Small (and Intermediate) Storm Hydrology and Urban Stormwater Quality Management

Bogota getting washed… Universidad de los Andes completed stormwater planning and demonstrations using WinSLAMM

Small Storm Hydrology – Runoff Volume

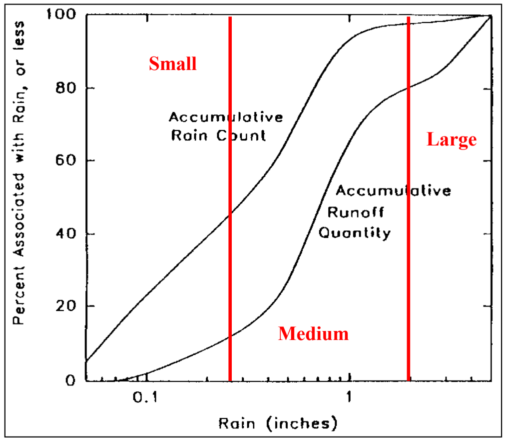
Most of the pollutants in stormwater runoff come from small and moderate size storms . . .

. . .in contrast to design storms, because the smaller storms are much more frequent and account for the majority of runoff water and pollutants

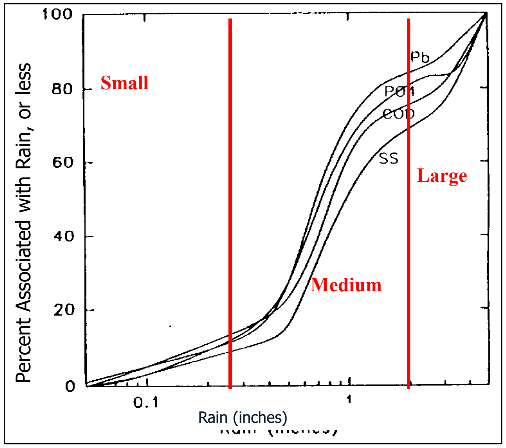
Knowing the Runoff Volume is the Key to Estimating Pollutant Mass

- There is usually a simple relationship between rain depth and runoff depth in urban systems.
- Changes in rain depth affects the relative contributions of runoff and pollutant mass discharges:
  - Directly connected impervious areas contribute most of the flows during relatively small rains
  - Disturbed urban soils may dominate during larger rains

Monitored Milwaukee Rainfall and Runoff Distributions



Monitored Milwaukee Pollutant Distribution



Rainfall Sorts into Three Distinct Categories

- Small Rains – Accounts for most events, by number
  - Typically, can be easily captured for infiltration or on-site beneficial uses.
  - Relatively low pollutant loadings per event, but frequent discharges.
  - Key rains associated with water quality concentration violations, especially for bacteria and total recoverable heavy metals.
  - “Every” time it rains, some discharge numeric concentration limits (NELs) may be exceeded. Therefore, try to eliminate the small events.

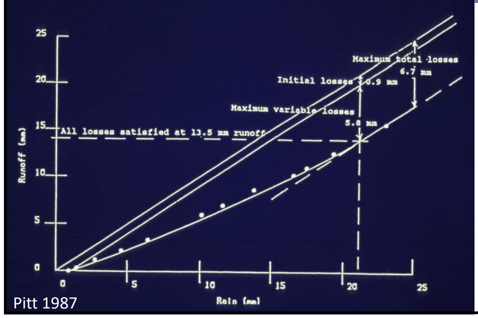
Rainfall Sorts into Three Distinct Categories (continued)

- Medium Rains – Responsible for most pollutant mass discharges
  - Smaller events in this category can be easily captured and infiltrated or re-used.
  - Larger events in this category exceeding on-site removal need to be treated.
  - Typically, responsible for about 75% of pollutant mass discharges.

Rainfall Sorts into Three Distinct Categories (continued)

- Large Rains – Infrequent Large Events
  - Not cost effective to treat all runoff, especially for large rains.
  - Typically cause flooding and significant erosion.
  - Treatment practices designed for smaller storms will mitigate impacts of larger events to some extent.

Controlled tests in small areas were used in conjunction with long-term rainfall/runoff monitoring at larger parking lot areas to develop actual hydrological relationships for paved areas, the most significant source of runoff for most urban areas during small to intermediate-sized rains.



Pitt 1987

This is an example of a rainfall-runoff plot from one of many controlled street washoff and runoff tests. About 1/3 of the rainfall is infiltrated through the street pavement for many of these events (up to 20 mm rains in this plot). No further infiltration was observed for larger events, resulting in classical pavement Rv values of 0.8 to 0.95 for large rains of interest for drainage design.

Disturbed Urban Soil Evaluations

- Needed to characterize and quantify:
  - Site soil conditions (infiltration capacity, soil texture, soil density and bulk density, cation exchange capacity, sodium adsorption capacity, etc.)
  - Groundwater conditions (depth and movement, along with potential for groundwater mounding)

Site Evaluations Needed to Better Predict Bioretention Device

- Small-scale soil testing is suitable for small rain gardens, with suitable factors of safety and care in construction.
- Large-scale testing is needed if failure would result in serious consequences (such as if an integral part of a drainage system having little redundancy, or if critical environmental protection is needed).

