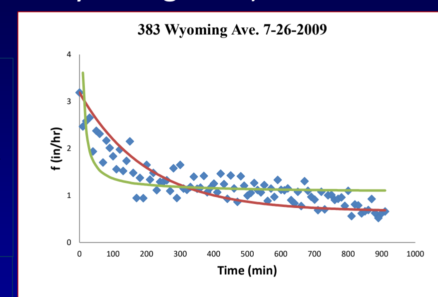
78



79

Residual Plots for Horton and Green Ampt fitted values (383 Wyoming Ave.)



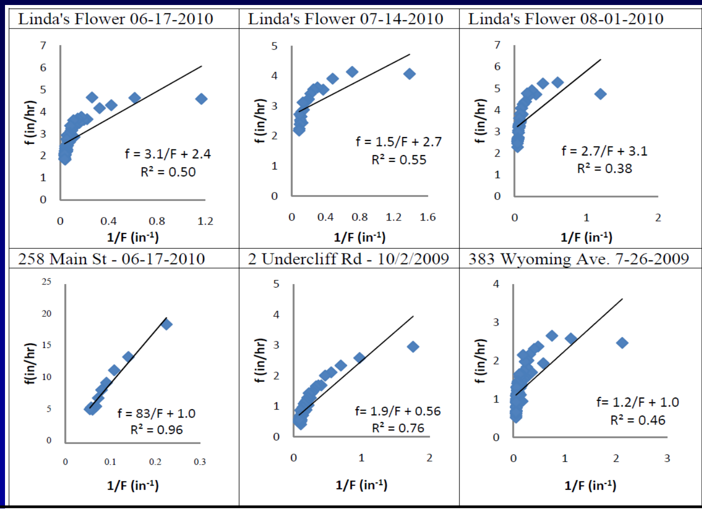


Slight residual trend with fitted value with Horton equation, but much better than for Green Ampt equation

80

80

Linear regression of f_t vs (1/F) for some sites in Millburn, NJ (as required for Green Ampt equation use).



81

Horton Equation Coefficient Summery for Millburn Dry Wells

Site Address	Soil Group	Date	Horton's parameters (Millburn observed dry well data)			Akan (1993)	Pitt et al. (1999)*		
			f_0(in/hr)	f_c(in/hr)	k (1/min)	f_0(in/hr)	f_0(in/hr)	f_c(in/hr)	k (1/min)
Linda's Flower	C	06-17-2010	5.7	1.9	0.0065	2-6	1.0-3.75	0.0-0.5	0.03-0.1
		07-14-2010	5.6	2.2	0.011				
		08-01-2010	5.3	2.5	0.0055				
258 Main St.	A	06-17-2010	35	5.3	0.06	6-10	1.5-12	0.25-1.3	0.05-0.2
		07-14-2010	75	6.8	0.07				
		08-01-2010	75	4.7	0.045				
2 Undercliff	C	10-02-2009	3.9	0.57	0.013	2-6	1.0-3.75	0.0-0.5	0.03-0.1
383 Wyoming Ave.	C	7-26-2009	3.2	0.66	0.005	2-6	1.0-3.75	0.0-0.5	0.03-0.1
		7-29-2009	10	1.1	0.0035				
		8-02-2009	5.5	0.93	0.003				
		8-22-2009	3.6	1.2	0.03				
		10-02-2009	5.6	1.2	0.0045				

* 25^{th} and 75^{th} percentile values for compact sandy surface soil conditions

82

Best Fit Green-Ampt Equation Coefficients for Millburn Dry Well Observations

Site Address	Date	Hydraulic conductivity K (in/hr)	
		Millburn (case study)	**Rawls et al. (1983)**
Linda's Flower	06-17-2010	2.435	0.429
	07-14-2010	2.685	
	08-01-2010	3.131	
258 Main St.	06-17-2010	1.018	1.17
2 Undercliff	10-02-2009	0.557	0.429
383 Wyoming Ave.	7-26-2009	1.039	0.13-0.43

- For the other sites "K" values estimated from fitted curves were *negative and therefore not reasonable*.

83

Conclusions for Infiltration Equations used for Millburn Dry Well Observations

- The fitted graphs and resulting derived coefficients of each of the two equations indicate that although the fitted Horton curve is visually and statistically better fitted to the observed data at these dry wells than Green-Ampt curve, the **calculated parameters** of both infiltration models **don't compare well to literature values for surface soil infiltration**.

- It is necessary to have **local measured data** for modeling and design and not to only rely on literature values.

84

84

Main References for Examples and Data in Presentation

- Pitt, R., J. Lantrip, R. Harrison, C. Henry, and D. Hue. *Infiltration through Disturbed Urban Soils and Compost-Amended Soil Effects on Runoff Quality and Quantity*. U.S. Environmental Protection Agency, Water Supply and Water Resources Division, National Risk Management Research Laboratory. EPA 600/R-00/016. Cincinnati, Ohio. 231 pgs. December 1999. http://rpitt.eng.ua.edu/Publications/BooksandReports/Compacted%20and%20compost%20amended%20soil%20EPA%20report.pdf.
- Pitt, R. and L. Talebi. *Evaluation and Demonstration of Stormwater Dry Wells and Cisterns in Milburn Township, New Jersey*. Urban Watershed Management Branch, U.S. Environmental Protection Agency, Edison, NJ 08837. August 2012. 302 pgs. http://unix.eng.ua.edu/~rpitt/Publications/5_Stormwater_Treatment/Bioretention_and_infiltration_stormwater_controls/dry%20wells%20millburn%20final%20July%2012%202012.pdf.
- Sileshi, Redahegn. Ph.D. *Soil Physical Characteristics Related to Failure of Stormwater Bioinfiltration Devices*. Ph.D. dissertation, Department of Civil, Construction, and Environmental Engineering, the University of Alabama. 2013. http://unix.eng.ua.edu/~rpitt/Publications/11_Theses_and_Dissertations/Redi_dissertation.pdf.

85