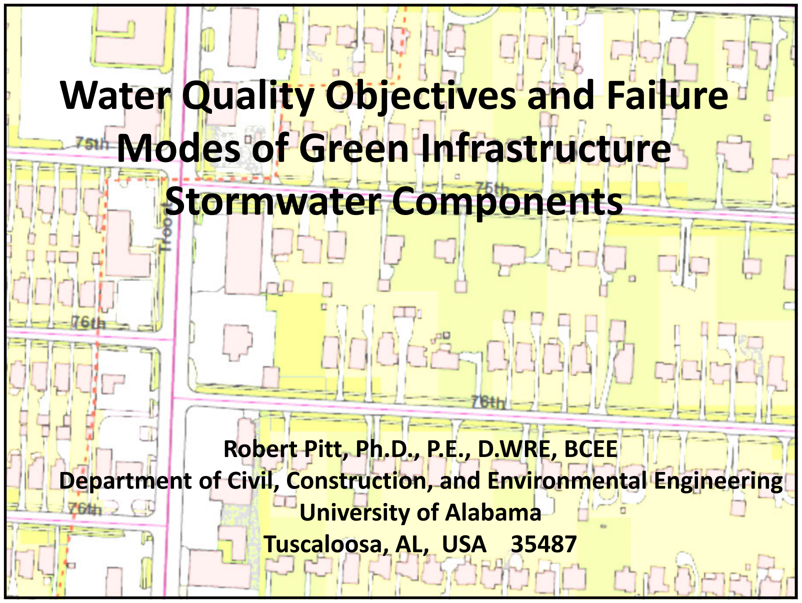

Water Quality Objectives and Failure Modes of Green Infrastructure Stormwater Components

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1

Dozen Issues of Concern

- Improper Modeling
- Clogging
- Compaction
- Chemical Breakthrough
- Sodium Adsorption Ratio
- Improper Sizing and Locations
- Groundwater Interactions
- Improper Construction
- Poor Maintenance
- Anaerobic Conditions
- Large Underdrains and Short-Circuiting
- Need Combinations of Controls and Unit Processes

2

1) Improper Modeling and Poor Selection of Targeted Rain Events

- Many agencies and stormwater managers focus on single design storms that do not adequately represent the long-term discharges of water and pollutants during wet weather
- Legacy of drainage design approaches

3

Probability distribution of rains (by count) and runoff (by depth):

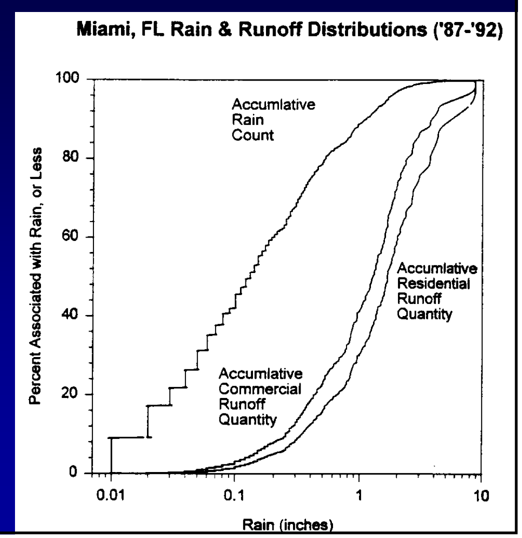
Miami Rains:

<0.5": 70% of rains (15% of runoff)

0.5 to 3": 25% of rains (65% of runoff)

3 to 8": 5% of rains (15% of runoff)

>8": <0.1% of rains (5% of runoff)

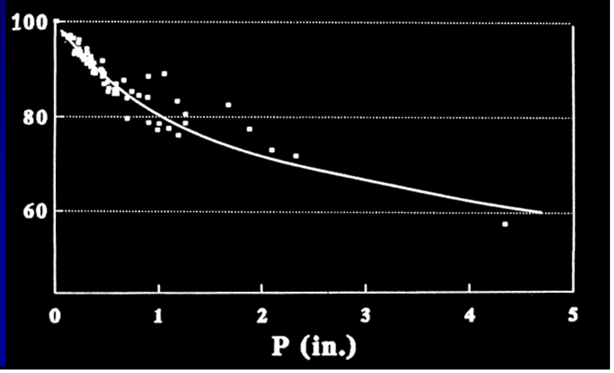


4

Typical plot of calculated curve numbers for actual site monitoring (FL resid. area). This date is from the Univ. of Florida's rainfall-runoff database that contains historical SCS/NRCS and COE monitoring data that was used to develop TR-55. Obviously, the CN method is only applicable for the large drainage design storms for which it was intended!

Observed Curve Numbers for Residential Area (39% Imperviousness)

0.25 acre lots, sandy soils (CN for A soils: 61 and CN for B soils: 75)



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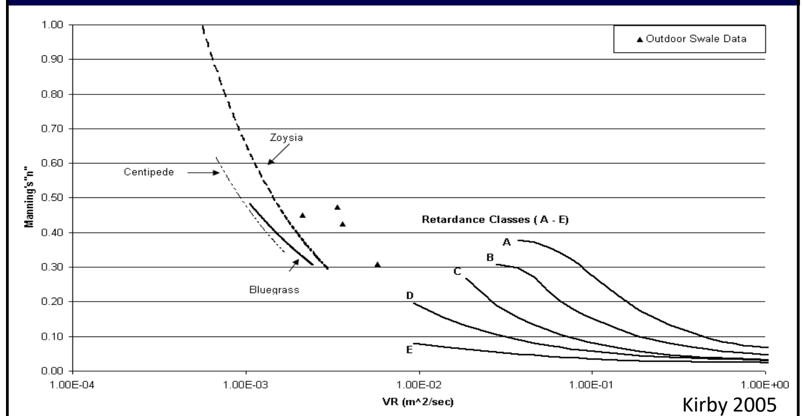
Indoor vs. Historical Stillwater, Oklahoma, Retardance Curves



Kirby 2005

From such graphs, swale hydraulic characteristics can be predicted on the basis of flow rate, cross sectional geometry, slope, and vegetation type. Small-scale urban drainage systems and flows are quite different from originally studied larger systems.