Basic Characteristics for Soils and Materials Used in Biofilters

Soil Texture	**Saturation Water Content (%) (Porosity)**	**Available Soil Moisture (Field Capacity to Permanent Wilting Point) inches water/inches soil**	**Infiltration Rate (in/hr) assumed to be slightly compacted**	**CEC (meq/100 gms)**	**Dry density (grams/cm^3), assumed to be slightly compacted**
Coarse Sand and Gravel	32	0.04	40	1	1.6
Sandy Loams	40	0.13	1	8	1.6
Fine Sandy Loams	42	0.16	0.5	10	1.6
Silty Clays and Clays	55	0.155	0.05	30	1.6
Peat as amendment	78	0.54	3	300	0.15
Compost as amendment	61	0.60	3	15	0.25

Double-Ring Infiltration Tests

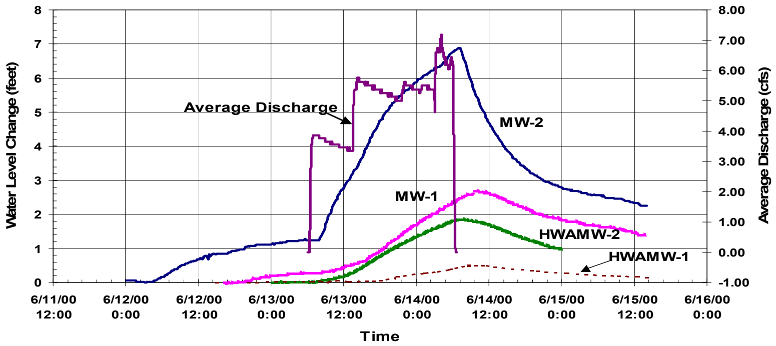
Soil Density Measurements

Large-Scale Infiltration Bench and Verification Testing in Washington

Discharge Flow Dissipater while Filling Infiltration Bench from Stormwater Pond

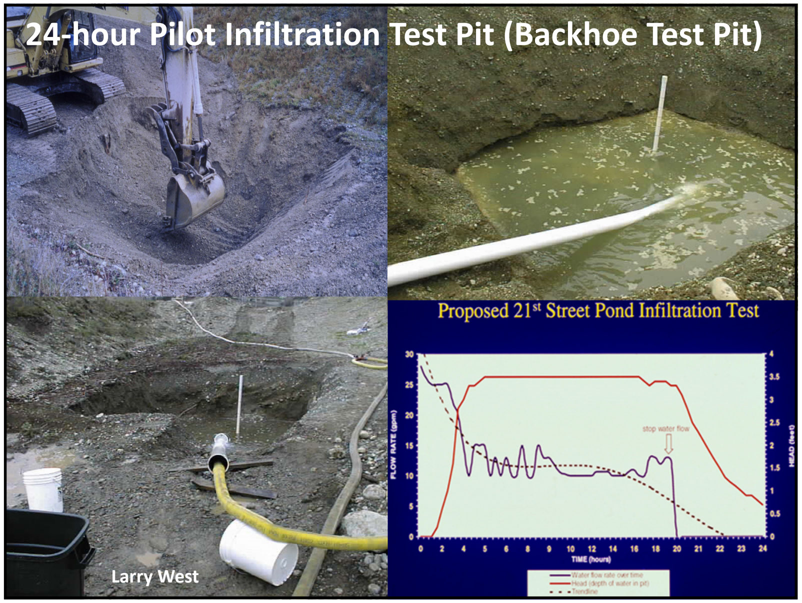
Full-scale 24-hr Infiltration Test

Ground Water Levels and Average Flow Discharge



Larry West

24-hour Pilot Infiltration Test Pit (Backhoe Test Pit)



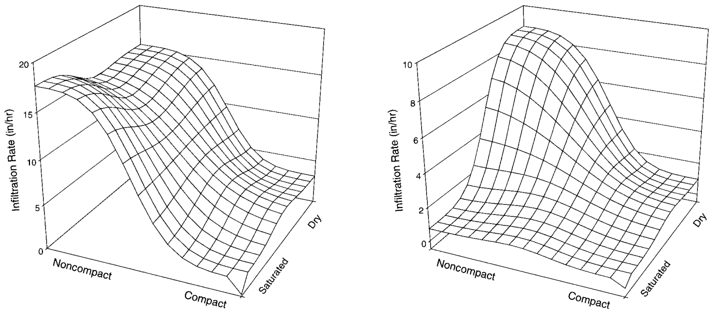
Larry West

Soil Compaction and Recovery of Infiltration Rates

- Typical site development dramatically alters soil density.
- This significantly reduces infiltration rates, especially if clays are present.
- Also hinders plant growth by reducing root penetration (New Jersey NRCS was one of the first groups that researched this problem).

