green roofs: why they work

with Charlie Miller

If You Don’t Use It… You Lose It

Controlling + harnessing urban rainfall

Green roofs

Living walls and vine walls

Landscapes

Street trees

Utility uses

Water-based adiabatic cooling systems

Solar thermal systems

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Green Roofs are Composite Systems

Foliage

Growth Medium

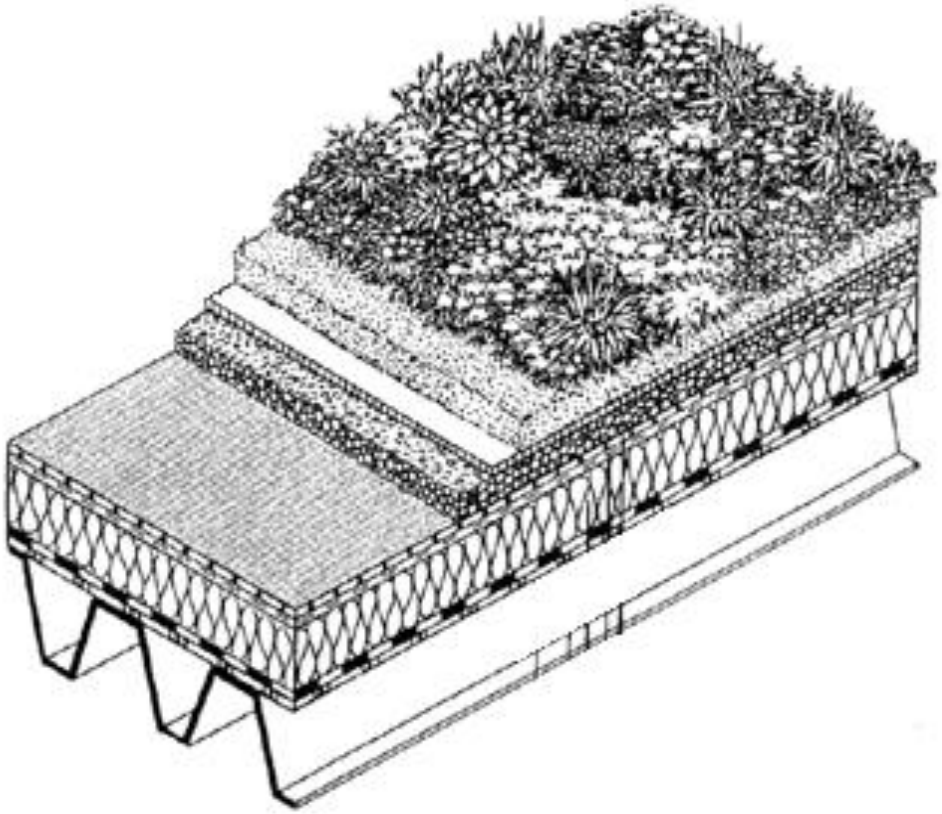
Filtration Fabrics

Drainage Layer

Protection Layer

Waterproofing

Performance varies depending on the choice of properties for each of component



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Physical Properties of Green Roof Components + Assemblies Poorly Understood

Effect of media matric potentials

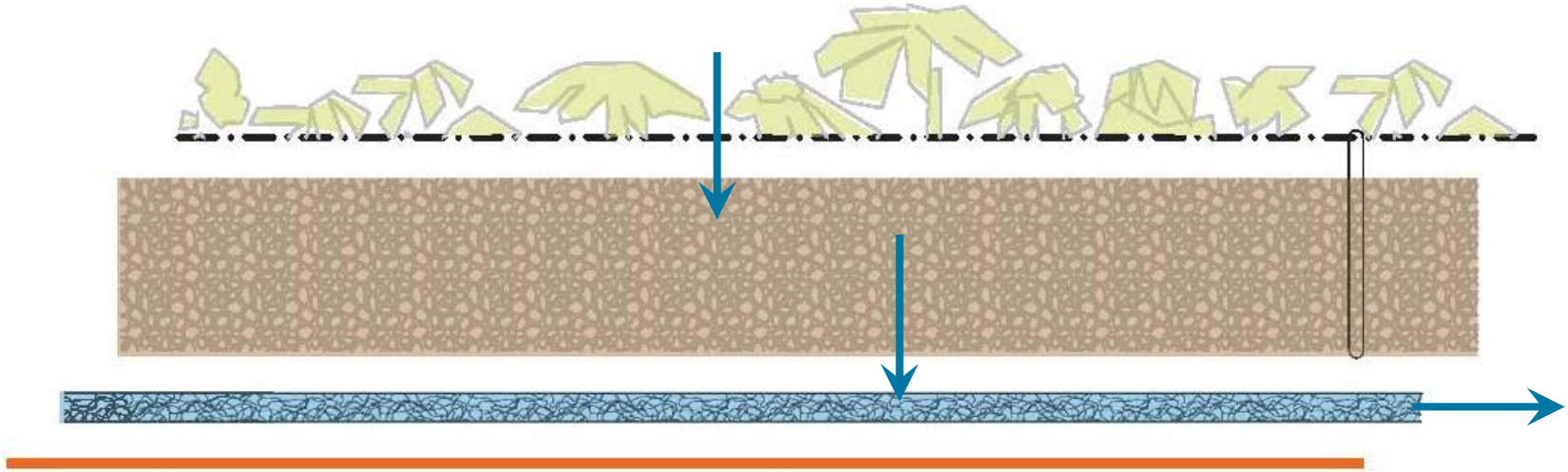
Importance of capillary breaks in increasing moisture uptake

Potential for dense filter fabrics to reduce percolation and to inhibit root growth

Availability of free water captured in reservoir sheets to plants

Heat capacity of various media, as a function of moisture

Effect of basal fabrics in moderating moisture variability



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Green Roofs as Dynamic Detention Systems

Retention Function (semi-permanent storage):

15% by volume (field capacity)

Detention Function (delayed release):

25% by volume (maximum water capacity*)

In warm months much of this water is returned to the atmosphere via plant transpiration

Detention Function (transient storage):

10% by volume (air-filled porosity)

Each Detention Process associated with a first-order discharge rate constant (half-life)

* Maximum media water retention (ASTM E2399) = maximum water capacity + field capacity

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Transmissivity for Simple Drainage Layers

Measures the in-plane flow capacity at laminar or near-laminar flow conditions [ASTM D4716 and ASTM E2396]

Typical geocomposite drain sheet:	**.050 - .200** m^2/s
Typical 2 inch granular drainage layer:	**.001 - .004** m^2/s
Typical synthetic mat (foam or fabric):	**.002 - .008** m^2/s

Drainage layer typically 1,000s of times more permeable than overlying media

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Understanding Hydraulic Residence Time:
The Key to Developing Useful Predictive Tools

The pathway through the drainage layer is 100s of times longer and therefore of particular importance to the green roof designer

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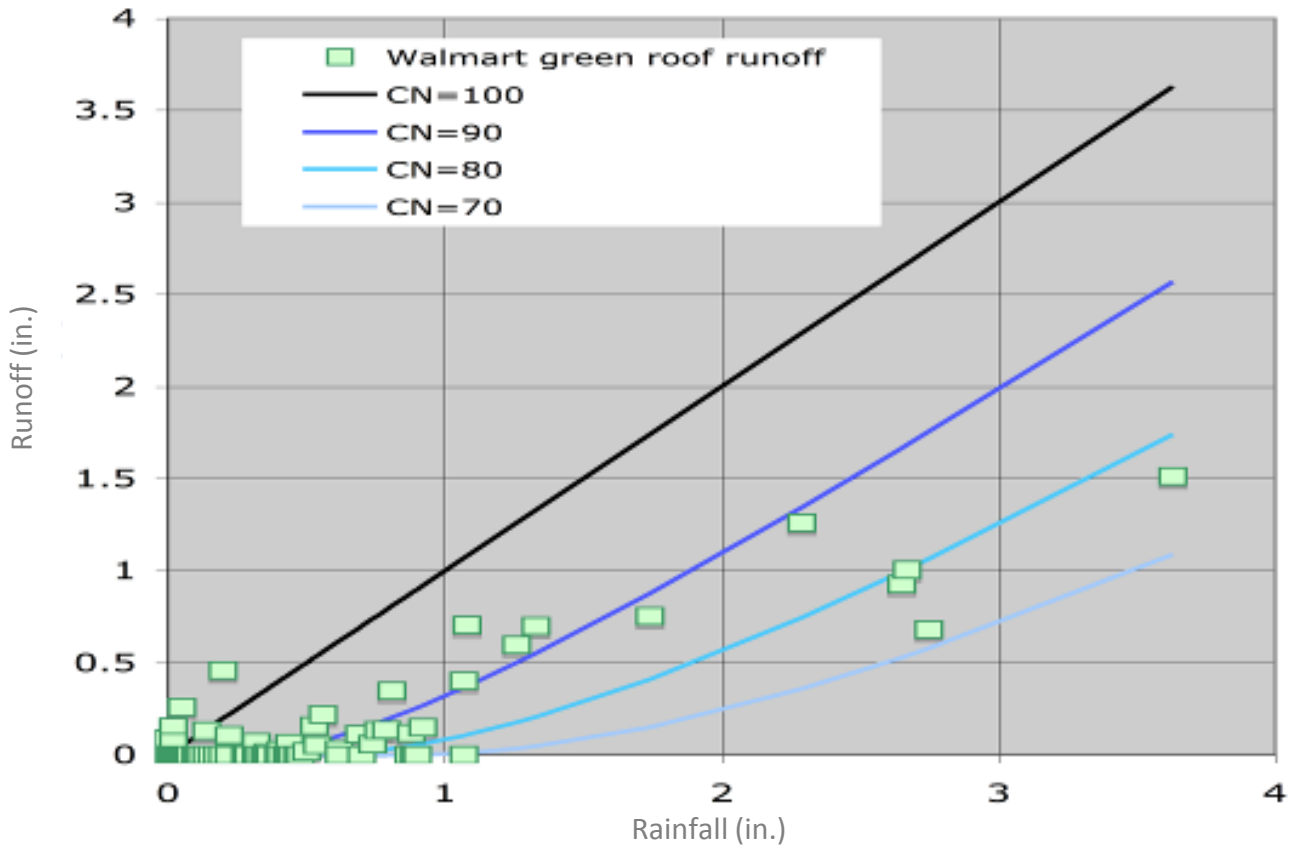
Curve Number:
One Measure of Moisture Uptake

