

Comparing SWMM LID Module Results to Field Studies' Data

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Outline

https://www.louisberger.com/our-work/project/hoboken-green-infrastructure-strategic-plan-new-jersey-us

- Introductions
- Urban Watersheds
- Water Infrastructure
- Models
  - EPANET – Drinking Water
  - SWMM – Storm and Waste Water
- Ground-truthing models
  - Uncertainty
  - Calibration
  - Testing\Validation
- Conclusions
- Discussions

EPA

Introduction

Michelle Simon

BS Chemical Engineering, University of Notre Dame
MS Chemical Engineering, Colorado School of Mines
PhD Environmental Science,
Minor Chemical Engineering, University of Arizona

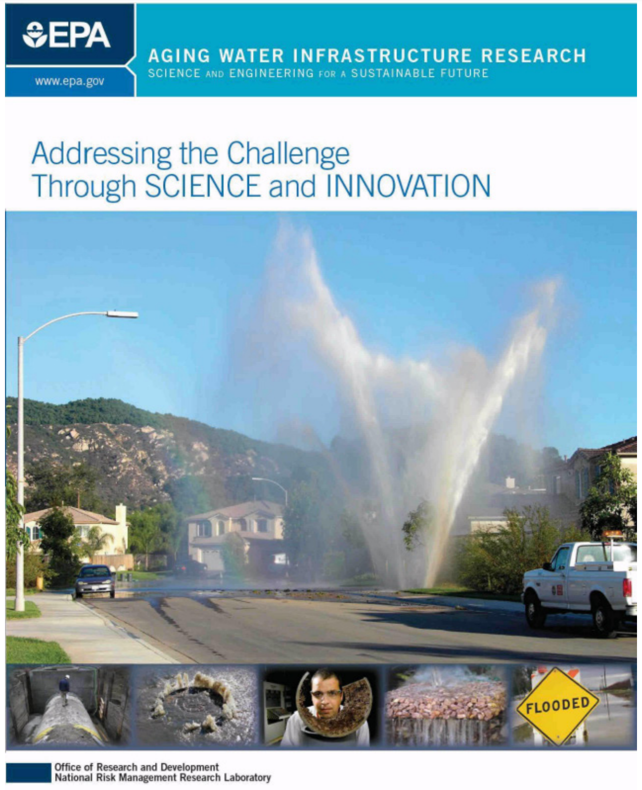
Went to US EPA in 1990 – Vadose Zone and Groundwater

Worked on Superfund Site Cleanup until 2010

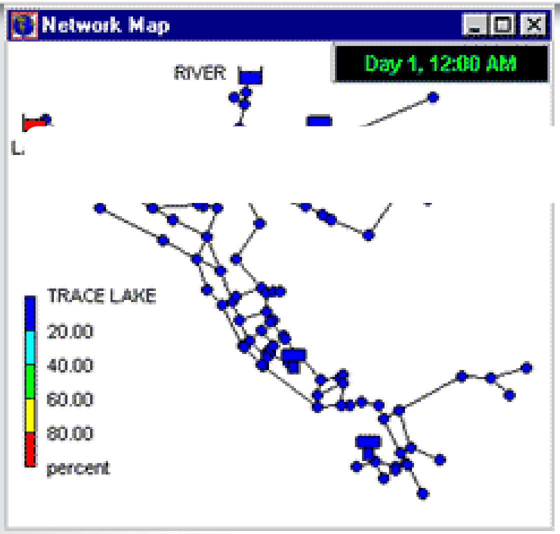
Since then, I worked on Storm Water Run-off

Aging US Water Infrastructure

- ASCE Grade D +
- Drinking Water
- Storm Water and Waste Water
- https://www.infrastructurereportcard.org/
- https://www.infrastructurereportcard.org/wp-content/uploads/2016/10/ASCE-Failure-to-Act-2016-FINAL.pdf

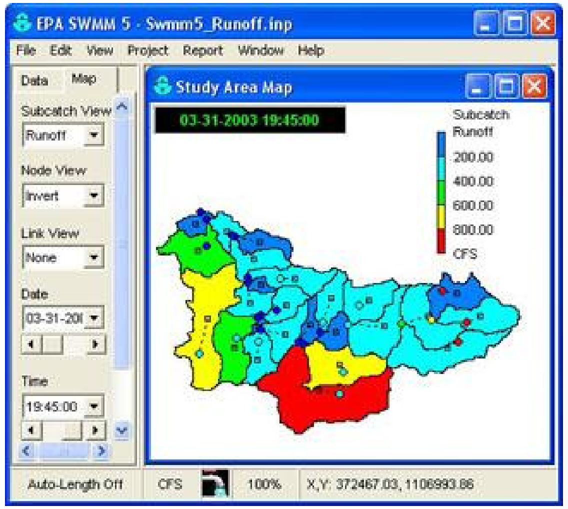


How to Upgrade the Infrastructure



Drinking Water – EPANET

https://www.epa.gov/water-research/epanet



Storm Water and Waste Water – Storm Water Management Model - SWMM

https://www.epa.gov/water-research/storm-water-management-model-swmm

SWMM Contains Green Infrastructure

SWMM was developed in 1970's, and then redeveloped by Dr. Lew Rossman (EPA 1978 – 2014 emeritus) in the 2000s

Accuracy\Uncertainty

- Physical Reality
- Scientific Understanding
- Mathematical Abstraction
- Program
- Parameter estimation
- Results, compared to observations
- Repeat

What is a model?