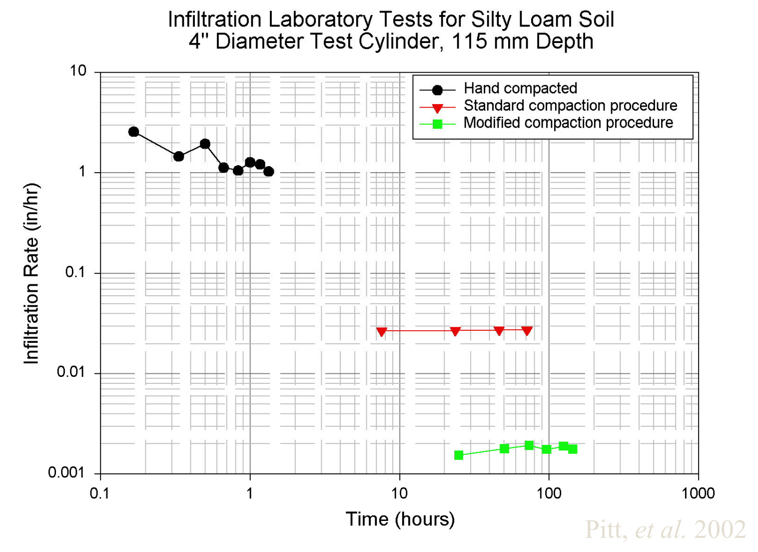
Ponding of runoff water in coarse sand at a coastal community, with overflow to conventional storm drainage system.

Infiltration Rates in Disturbed Urban Soils (AL tests)



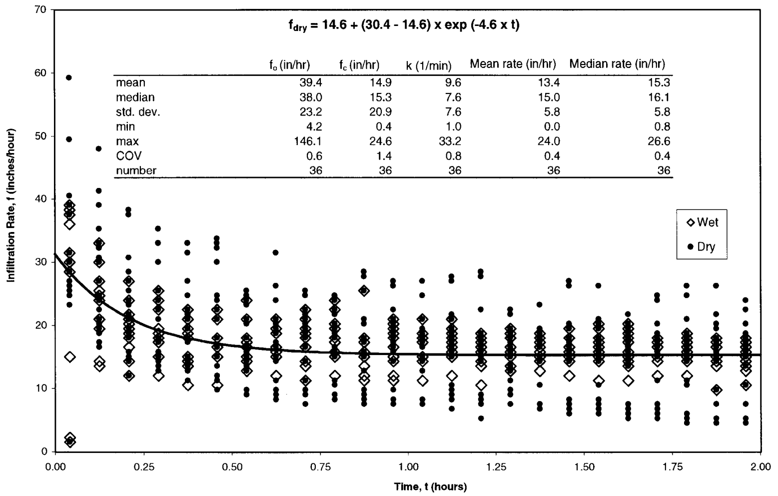
Sandy Soils **Clayey Soils**

Research has shown that the infiltration rates of urban soils are strongly influenced by compaction, probably more than by moisture saturation.



Pitt, *et al.* 2002

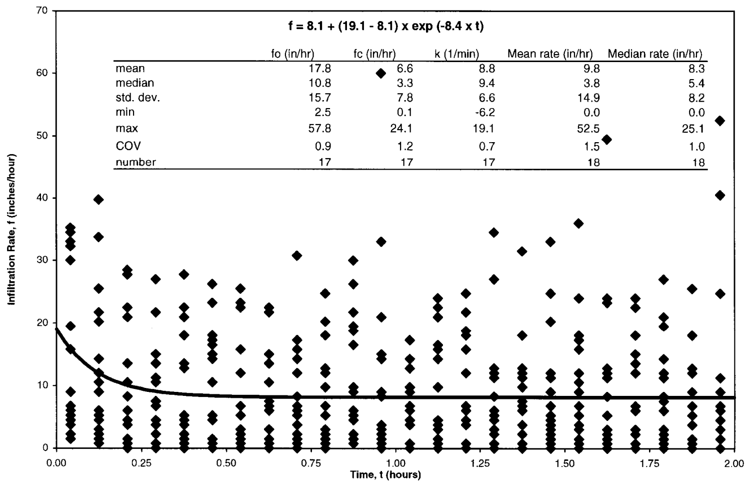
Infiltration Measurements for Noncompacted, Sandy Soils (Pitt, *et al.* 1999)



$f_{dry} = 14.6 + (30.4 - 14.6) \times \exp(-4.6 \times t)$

	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

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



$f = 8.1 + (19.1 - 8.1) \times \exp(-8.4 \times t)$

	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

Long-Term Sustainable Average Infiltration Rates

Soil Texture	Compaction Method	Dry Bulk Density (g/cc)	Long-term Average Infilt. Rate (in/hr)
Sandy Loam	Hand	1.60	35
	Standard	1.65	9
	Modified	1.99	1.5
Silt Loam	Hand	1.50	1.3
	Standard	1.59	0.027
	Modified	1.69	0.0017
Clay Loam	Hand	1.50	0.29
	Standard	1.70	0.015
	Modified	1.91	<<0.001

Compaction, especially when a small amount of clay is present, causes a large loss in infiltration capacity. No clay should be allowed in biofilter media.