Berghage, et al. (2010) (courtesy of Walmart and Pennsylvania State University)



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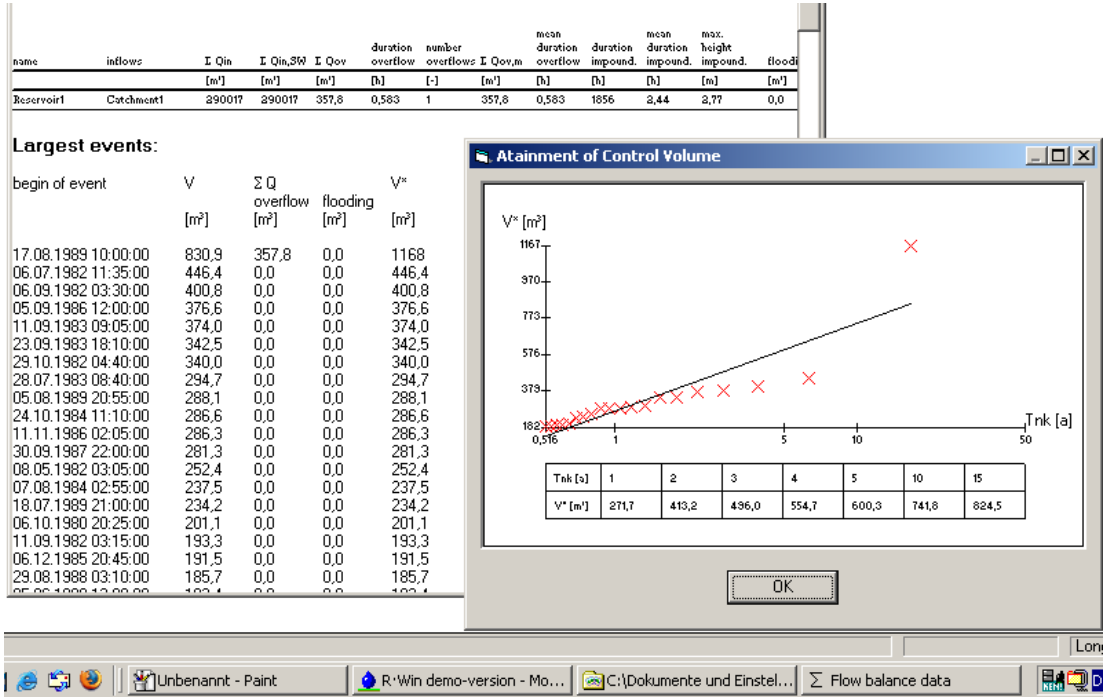
Long-Term Simulation Develops System Statistics

Continuous Modeling using 10-30 years of local rainfall data

Average antecedent moisture conditions

Average seasonal runoff volume reduction

Average peak runoff coefficient (i.e., Rational Coefficient or Runoff)

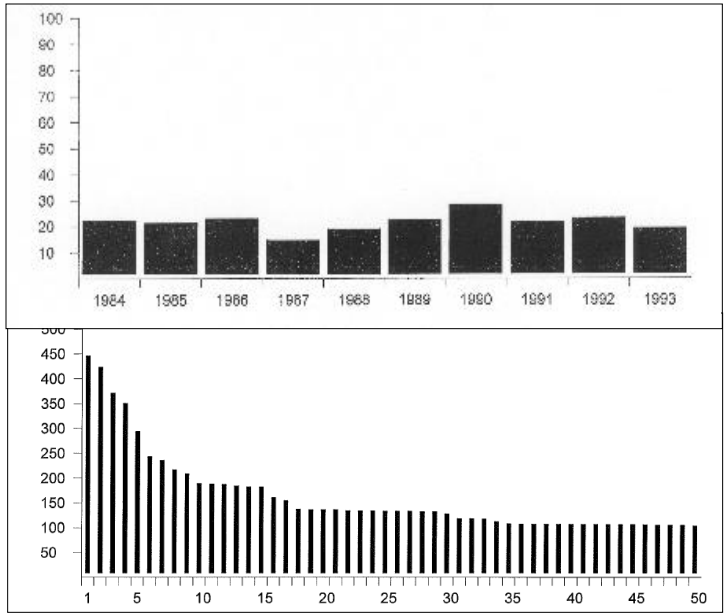


name	inflows	Σ Qin	Σ Qin,SW	Σ Qov	duration overflow	number overflows	Σ Qov,m	mean duration overflow	duration impound.	mean duration impound.	max. height impound.	flooding
		[m³]	[m³]	[m³]	[h]	[-]	[m³]	[h]	[h]	[h]	[m]	[m³]
Reservoir1	Catchment1	290017	290017	357,8	0,583	1	357,8	0,583	1856	2,44	2,77	0,0

Largest events:

begin of event	V [m³]	Σ Q overflow [m³]	flooding [m³]	V* [m³]
17.08.1989 10:00:00	830,9	357,8	0,0	1168
06.07.1982 11:35:00	446,4	0,0	0,0	446,4
06.09.1982 03:30:00	400,8	0,0	0,0	400,8
05.09.1986 12:00:00	376,6	0,0	0,0	376,6
11.09.1983 09:05:00	374,0	0,0	0,0	374,0
23.09.1983 18:10:00	342,5	0,0	0,0	342,5
29.10.1982 04:40:00	340,0	0,0	0,0	340,0
28.07.1983 08:40:00	294,7	0,0	0,0	294,7
05.08.1989 20:55:00	288,1	0,0	0,0	288,1
24.10.1984 11:10:00	286,6	0,0	0,0	286,6
11.11.1986 02:05:00	286,3	0,0	0,0	286,3
30.09.1987 22:00:00	281,3	0,0	0,0	281,3
08.05.1982 03:05:00	252,4	0,0	0,0	252,4
07.08.1984 02:55:00	237,5	0,0	0,0	237,5
18.07.1989 21:00:00	234,2	0,0	0,0	234,2
06.10.1980 20:25:00	201,1	0,0	0,0	201,1
11.09.1982 03:15:00	193,3	0,0	0,0	193,3
06.12.1985 20:45:00	191,5	0,0	0,0	191,5
29.08.1988 03:10:00	185,7	0,0	0,0	185,7

Tnk [a]	1	2	3	4	5	10	15
V* [m³]	271,7	413,2	496,0	554,7	600,3	741,8	824,5



RWS Program, IFS-Hannover

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Resulted in Unexpectedly Low Estimates for Runoff Rate Coefficients