6

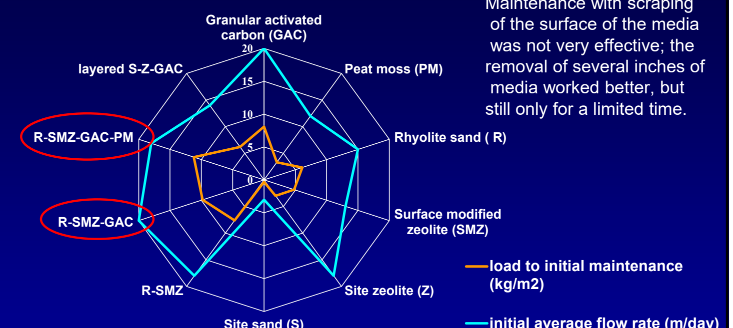
2) Clogging

- Clogging of biofiltration/bioretention devices hinders their long-term performance.
- Grass swales are relatively robust as they are very large in comparison to the service area and sediment load.
- Many smaller infiltration devices suffer due to excessive sediment without adequate pre-treatment.

7

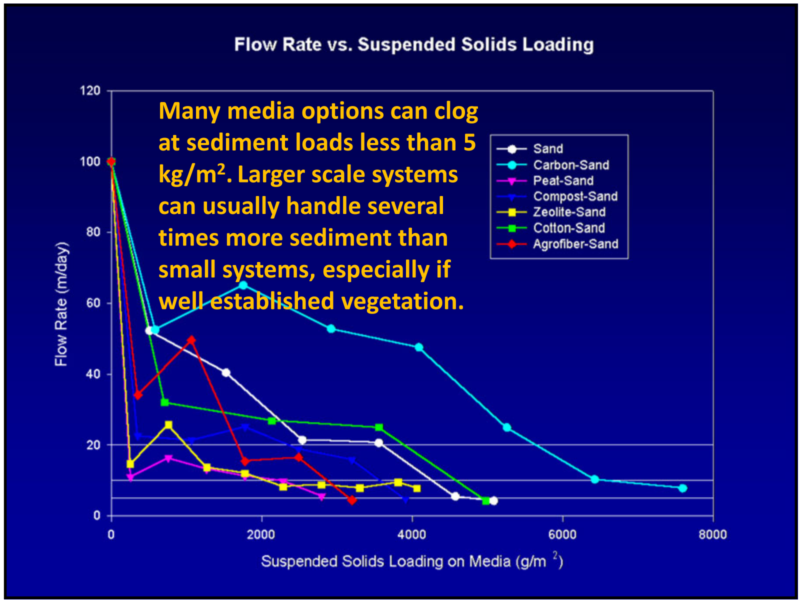
Want media with good clogging and good flow rate characteristics

Maintenance with scraping of the surface of the media was not very effective; the removal of several inches of media worked better, but still only for a limited time.



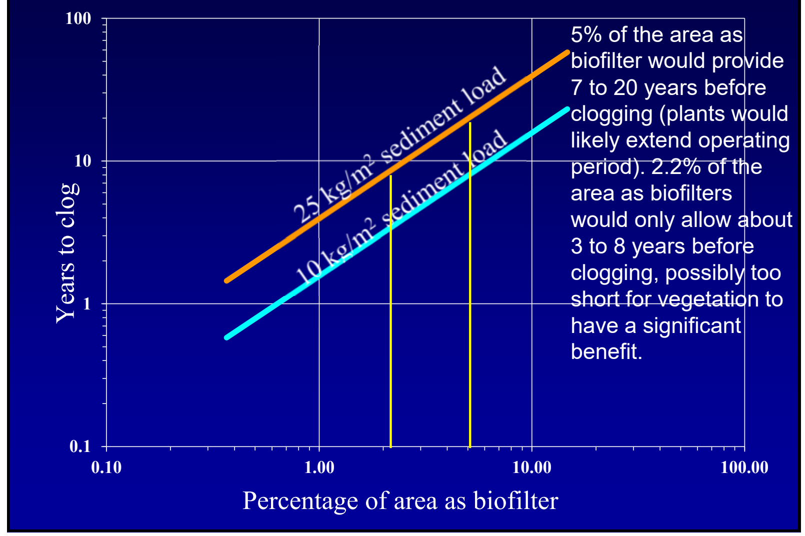
1. Site sand clogged first and had the lowest flow rate
2. Site zeolite and peat alone were next to clog
3. Biofiltration mixed media combination performed better than current site layered media combination