Pitt, *et al.* 2002

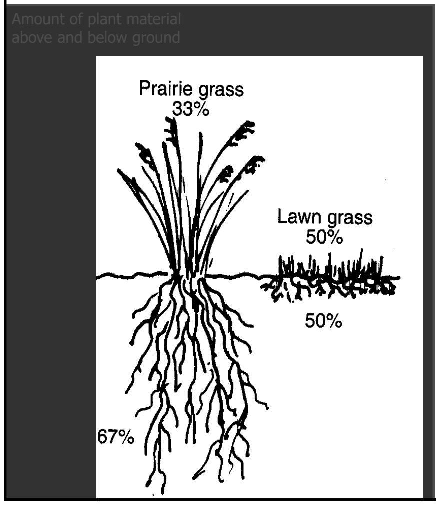
Types of Solutions to Infiltration Problems

- Use organic soil amendments to improve existing soil structure or restore soil structure after construction
- Remove soil layer with poor infiltration qualities
- Replace soil with improved soil mix
  - Mix sand, organic matter, and native soil (if no clay)
- Use deep rooted plants or tilling to improve structure (but only under correct moisture conditions)
  - Chisel plow, deep tilling, native plants
- Pre-treat water
- Select different site

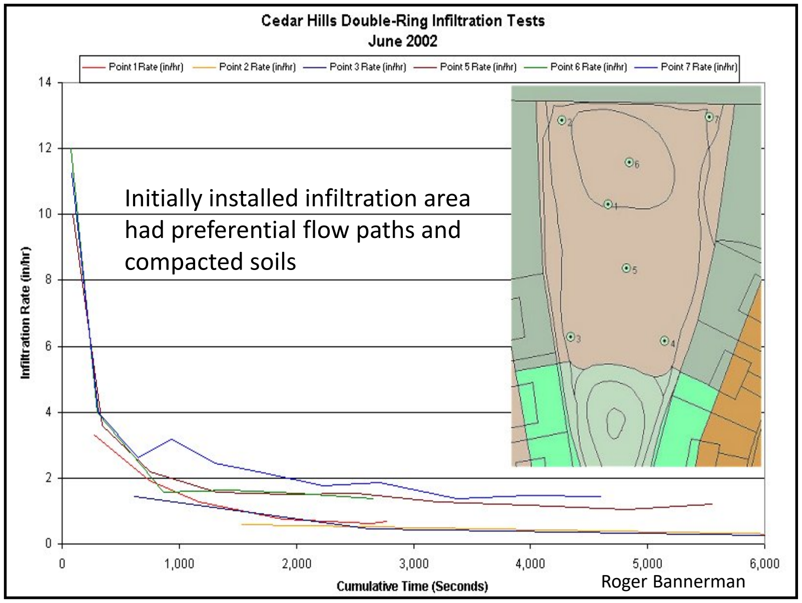
Typical household lawn aerators are ineffective in restoring infiltration capacity in compacted soils.

Natural processes work best to solve compaction, but can take decades.

Value of Using Native Plants



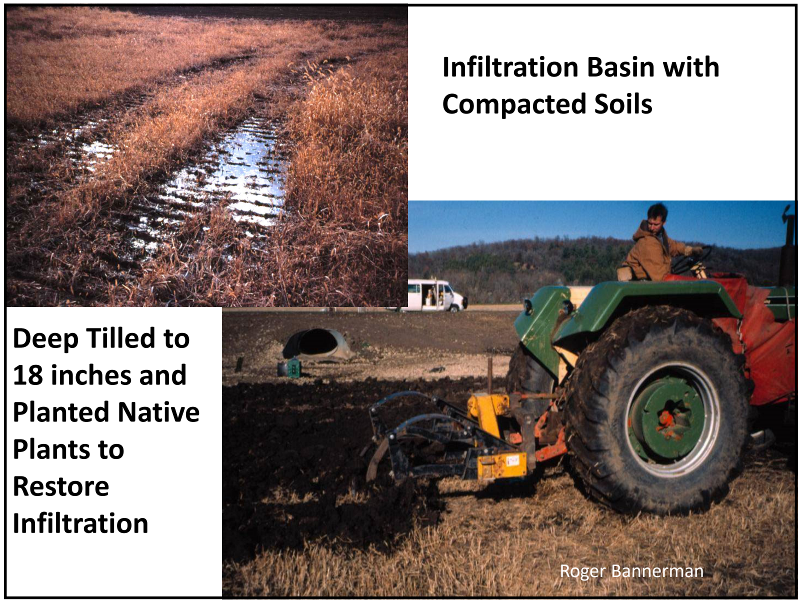
- Deeper roots – absorbs more water and help loosen compacted soil
- Uses no fertilizer
- Uses little or no pesticides
- Maintenance similar to other gardens
- Does not require watering in droughts after establishment



Cedar Hills Double-Ring Infiltration Tests
June 2002

Initially installed infiltration area had preferential flow paths and compacted soils