10-years of Boston area rainfall data

4 inch thick dual media assembly

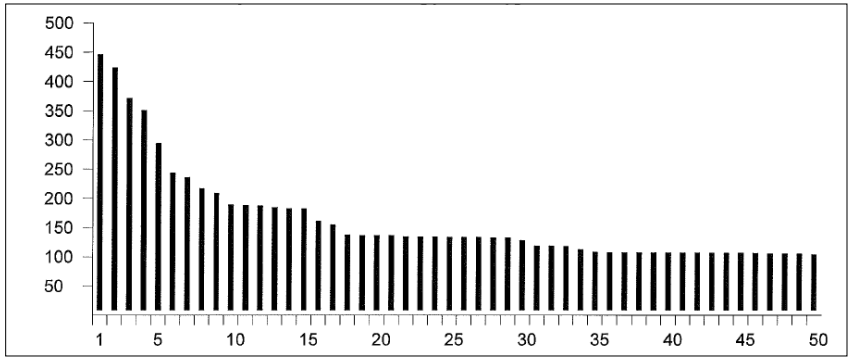
Computer simulation using RWS program

Rational Coefficient

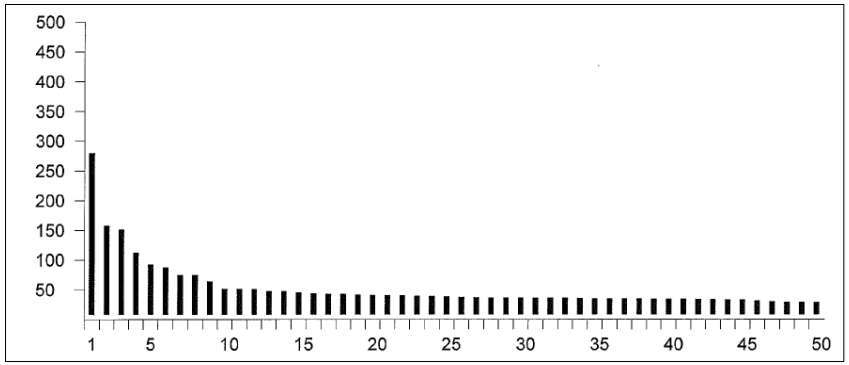
$C_{R_1} = 0.37$

$C_{R_2} = 0.39$

$C_{R_{10}} = 0.42$



Without a green roof



With a 4 inch thick green roof

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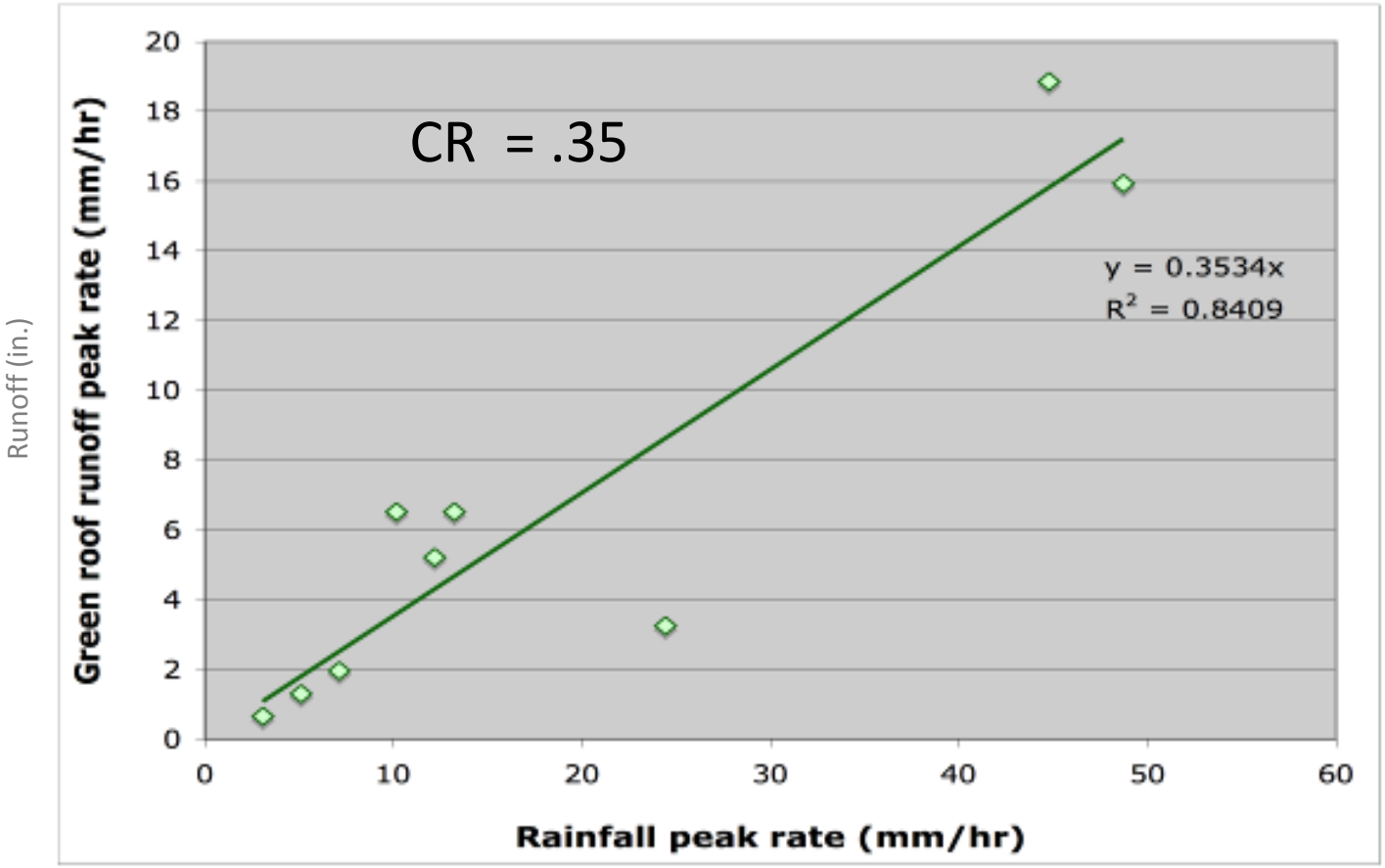
Corroborated by Field Measurement of Large Green Roofs

Berghage, et al. (2010) (courtesy of Walmart and Pennsylvania State University)



Runoff (in.)

Rainfall (in.)

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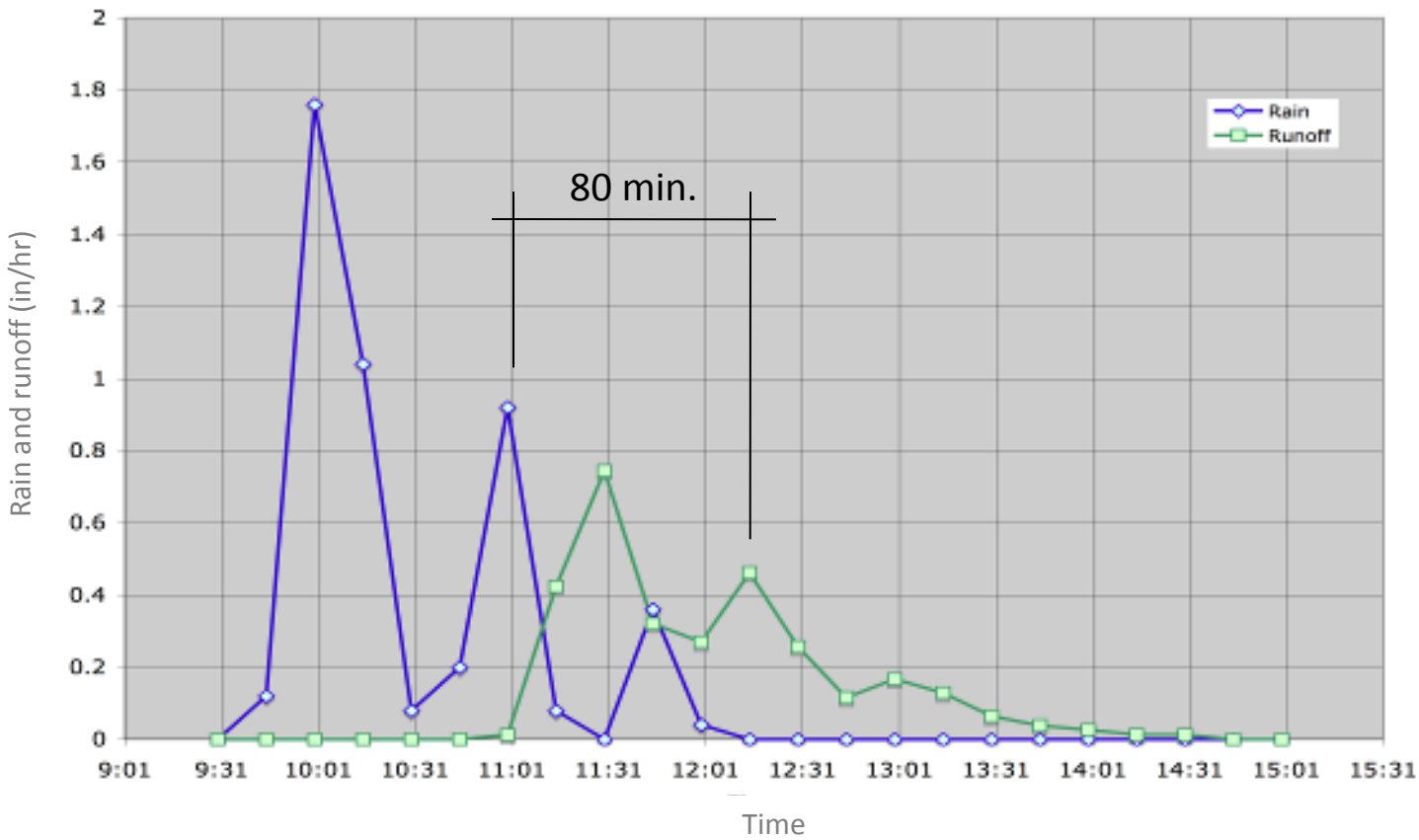
The Missing Piece of the Puzzle:
Time of Concentration Was Ignored

Berghage, et al. (2010) (courtesy of Walmart and Pennsylvania State University)



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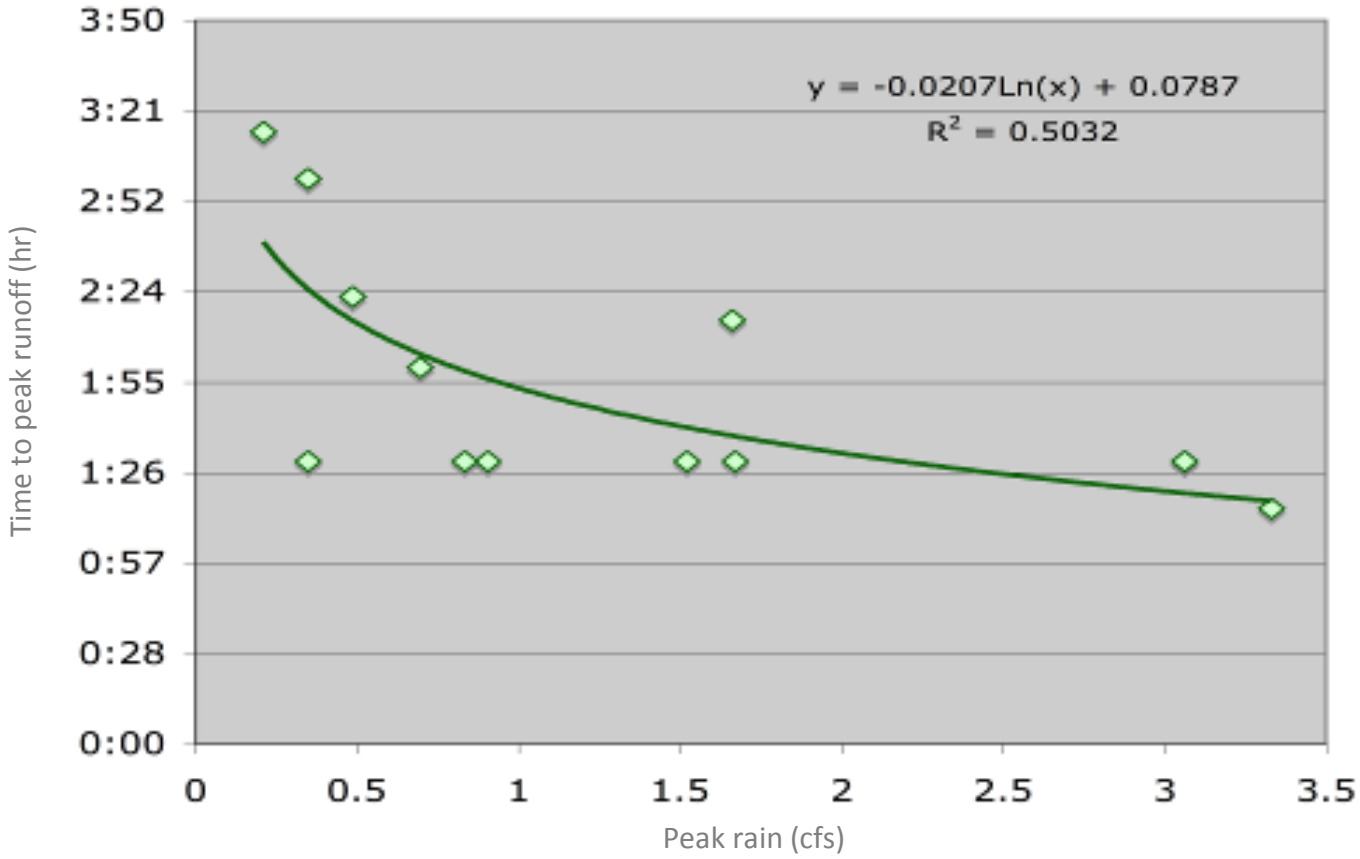
Time to Peak