8



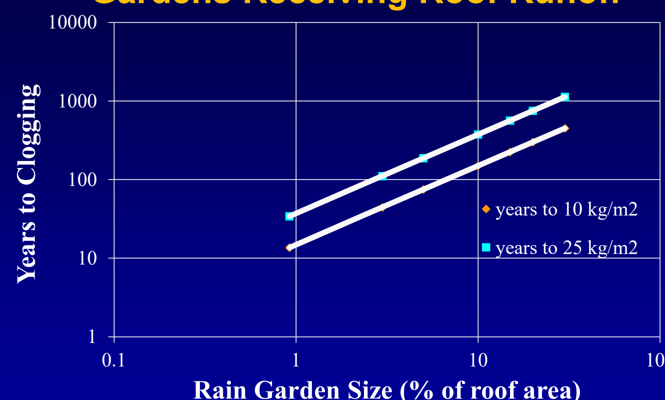
9

Years to clog as a function of biofilter size



10

Clogging Potential for Different Sized Rain Gardens Receiving Roof Runoff



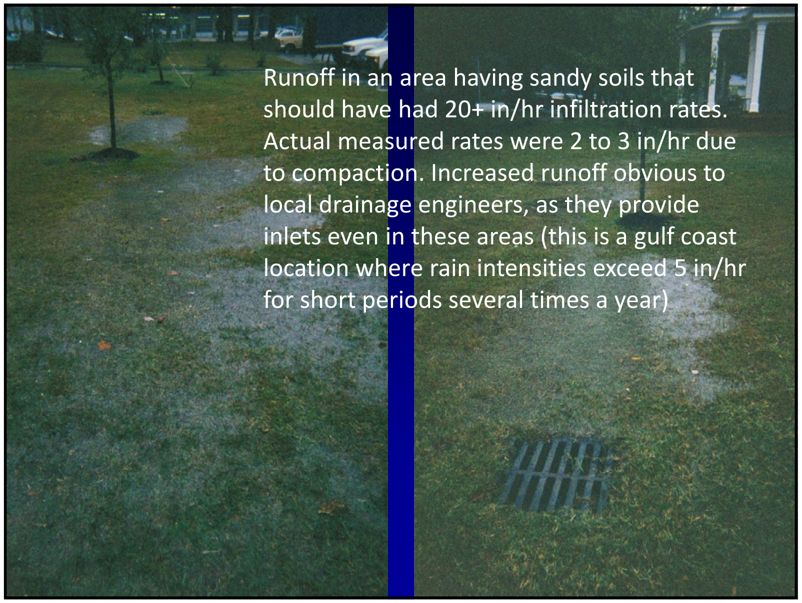
Clogging not likely a problem with rain gardens from roofs (due to low sediment loads)

11

3) Compaction

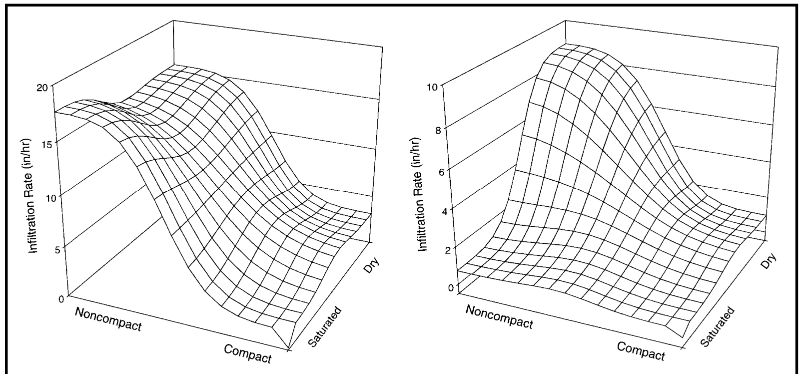
- Compaction of soils or media in an infiltration area (let alone in all pervious areas!) severely hinders infiltration capacity.
- Difficult to recover from compaction, so care is needed during construction and use.

12



Runoff in an area having sandy soils that should have had 20+ in/hr infiltration rates. Actual measured rates were 2 to 3 in/hr due to compaction. Increased runoff obvious to local drainage engineers, as they provide inlets even in these areas (this is a gulf coast location where rain intensities exceed 5 in/hr for short periods several times a year)

13



Infiltration Rates in Disturbed Sandy Urban Soils

Infiltration Rates in Disturbed Clayey Urban Soils

Pitt, *et al.* 1999

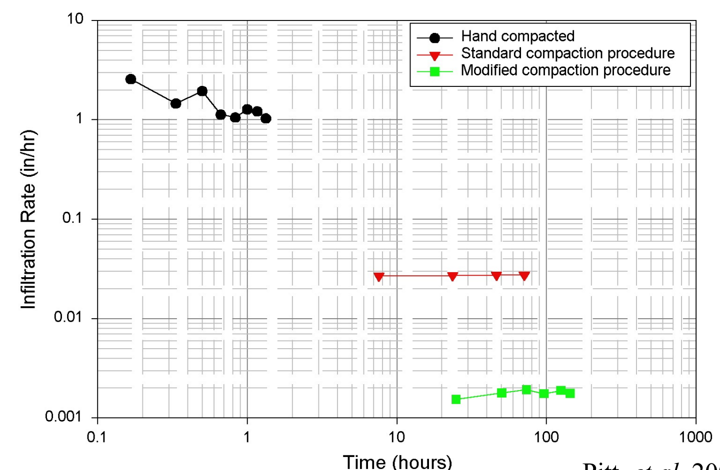
14

In-situ soil density sampling and measurements:

1) Small hole is excavated and soil brought to lab for moisture and dry weight analyses (and usually texture measurements also)
2) The hole is backfilled with a free-flowing sand to measure the volume
3) The soil density is then directly calculated (infiltration rates are also simultaneously measured in the same area)

15

Laboratory Infiltration Tests for Silty Loam Soil
4” Diameter Test Cylinder, 4.5” Depth



Pitt, *et al.* 2002

16

4) Breakthrough of Chemical Capacity

- Besides sediment clogging, media can fail due to exceeding chemical treatment capacity of the media.
- Long-term column tests more reliable indicators of chemical capacity than short-term batch tests.
- Need to use actual stormwater to represent the wide range of competing chemicals in the water, compared to tests using artificially high concentrations of single pollutant.