Roger Bannerman

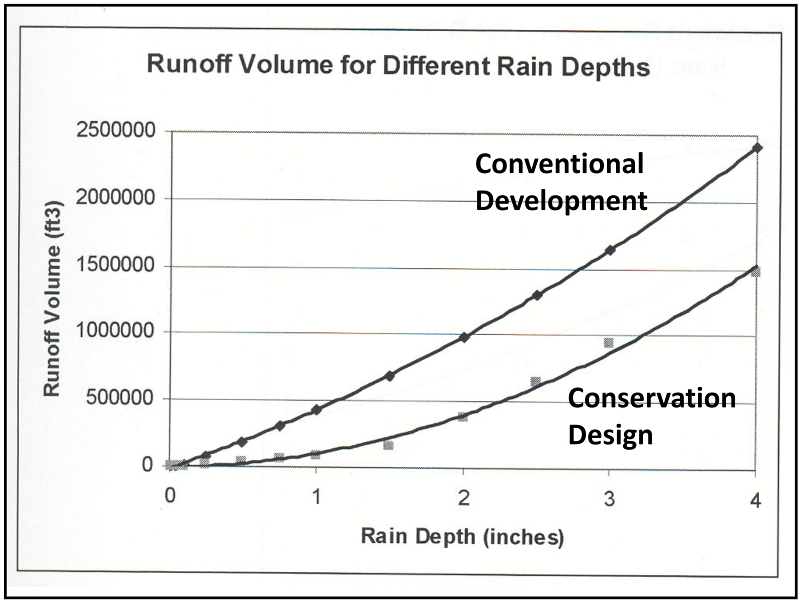


Infiltration Basin with Compacted Soils

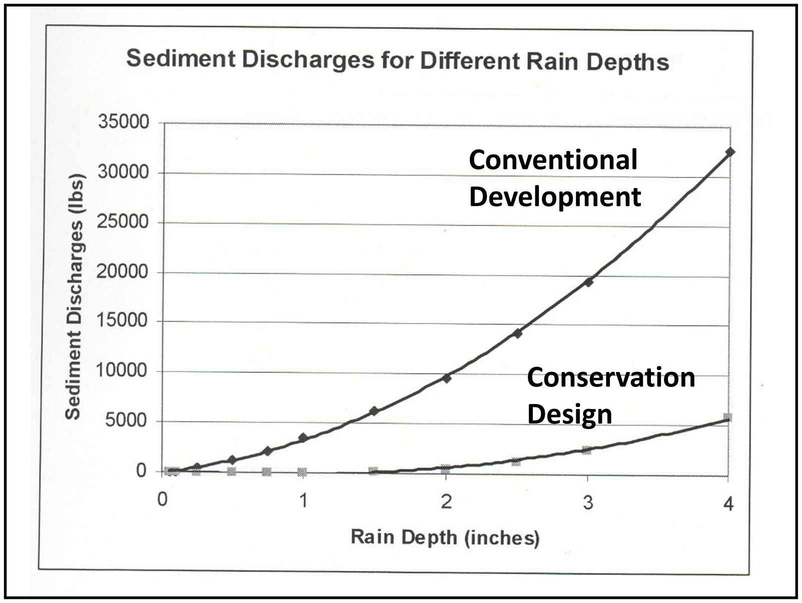
Deep Tilled to 18 inches and Planted Native Plants to Restore Infiltration

Roger Bannerman

NORTH HUNTSVILLE CONSERVATION DESIGN INDUSTRIAL PARK



Runoff Volume for Different Rain Depths


Sediment Discharges for Different Rain Depths

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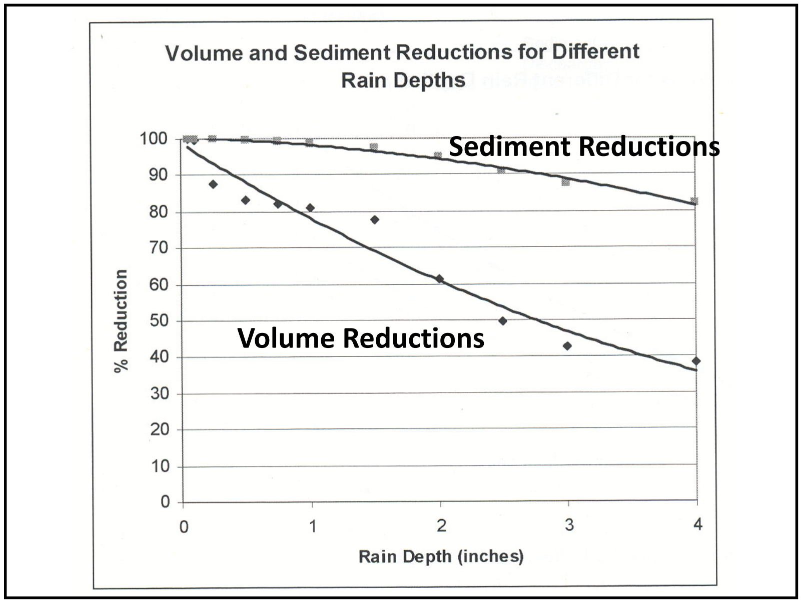
Volume and Sediment Reductions for Different Rain Depths