Berghage, et al. (2010) (courtesy of Walmart and Pennsylvania State University)



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Walmart Store #5402 Conclusions

Roof size matters

Flow path length matters

Time of concentration critical to hydrologic response

Very thin assemblies can be very effective *

* Other lines of inquiry suggest that media thickness has a comparatively minor role in reducing runoff RATES

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Benefits of Longer Hydraulic Residence Times

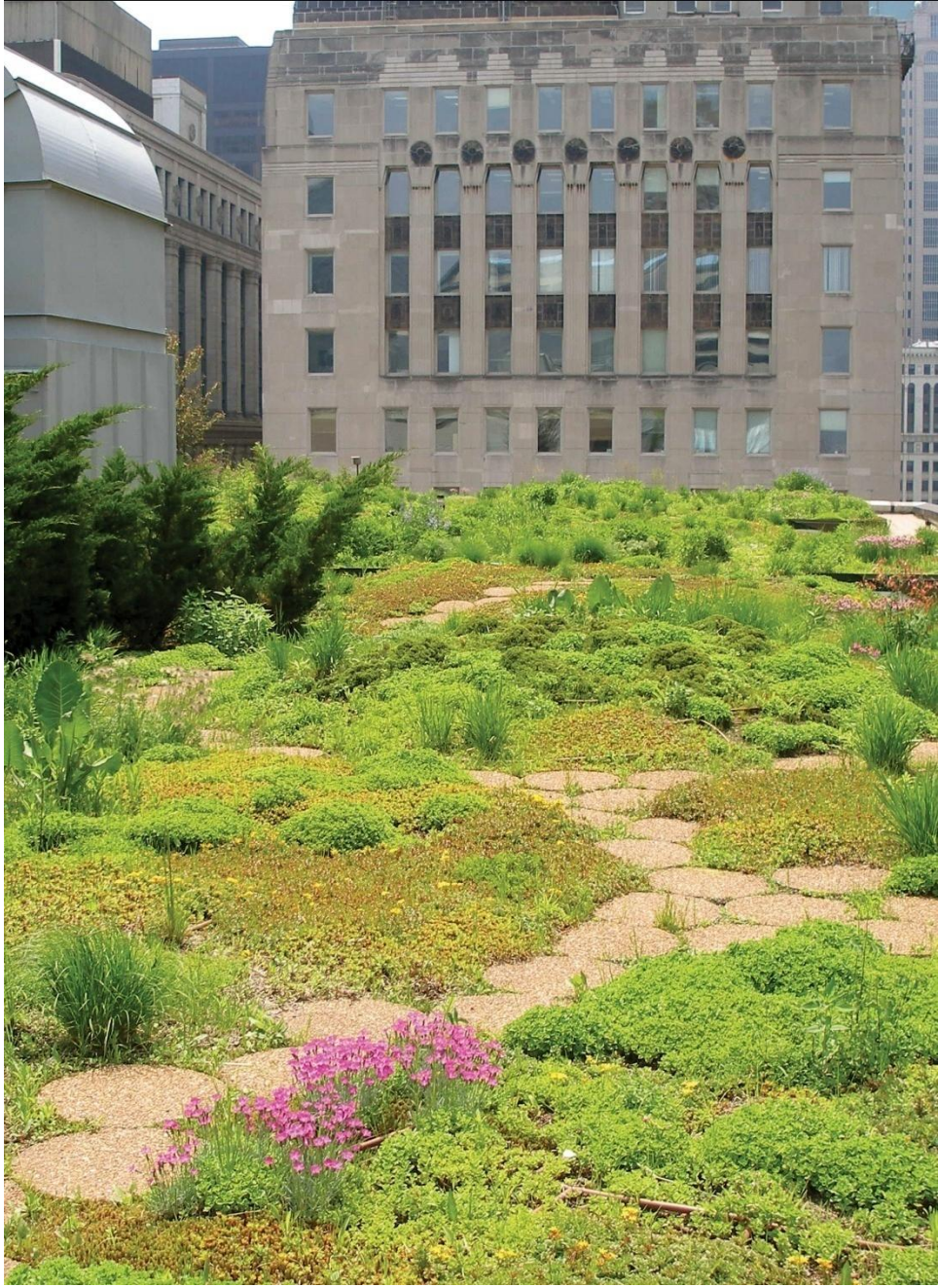
More efficient retention of rainfall

(media absorption + real-time plant uptake)

Peak runoff delay

Runoff peak rate reduction

Improved water treatment



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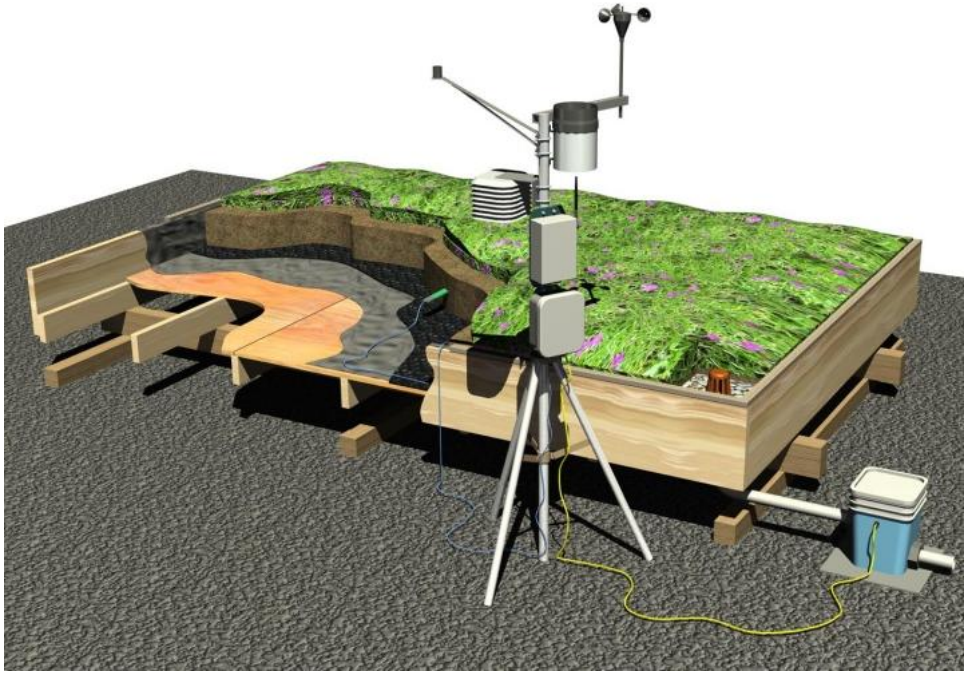
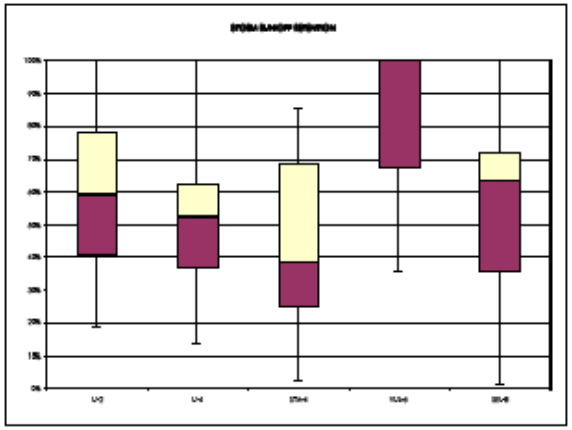
Factors Influencing Performance

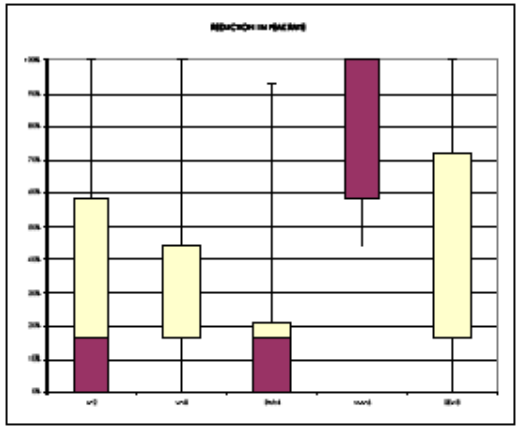
Seattle Public Utilities Green Roof Retrofit Study, Magnuson Klemencic (2007)



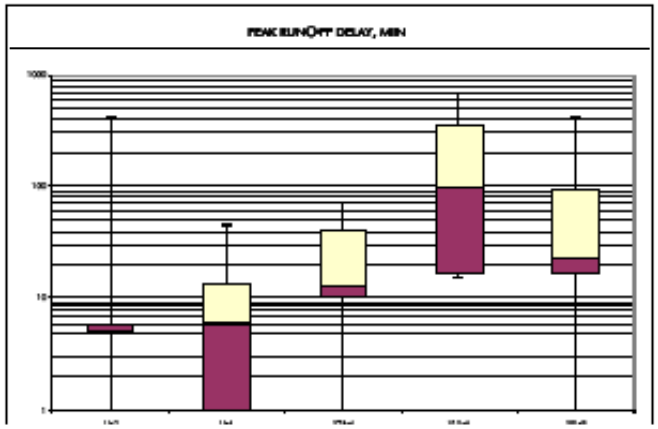
Categorization of green roof systems on basis of **media thickness** alone may not be useful