Mostly ionic forms in filtered stormwater (with some notable exceptions); also, several removal processes occur, beyond ion exchange and sorption

Analyte	% Ionic	% Colloidal
Magnesium	100	0
Calcium	99.1	0.9
Zinc	98.7	1.3
Iron	97	3
Chromium	94.5	5.5
Potassium	86.7	13.3
Lead	78.4	21.6
Copper	77.4	22.6
Cadmium	10	90

Morquecho 2005

Breakthrough Capacity Compared to Clogging Period

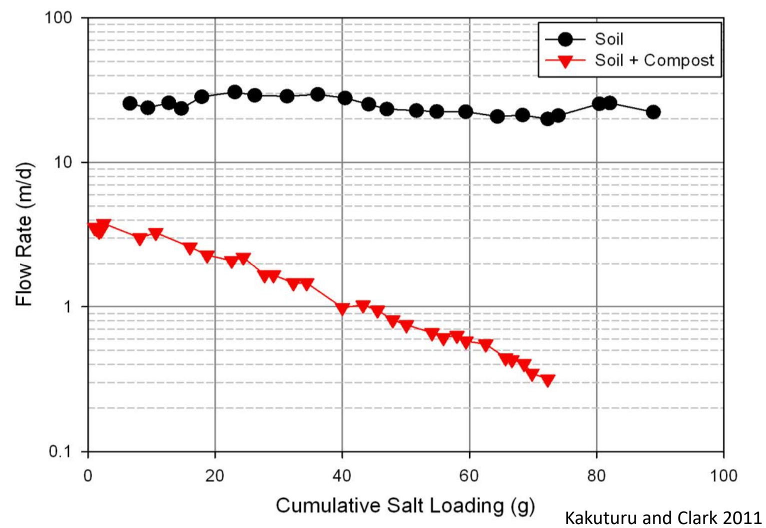
Ratios of Media Capacity to Clogging Period	R-SMZ	R-SMZ-GAC	R-SMZ-GAC-PM	Site Sand-GAC-Site Zeolite Layered
Cadmium, Total	>230	>170	>130	>150
Copper, Total	>2.2	>3.4	>1.7	>2.2
Gross Alpha radioactivity	>0.3	>0.3	>0.2	>0.2
Lead, Total	>2.1	>1.6	>0.9	>0.9
Mercury	>250	>230	>130	>140
Oil and Grease	0.1	>0.1	>0.1	<0.1
TCDD	>3.1	>2.5	>1.3	>1.5

Green: will clog before breakthrough (desired, as easier to detect)
Red: breakthrough before clogging

5) Sodium Adsorption Ratio (SAR)

- Excessive amounts of sodium in relation to calcium and magnesium causes the dispersion of clays in a soil, severely restricting infiltration capacity.
- Problem when deicing salts and snowmelt entering infiltration devices that have even small amounts of clay in the soil or media mixture.
- Not much of an issue for roof runoff rain gardens (as long as heavily salted walks or driveways do not drain towards them).
- Acceptable media and soil mixtures should prohibit clays, focusing on sandy material with organic amendments.

Flow Rate as a Function of Salt Loading



Kakuturu and Clark 2011

21

A new infiltration pond after first winter; receives snowmelt from adjacent salted parking areas (plus sediment from area construction); lost almost all of the infiltration capacity and is rapidly becoming a (poorly designed) wet pond. [was restored this past summer]

22

Soils in area of curb-cut biofilters being retrofitted, indicating high clay content, debris, and compaction (these soils will be removed and new media used after the other components (underground storage and new sidewalks) are constructed)

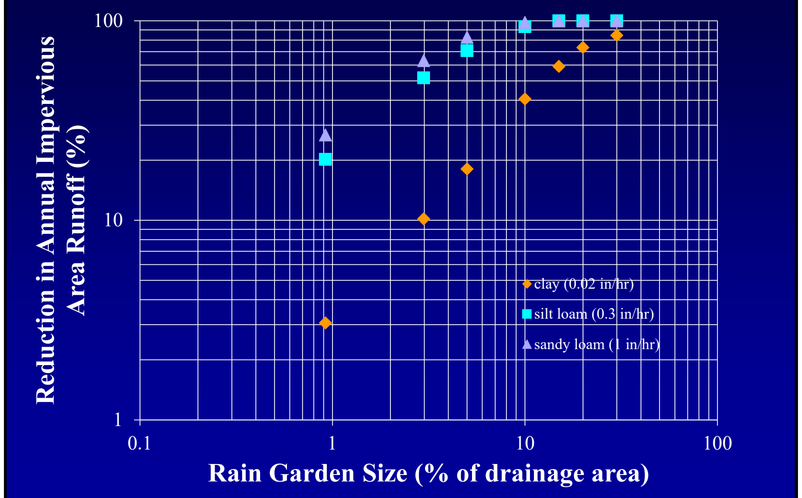
23

6) Improper Sizing and Poor Locations

- Improper modeling and design storm use can result in (usually) overly-optimistic performance expectations.
- Long-term simulations needed to access likely failures and maintenance issues.
- Over-sizing is usually needed (especially in northern climates) to overcome many uncertainties in infiltration behavior.