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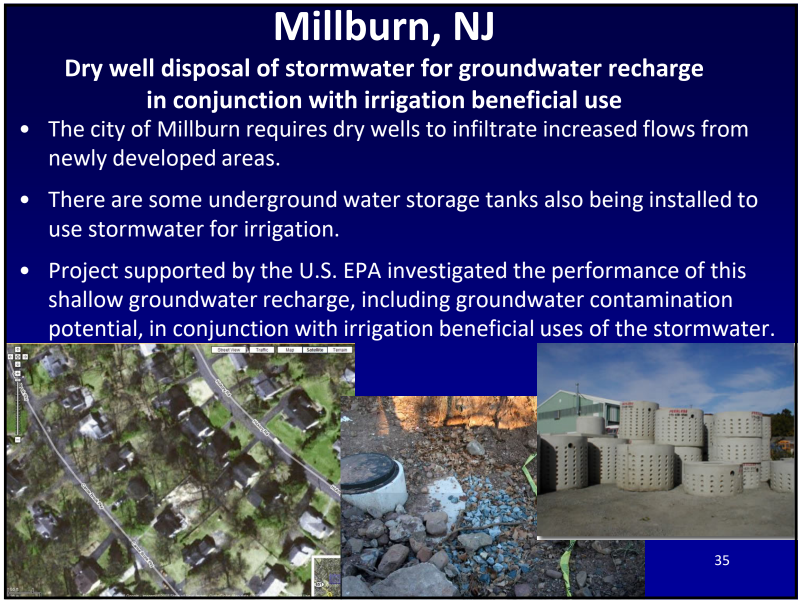
Millburn, NJ

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

- The city of Millburn requires dry wells to infiltrate increased flows from newly developed areas.
- There are some underground water storage tanks also 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.

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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.

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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.

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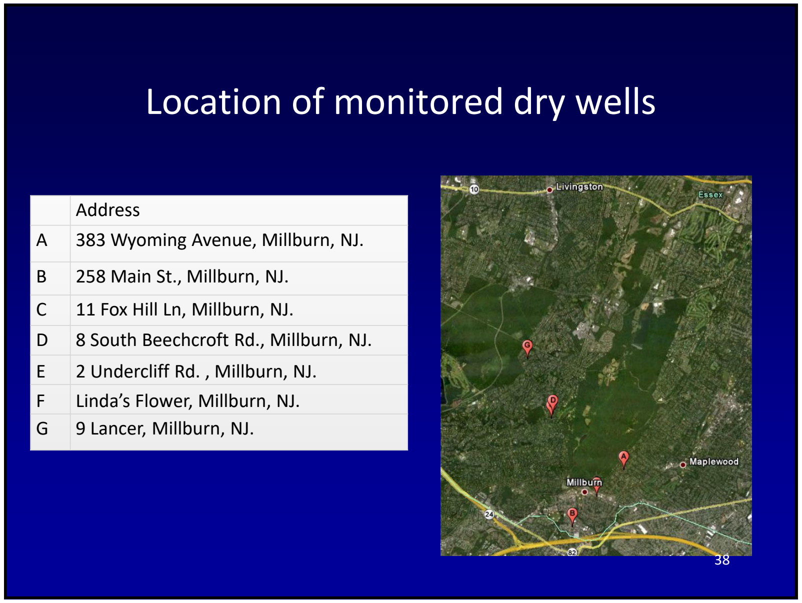

Location of monitored dry wells

	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.

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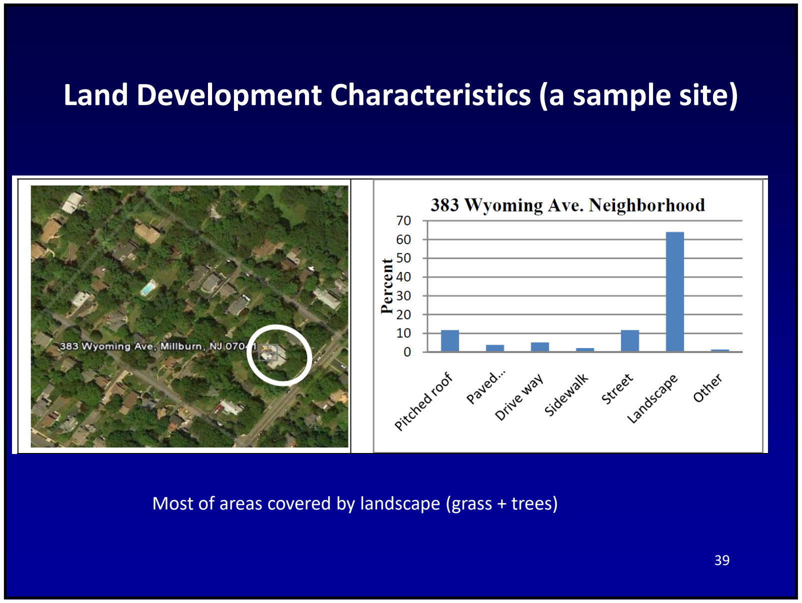

Land Development Characteristics (a sample site)

Most of areas covered by landscape (grass + trees)