Retention



Peak attenuation



Runoff delay

Field Scale Measurements

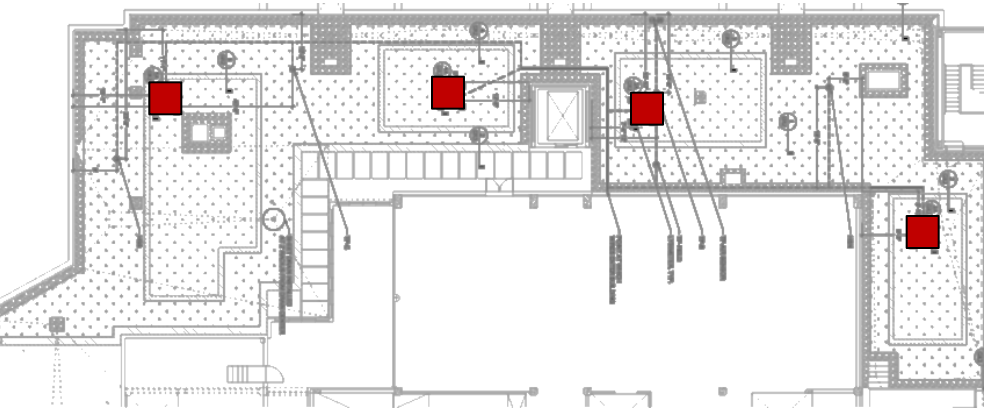
St. Joseph's Green Roof Experiment Station, Philadelphia, PA
Green Roof Performance Investigation (Ongoing; funding by DOE), Michael McCann, PhD

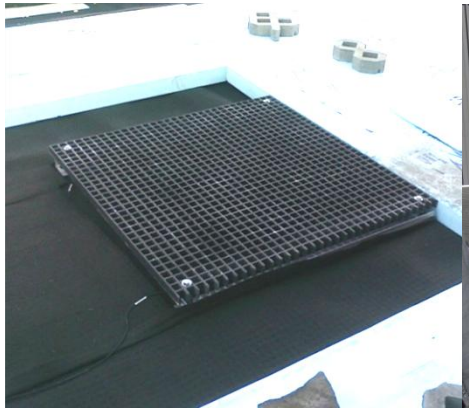
Runoff volume and rate estimated using load cells, rain gauge, and evapotranspiration estimate

Data collected from four 500 sf gravimetric lysimeters

Lysimeters are fully integrated into four distinct green roof areas

(sample moisture movement through a much larger adjacent green roof area)





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Green Roof Assembly Types

St. Joseph's Green Roof Experiment Station, Philadelphia, PA, Michael McCann, PhD

Identical media with 3" thickness

Same plant community (mixed Sedum and perennials)

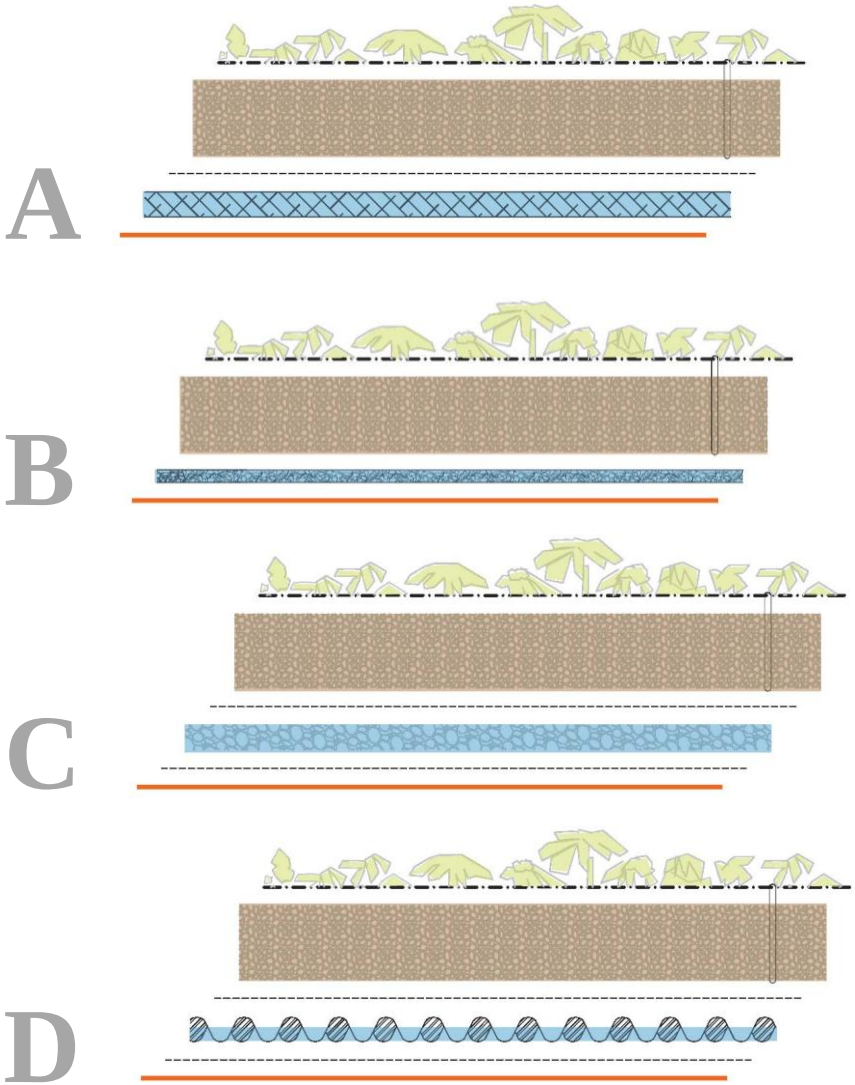
Same surface area

Drainage layer design is the only design variable

Notes: A & C have low-transmissivity drainage layers

B & D have high-transmissivity drainage layers

D includes reservoir water capture of 0.2 inches in plastic cup receptacles



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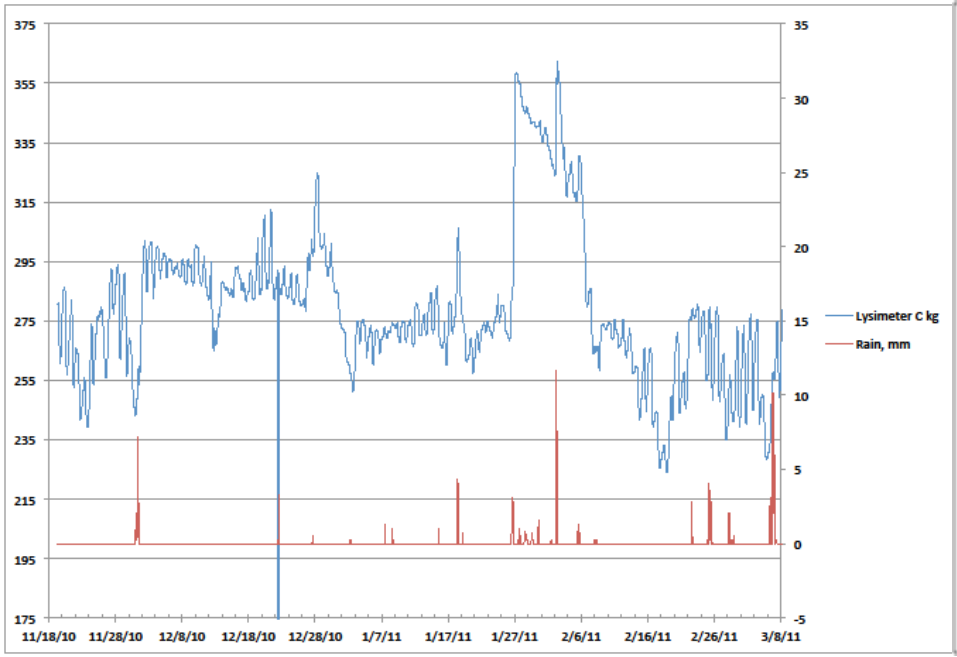
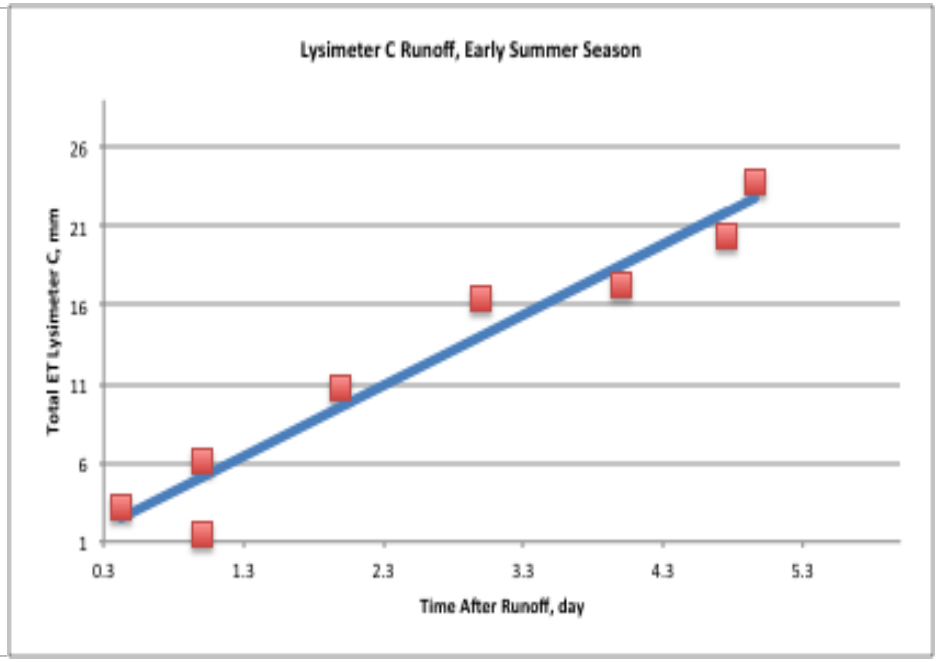
Example Results

St. Joseph's Green Roof Experiment Station, Philadelphia, PA, Michael McCann, PhD