24

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



25

Cistern/Storage Tank Sizing vs. Performance

Storage per house (ft^3 per ft^2 of roof area)	Reduction in annual roof runoff (%)	Number of 35 gallon rain barrels for 945 ft^2 roof	Tank height size required if 5 ft D (ft)	Tank height size required if 10 ft D (ft)
0.005	24	1	0.24	0.060
0.010	29	2	0.45	0.12
0.020	39	4	0.96	0.24
0.050	56	10	2.4	0.60
0.12	74	25	6.0	1.5
0.50	99	100	24	6.0

26

Unlikely suitable performance of grass pavement in heavily used parking area, with severely compacted soil and no vegetation. At least the table tops in the adjacent hotel had flourishing LID components!

27

7) Groundwater Interactions

- Groundwater contamination potential from infiltrating stormwater is decreased with treatment before discharge to the groundwater, proper media selection, or located in an area having little contamination potential.
- Mounding below infiltration sites can severely reduce infiltration rates
- Increased groundwater recharge may increase groundwater flows to adjacent urban streams (usually a positive outcome, but if groundwater is contaminated, then this is a potential problem).

28

Potential Problem Pollutants were Identified by Pitt, *et al.* (1994 and 1996) Based on a Weak-Link Model Having the Following Components:

- Their abundance in stormwater,
- Their mobility through the unsaturated zone above the groundwater, and
- Their treatability before discharge.

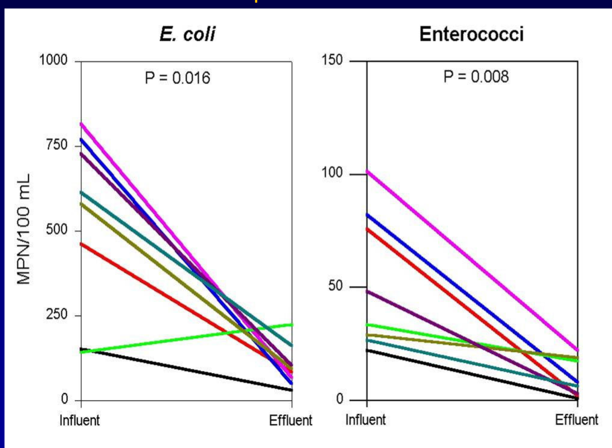
29

Moderate to High Contamination Potential

Surface Infiltration after Sedimentation plus sorption/ion-exchange (MCTT and bioretention)	Surface Infiltration with minimal Pretreatment (biofiltration and marginal soils)	Injection after Minimal Pretreatment (dry wells, gravel trenches, and most porous pavements)
	Lindane, chlordane	Lindane, chlordane
Fluoranthene, pyrene	Benzo (a) anthracene, bis (2-ethylhexl phthalate), fluoranthene, pentachlorophenol, phenanthrene, pyrene	**1,3-dichlorobenzene**, benzo (a) anthracene, bis (2-ethylhexl phthalate), **fluoranthene**, pentachlorophenol, phenanthrene, **pyrene**
Enteroviruses	**Enteroviruses**	**Enteroviruses, some bacteria and protozoa**
		Nickel, chromium, lead, **zinc**
Chloride	**Chloride**	**Chloride**

30

Media treatment can be quite effective for bacteria reductions



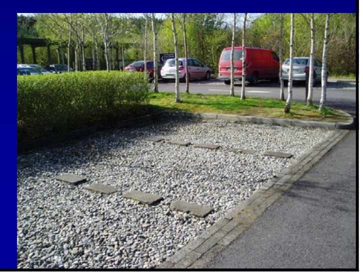
PEAT-SAND FILTER: Pilot-Scale Testing, Fall 1999

Clark and Pitt 1999

31

Minimal Pre-treatment before Infiltration Leads to Greater Groundwater Contamination Potential

Early approaches to infiltrating stormwater:



(also, filter fabric liners are usually not recommended anymore as many have failed due to clogging from silts)

32

8) Improper Construction and Poor Selection of Components

- Problems with media materials (did I mention clay before?)
- Over-filling biofilters (a surprisingly common problem), reducing storage capacity, usually with overflows set at too low of an elevation further decreasing storage.
- Difficult for water to enter device (not in flow path, no gradient, blocked entrances, and no drop off to top of media, allowing build-up of debris.

33

Red southern clay turned these terraced biofilters into something else. Constant flooding killed the vegetation and they are attempting to break up the surface clay layers.

34

Over-filled biofilter allowing short-circuiting of surface flows to slot drain inlet that is set slightly below top of media

35

Obvious short-circuiting flow path and washout of media in over-filled biofilter.

36

9) Poor Maintenance

- Proper maintenance is necessary to ensure expected performance.
- Excessive erosion of surrounding areas and at the device itself can lead to excessive sediment loads and clogging in a short period of time.
- Irrigation is needed during periods of low rainfall to keep biofilter plants alive and active. Similar needs for green roof plants during seasonal dry periods. Plants need to be selected to withstand a wide range of dry to flooding conditions.

37

Excessive erosion at edges of biofilter.

Lack of irrigation resulted in complete loss of these biofilter plants during extended drought.