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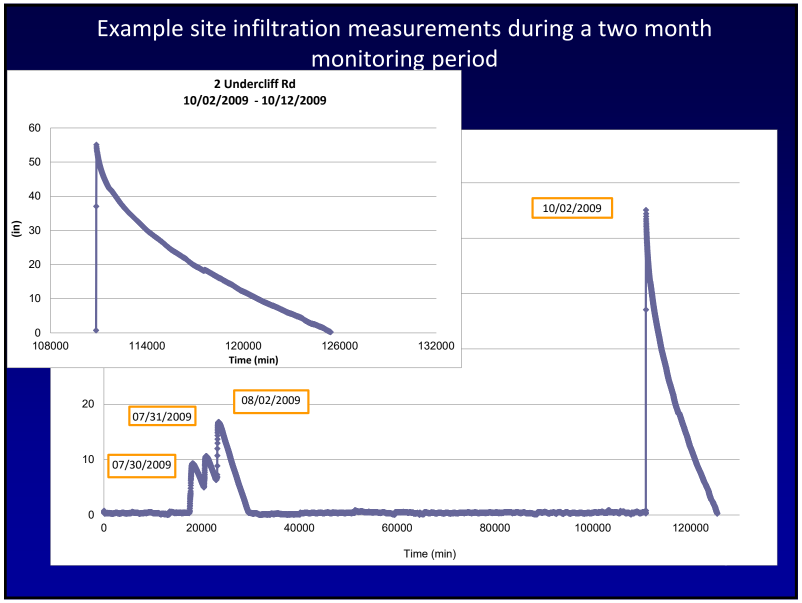

Example site infiltration measurements during a two month monitoring period

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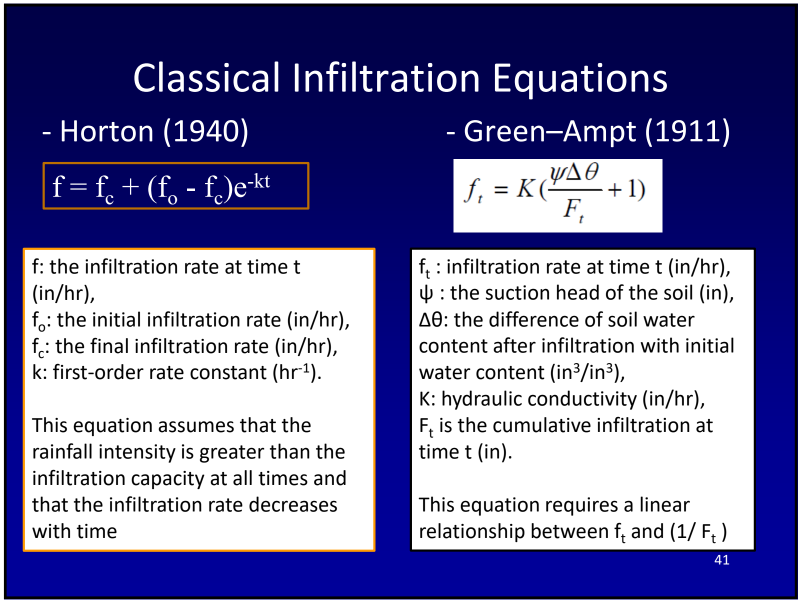


Classical Infiltration Equations

- 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}).

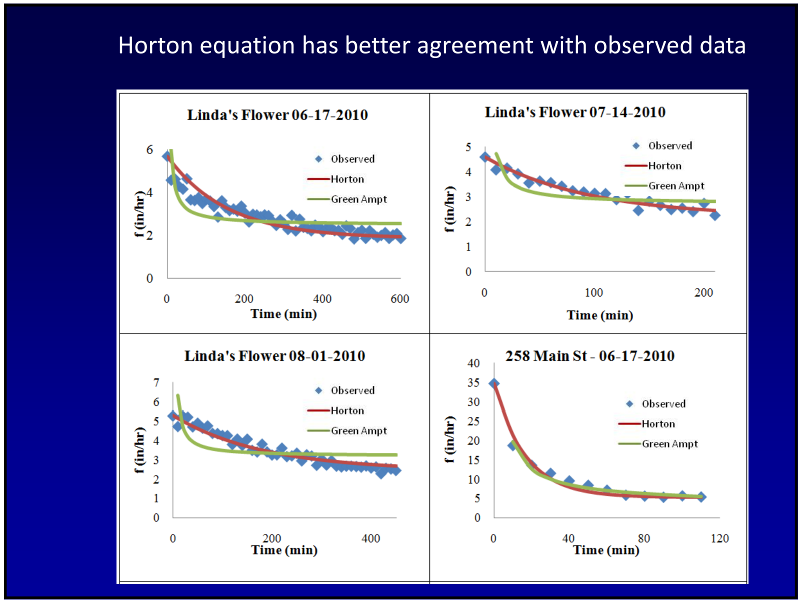
This equation assumes that the rainfall intensity is greater than the infiltration capacity at all times and that the infiltration rate decreases with time

- Green–Ampt (1911)