Moisture vs. Rainfall



ET Losses Following Rainfall

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Comparison of Different Assembly Types

St. Joseph's Green Roof Experiment Station, Philadelphia, PA, Michael McCann, PhD

Preliminary conclusions based on one year of data

Results **seasonally averaged** and comparisons normalized to performance of assembly 'B'

Assembly Type	Comparative ET Efficiency '*crop coefficient*' (%)	Comparative Runoff Volume vs. Rainfall Volume (%)	Comparative Runoff Peak Lag Time (%)
A	~200	~80	~300
B	~100	~100	~100
C	~250	~70	~350
D	~150	~90	~260

ET α runoff retention α lag time

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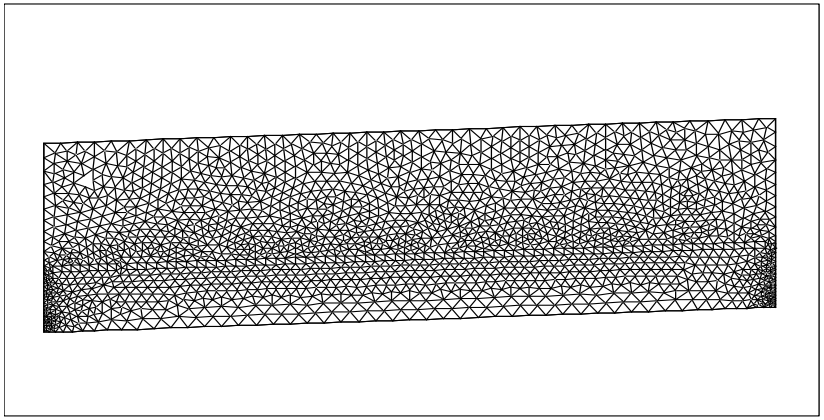
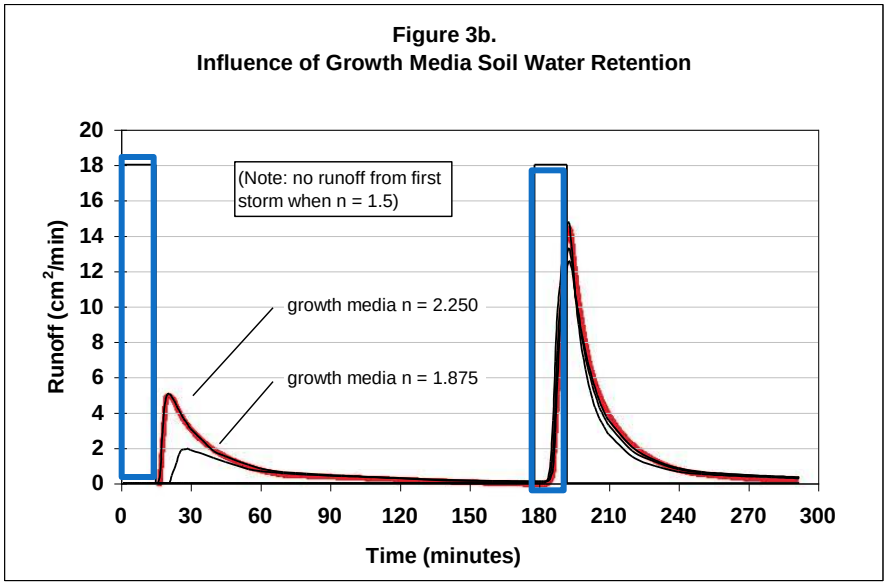
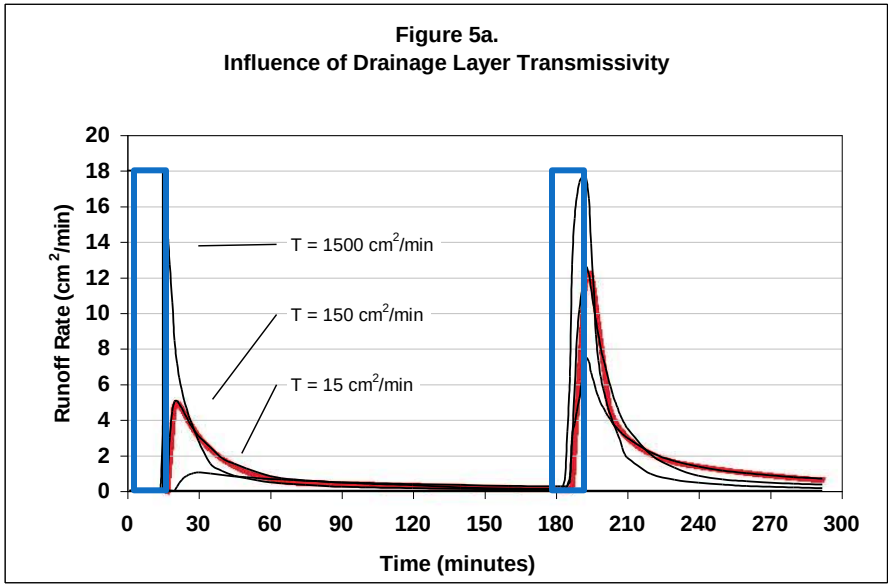
Green Roofs as Shallow Groundwater Systems

Miller (1999), ASCE Seattle



Results of finite element analysis





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How to Understand Green Roofs

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Metrics for Dynamic Behavior

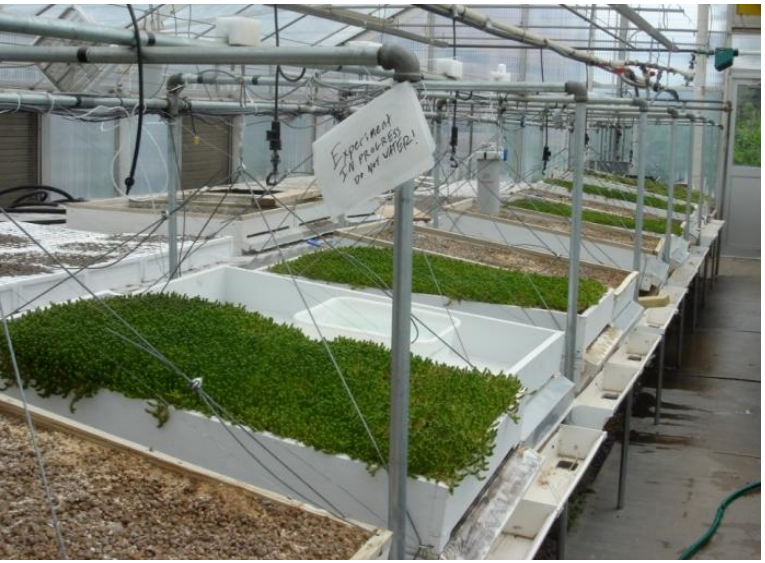
Which bench-scale measurements (existing or future) likely to provide best predictions for:

Lag to peak

Hydraulic residence time for percolated water (or *half-life*)

Seasonal ET uptake ≡ Runoff Reduction

Rational Runoff Coefficient



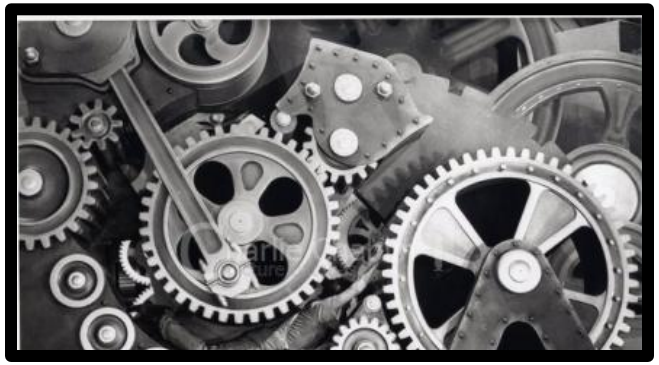
Systems Approach to Performance Testing
Green Roof as Black Box

Green roof assemblies as input-output systems

Focus on dynamic responses to applied stimuli

Measure simple parameters that are good indicators of field performance

INPUT



OUTPUT

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Anticipating Performance Changes Over Time

Moisture Uptake

Hydrologic Response

Soil Chemistry and Runoff Water Quality

Plant Type and Diversity

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Five-Part Coordinated Strategy

1| SMALL SCALE - measure **dynamic** response of an assembly at lab scale

2| MEDIUM SCALE - measure **dynamic** response at a field pilot scale

3| LARGE SCALE - measure **dynamic** response at full scale (in which geometric effects may become significant)

4| Determine which types of lab scale measurements are most likely to provide useful predictions of field behavior

5| Develop predictive algorithms that can reasonably be used by engineers to design for function and regulators to set achievable metrics for compliance