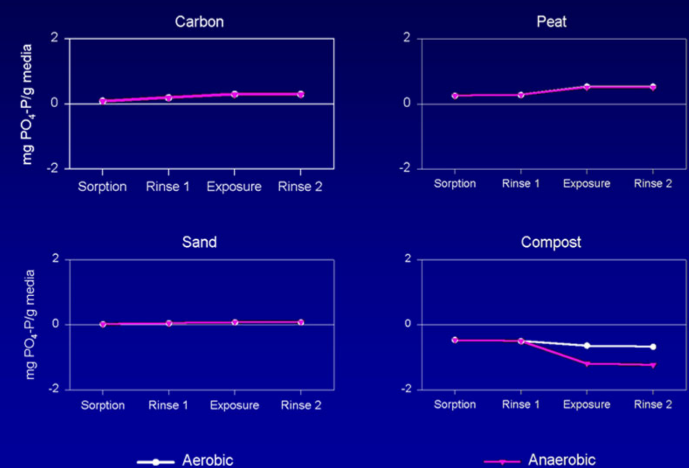
38

10) Anaerobic Conditions

- Anaerobic conditions in biofilter media can enhance nitrate removals, if used in conjunction with other properly designed attributes (media selection and underdrain design).
- Many organic media can loose previously captured pollutants, especially nutrients, under anaerobic conditions. Metal retention is usually more secure, but degradation of the media results in losses of all materials.
- “First-flushes” of retained water from biofilters that have gone anaerobic contain very high pollutant concentrations.
- Free-draining media that remain aerobic during interevent periods exhibit fewer of these problems.

39

ANAEROBIC STRIPPING OF SORBED POLLUTANTS
SOLUBLE PHOSPHATE
Star Lake Water,Hoover, Alabama



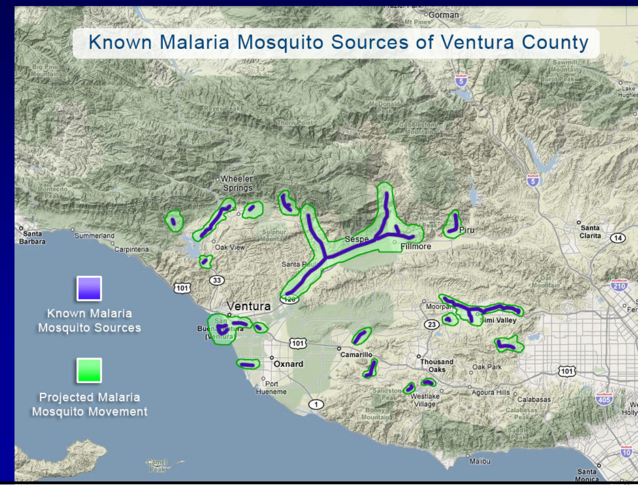
40

11) Large Underdrains and Short-Circuiting

- Underdrains are needed in areas where standing water for extended periods of time causes problems, and to reduce anaerobic conditions in biofilter media.
- Conventional large underdrains provide too large of a drainage flow rate causing short-circuiting and short residence times.
- Flow restrictions are causes of clogging or maintenance problems.
- Modified underdrains can provide a good solution.

41

Many Areas Require Biofilter Drainage within 72 hours to Prevent Mosquito Infestation



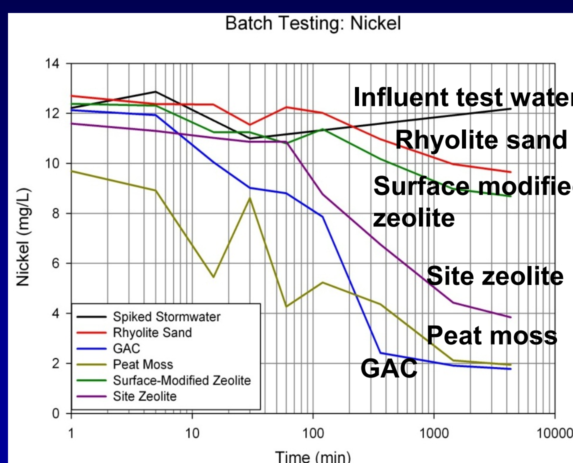
42

Contact Time Affects Pollutant Removals

Minimal filtered metal removal observed for all media except peat when contact time <10 minutes.

The optimal contact times for filtered metals removal ranged from 10 to 1,000 minutes (17 hrs), depending on the metal and the media type.

However too long of a contact time increased leaching losses from some media.



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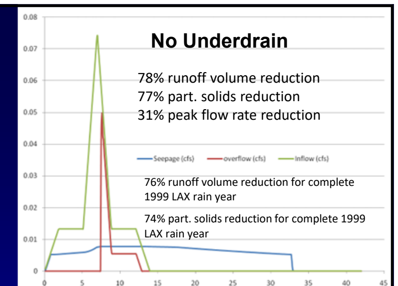
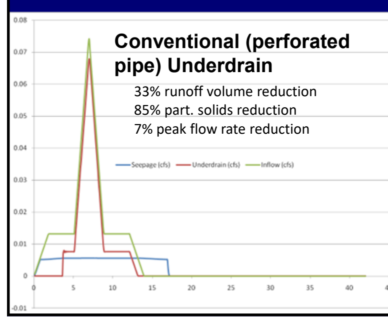
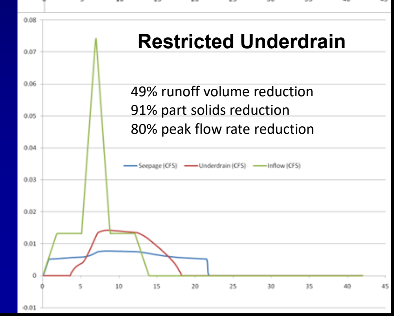
Underdrain Effects on Water Balance

0.75 inch rain with complex inflow hydrograph from 1 acre of pavement. 2.2% of paved area is biofilter surface, with natural loam soil (0.5 in/hr infilt. rate) and 2 ft. of modified fill soil for water treatment and to protect groundwater.