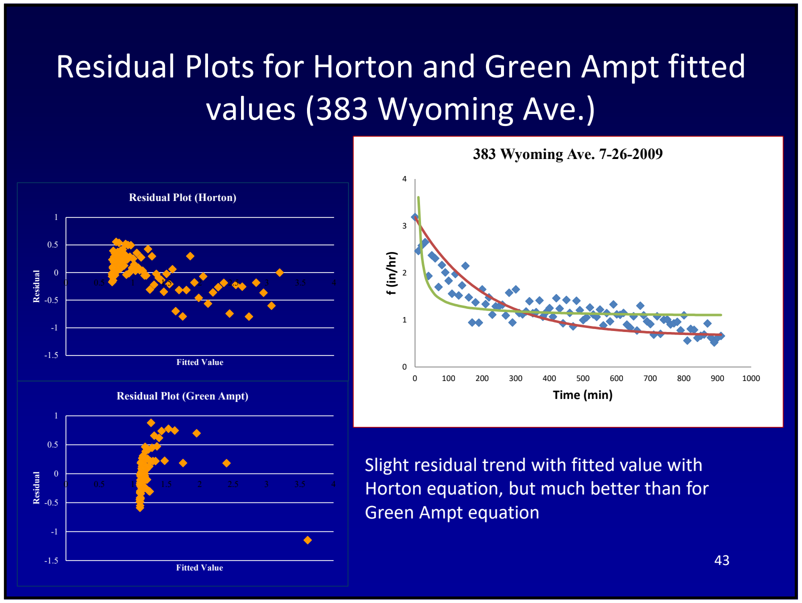
$$f_t = K(\frac{\psi \Delta \theta}{F_t} + 1)$$

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 $(1/F_t)$

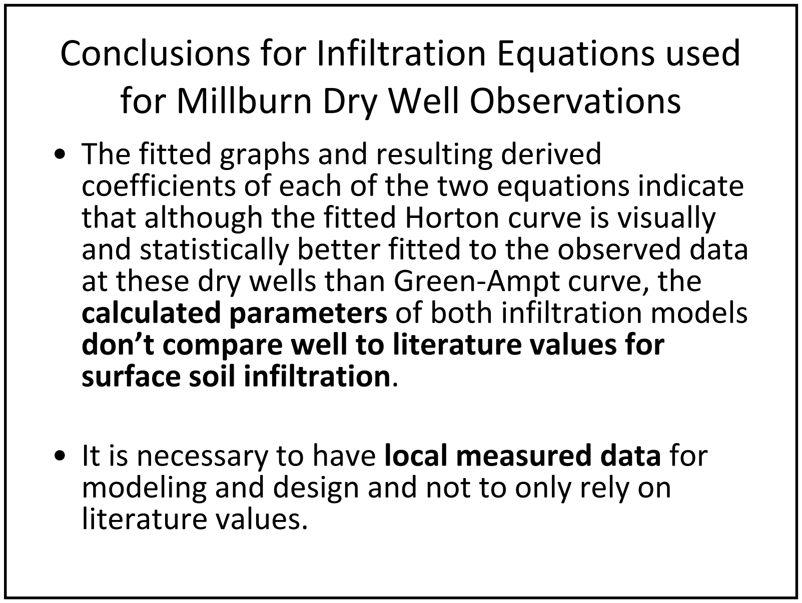


Horton equation has better agreement with observed data



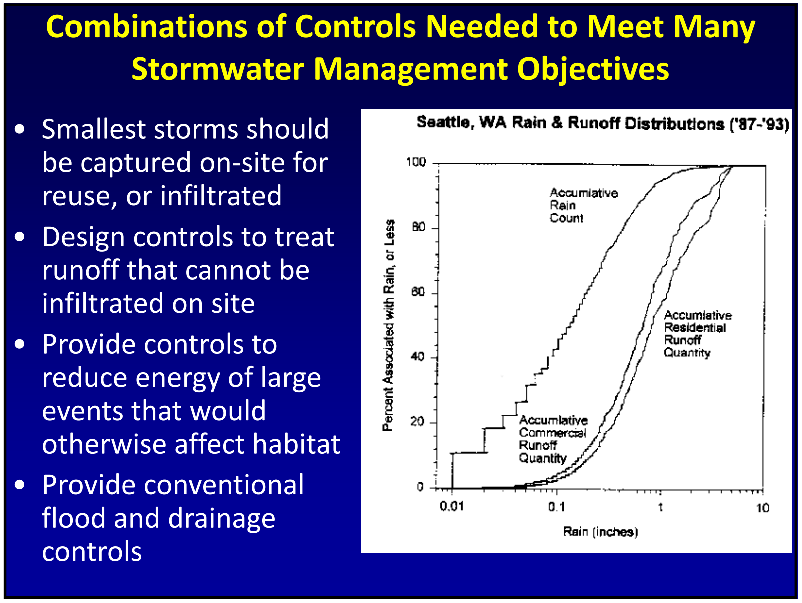
Residual Plots for Horton and Green Ampt fitted values (383 Wyoming Ave.)

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



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.



Combinations of Controls Needed to Meet Many Stormwater Management Objectives

- Smallest storms should be captured on-site for reuse, or infiltrated
- Design controls to treat runoff that cannot be infiltrated on site
- Provide controls to reduce energy of large events that would otherwise affect habitat
- Provide conventional flood and drainage controls

Seattle, WA Rain & Runoff Distributions ('87-'93)