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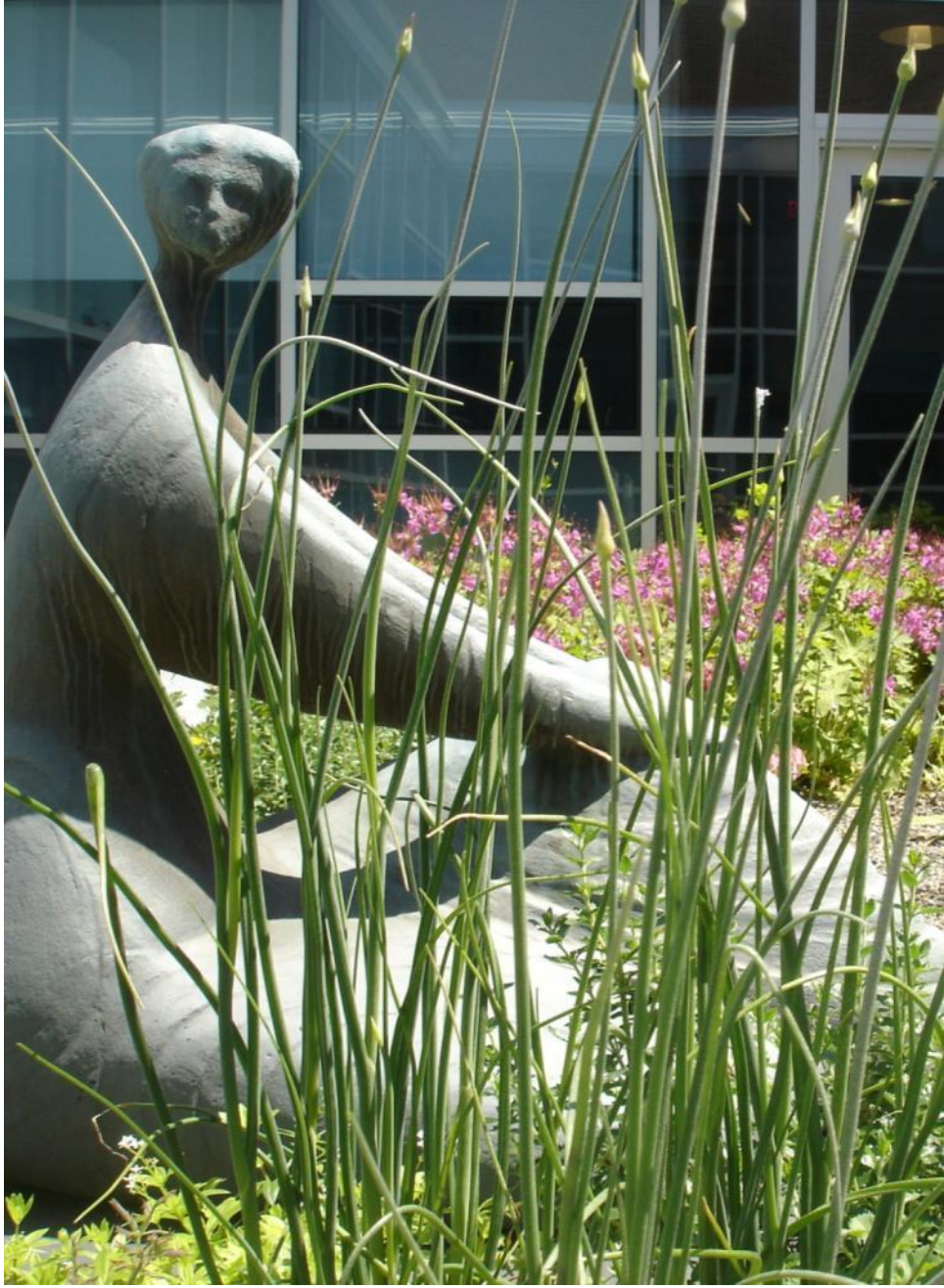

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SPARE SLIDES

Load Evaluation is Critical for Retrofit Projects

Wet and compressed soil

Stored free water

Mature plants

Miscellaneous fabrics

ASTM E2397)

No stable media is less dense than 50 pcf

Do the math!

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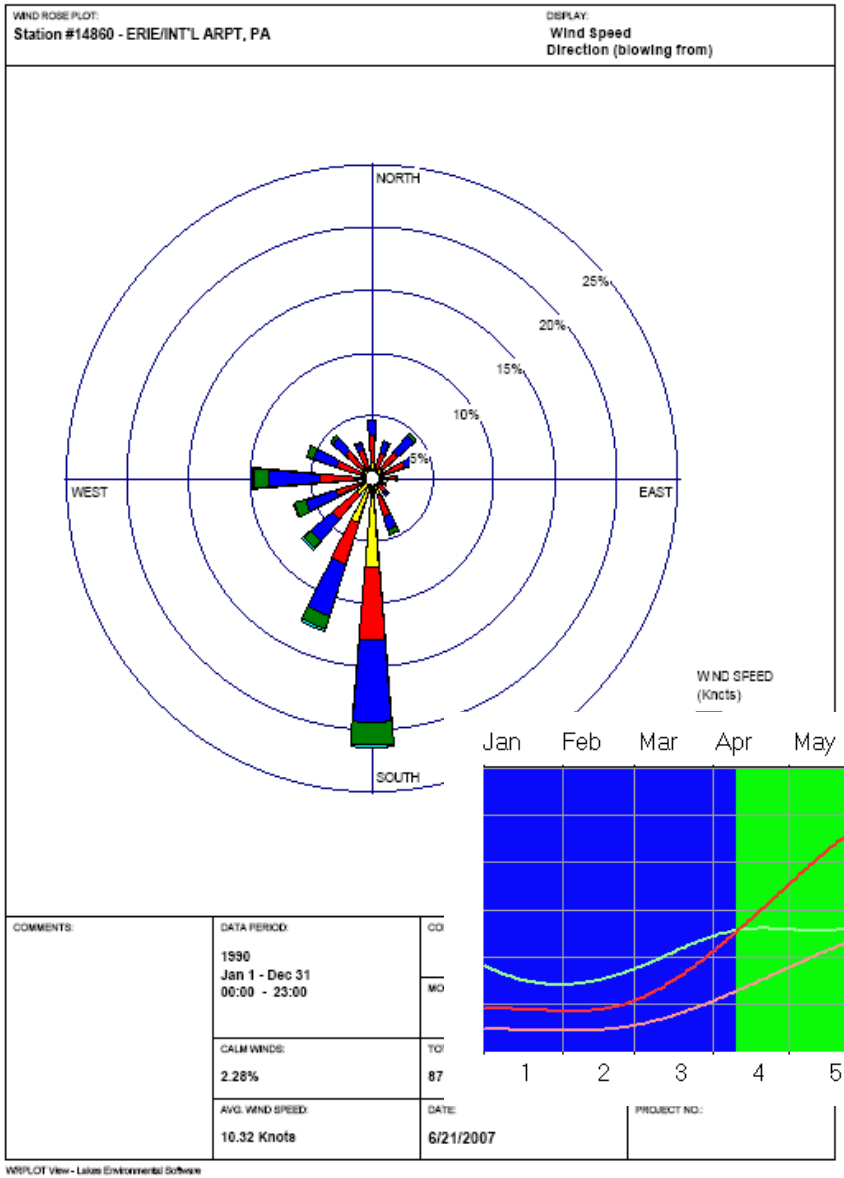
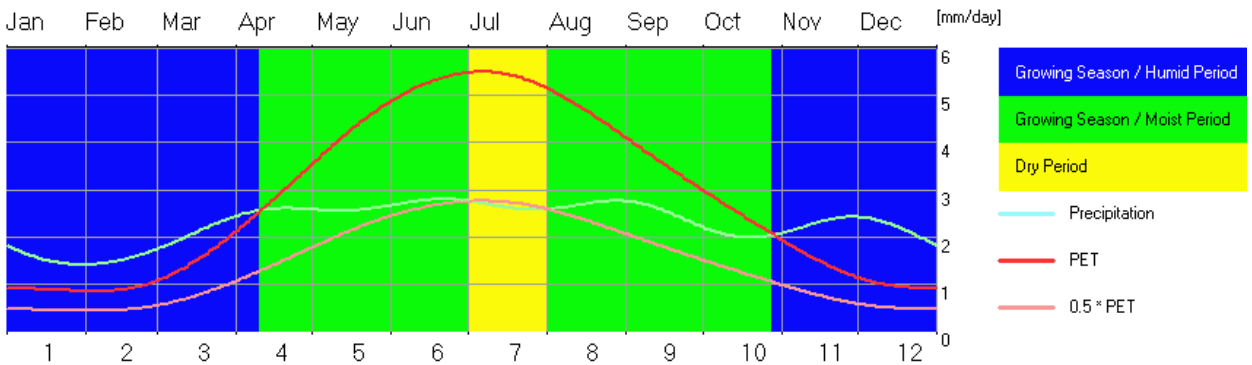
Micro- Climate Analysis





Aridity Index (Summer Rainfall/PET)

Frost Zone

Heat Zone

Wind intensity

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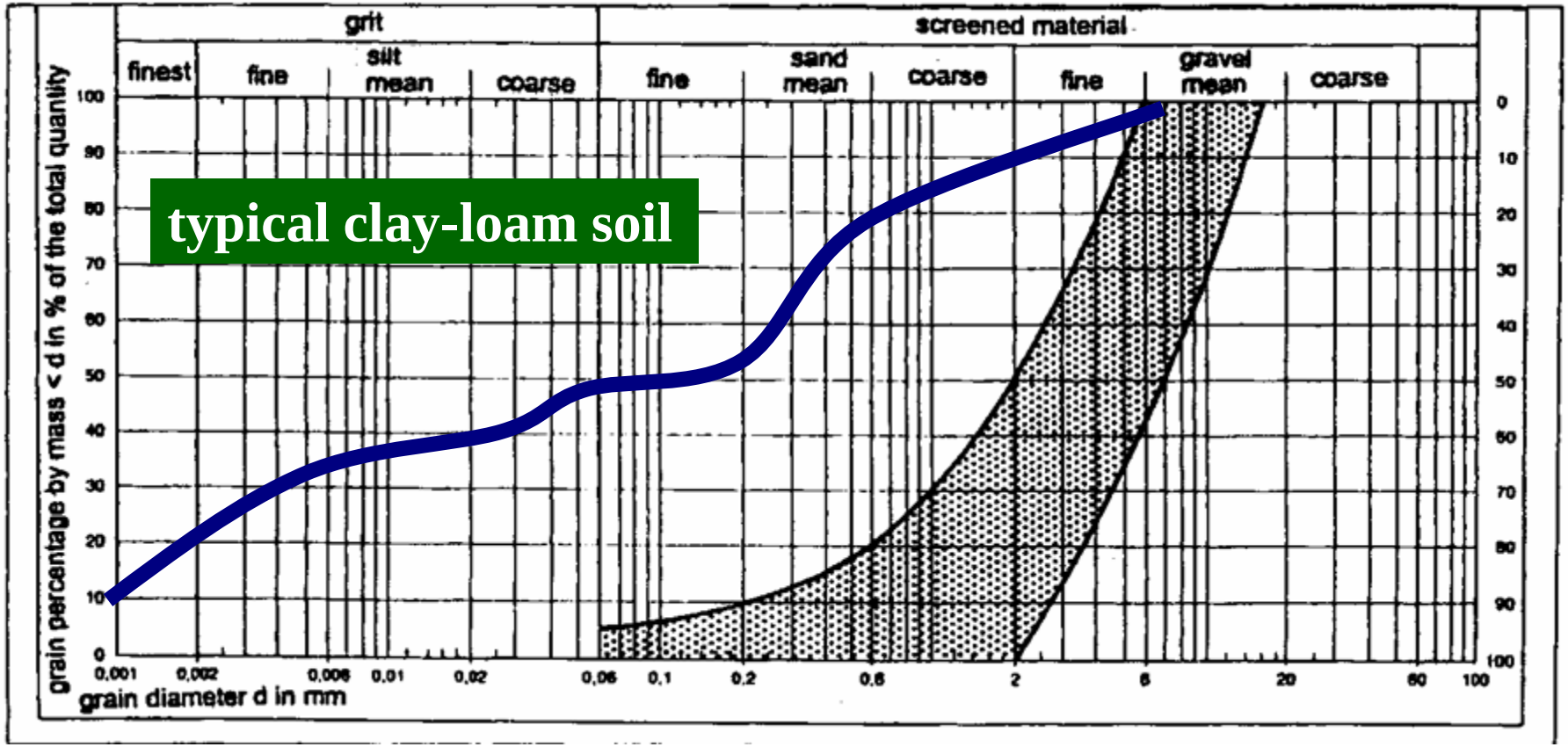
Metrics