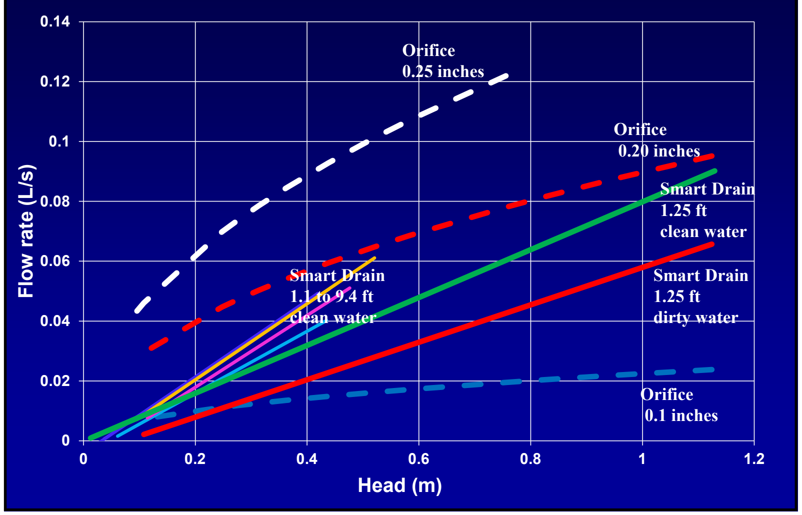






44

Smart Drain Flow Rates Compared to Very Small Orifices



45

12) Need Combinations of Controls (storage, sedimentation and infiltration)

- Infiltration alone can be effective in reducing most stormwater pollutants and flows.
- Sedimentation before infiltration offers advantages of pre-treatment and better sediment control.
- Storage before infiltration enhances treatment at low treatment flow rates.

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Parallel study areas, comparing test with control site, Cross Plains, WI, DNR and USGS

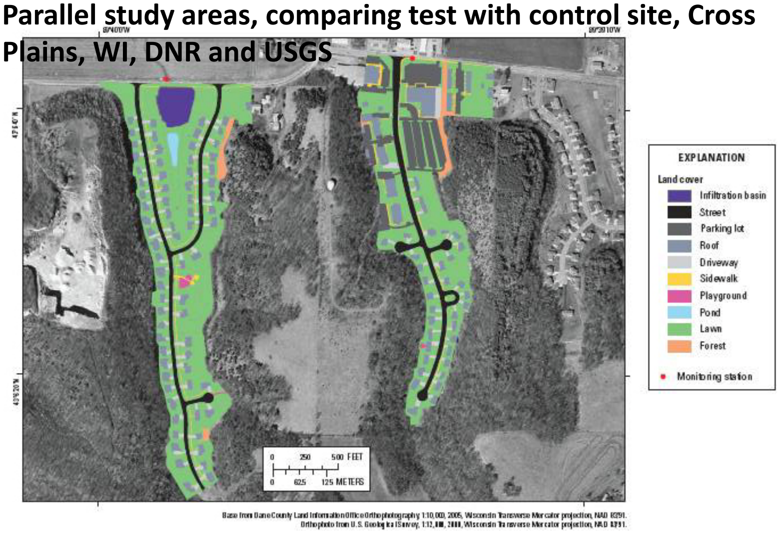
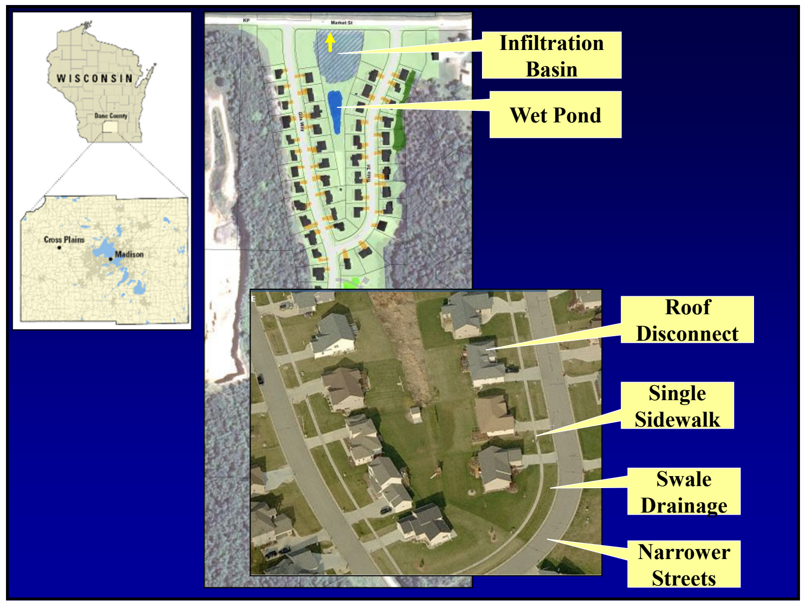


Figure 2. Land use in the low-impact-development (left) and conventional-development (right) basins and location of water-quality monitoring stations, Cross Plains, Wis.

47



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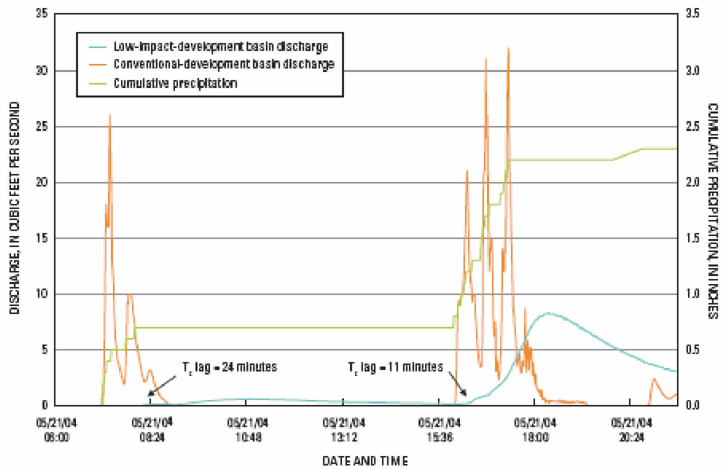

Figure 10. Hydrologic response of low-impact-development (LID) and conventional-development basins to two consecutive precipitation events, Cross Plains, Wis. [T_c, time of concentration]

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Monitored Performance of Controls at Cross Plains Conservation Design Development

Water Year	Construction Phase	Rainfall (inches)	Volume Leaving Basin (inches)	Percent of Volume Retained (%)
1999	Pre-construction	33.3	0.46	99%
2000	Active construction	33.9	4.27	87%
2001	Active construction	38.3	3.68	90%
2002	Active construction (site is approximately 75% built-out)	29.4	0.96	97%

WI DNR and USGS data

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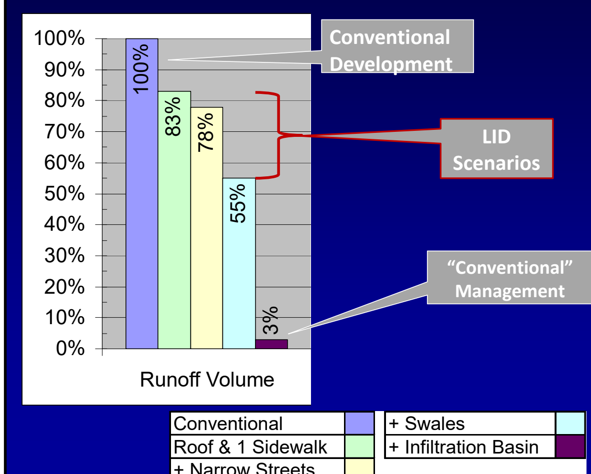
Runoff Reductions by Site Components



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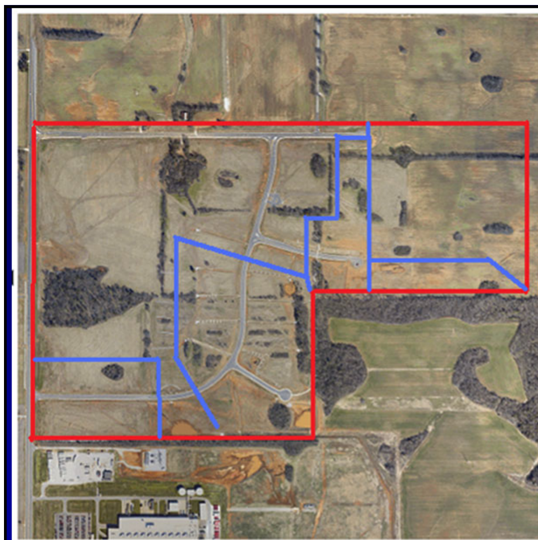

North Huntsville (AL) Conservation Design Industrial Park

- On-site bioretention swales
- Level spreaders
- Large regional swales
- Wet detention ponds
- Critical source area controls
- Pollution prevention (no Zn!)
- Buffers around sinkholes
- Extensive trail system linking water features and open space

Aerial Photo of Site under Construction (Google Earth)

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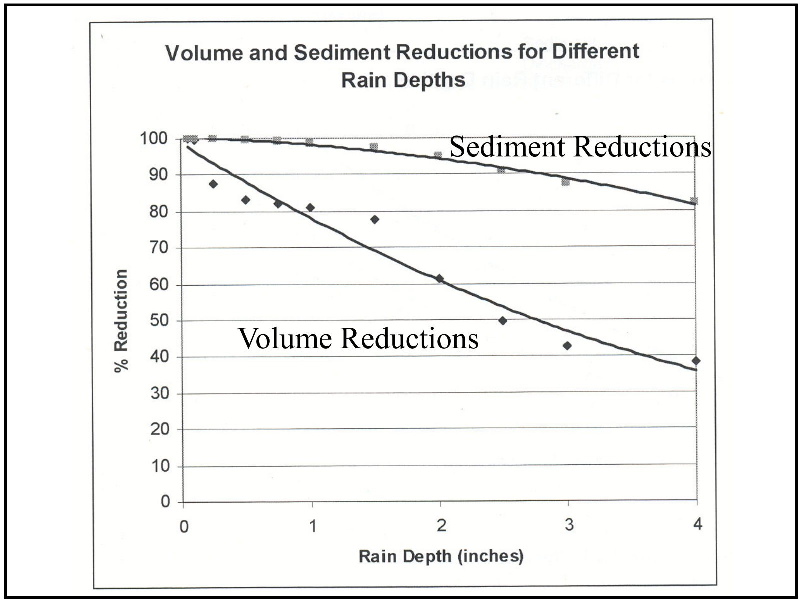

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Summary

- Learn from others (and yourselves)! Evaluate and monitor installations and modify approaches.
- Site conditions and local rains dramatically affect performance.
- Northern areas and locations using deicing salts are an extreme example that require special approaches to stormwater management.
- Groundwater issues need to be considered.
- Combinations of unit processes almost always result in the most robust, most cost-effective, and best water quality.

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Acknowledgements

- Many researchers and stormwater managers over the years have been true pioneers in developing and enhancing stormwater controls.
- The few examples of poor installations in this presentation are not intended to denigrate these efforts, but to thank all for their ideas and dedication, so others can learn.

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