USA STANDARD TESTING SIEVE
3/8 IN.
ELE
weight-pounds
total $ price

ANSI/SPRI Root-Resistance Standard

Grain-size Distribution Range for Vegetation Substrates



Implications of Load

Dry Density pcf	Wet Density pcf	Thickness in	System Dry Weight Psf	System Wet Weight psf	Relative System Cost
55	75	3	15	22	1
45	65	3	13	20	1.2
35	55	3	10 *	17	1.4

* Minimum accepted ballast weight for green roof cover systems (SPRI/ANSI)

Typical green roof media has a wet density of 75-80 pcf

Moisture retention of green roof media is 35-40%

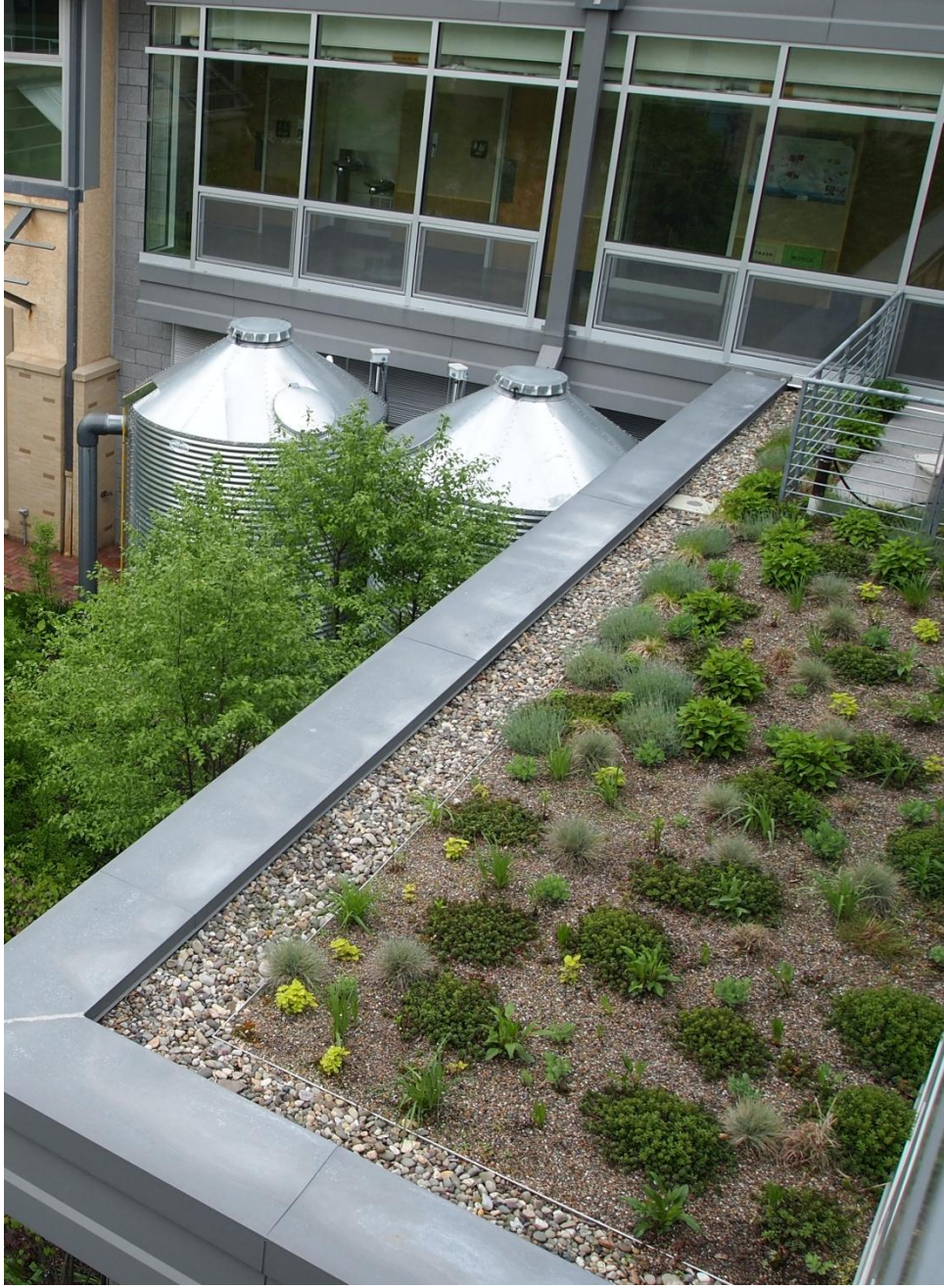
Drainage Layer Detention Volume

Moisture Holding Capacity

ASTM E2399 and E2397

Growth media:	30 - 45% of thickness
Reservoir sheet:	10 - 25% of thickness
Granular drainage layer:	5 - 15% of thickness
Synthetic mat*:	5 - 50% of thickness

* Typically only ¼” thick



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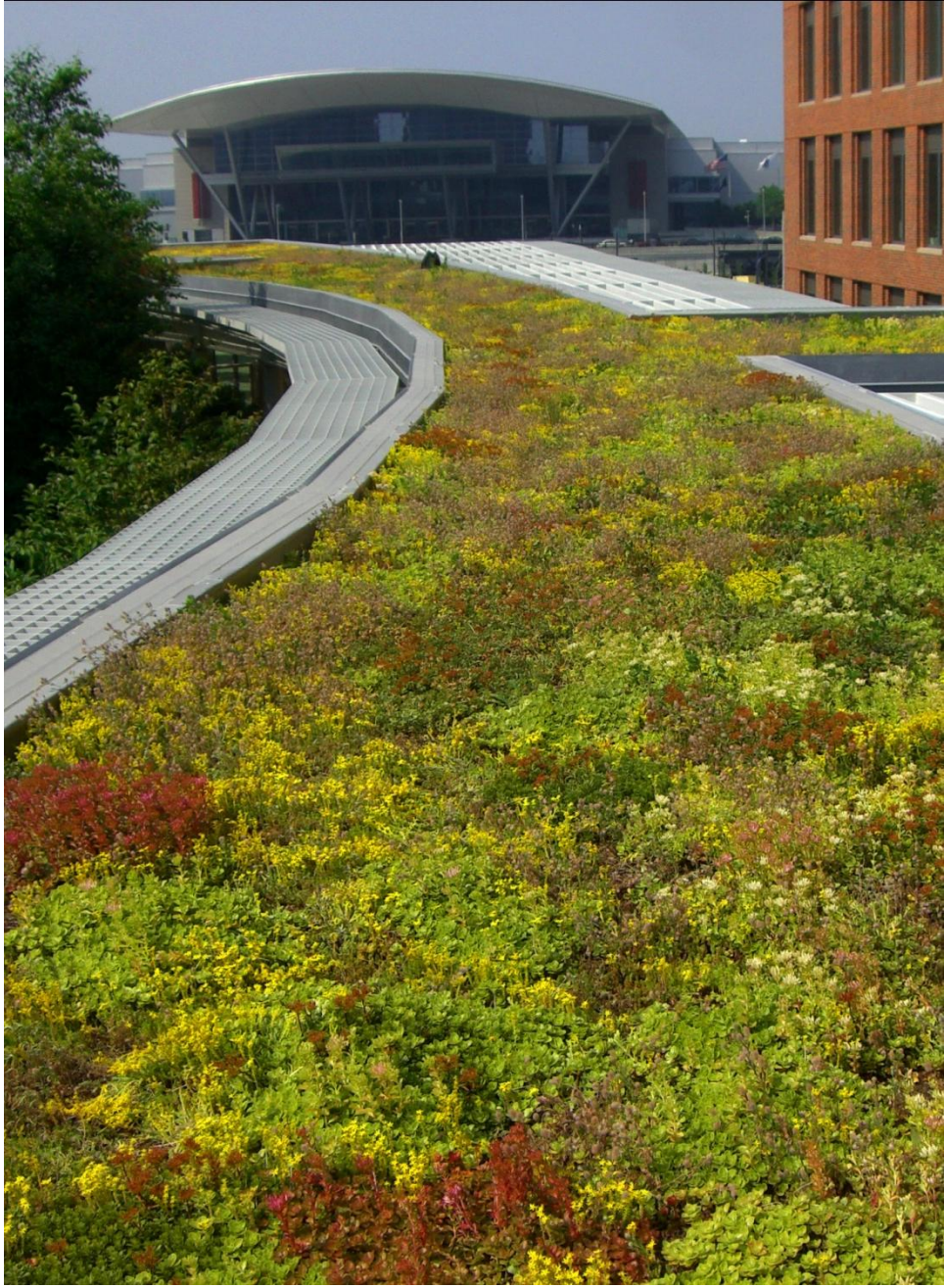

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