A useful simplification of a complex reality

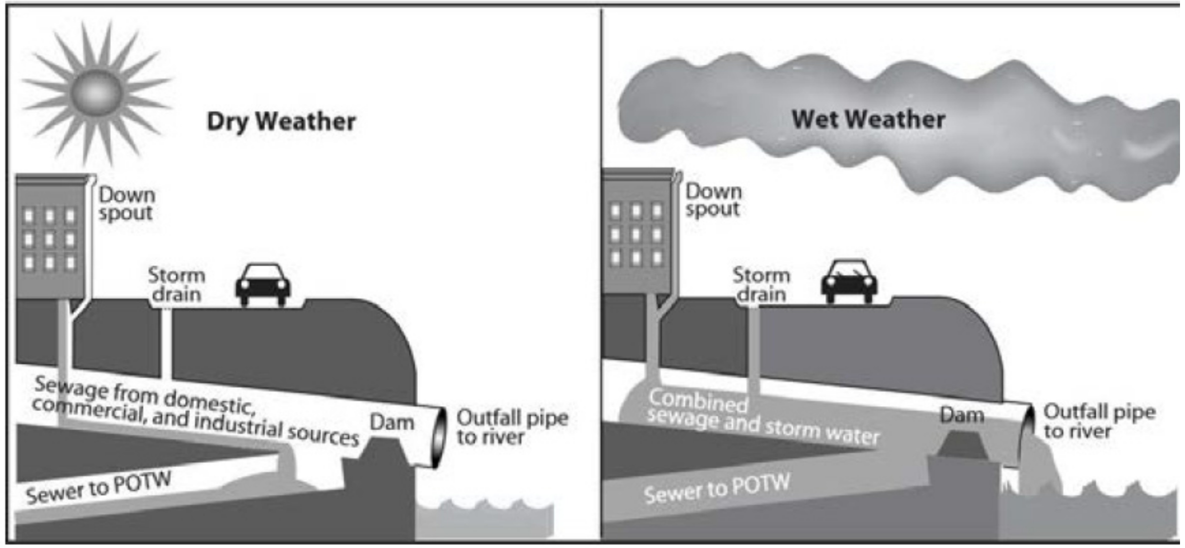
Abstraction

Fidelity — Behavior / Mechanism

What's the goal?

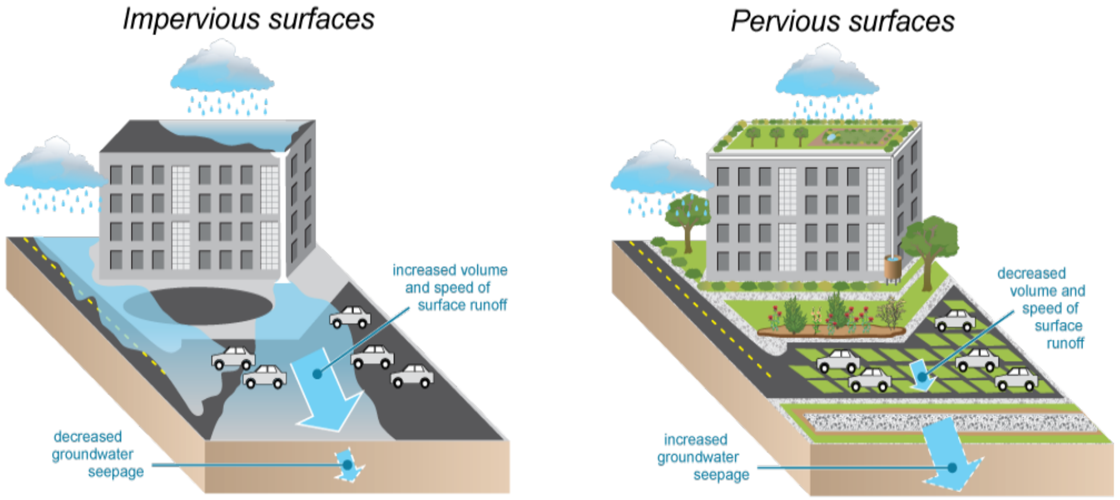
https://www.google.com/search?q=mathematical+abstraction+of+hydrology+images&tbm=isch&source=iu&ictx=1&fir=eDv9KY_znXaWlM%253A%252CYzICHXicd0xv_M%252C_&usg=AI4_-kS544Xrnn5UpDuff0UJU6D1Tpt-VA&sa=X&ved=2ahUKEwjT0vG6jb7eAhXN0VMKHWipC30Q9QEwAHoECAQQBA#imgdii=j7R4otA9j2apTM:&imgrc=B3LrwJmLR84z9M:

Combined Sewer Overflows



Source: U.S. Environmental Protection Agency

Figure 4. Combined Sewer Systems



Impervious 'hard' surfaces (roofs, roads, large areas of pavement, and asphalt parking lots) increase the volume and speed of stormwater runoff. This swift surge of water erodes streambeds, reduces groundwater infiltration, and delivers many pollutants and sediment to downstream waters.

Pervious 'soft' surfaces (green roofs, rain gardens, grass paver parking lots, and infiltration trenches) decrease volume and speed of stormwater runoff. The slowed water seeps into the ground, recharges the water table, and filters out many pollutants and sediment before they arrive in downstream waters.

Conceptual diagram illustrating impervious and pervious surfaces. Impervious surfaces are hard and increase stormwater runoff, causing pollutant and sediment delivery in downstream waters. Pervious surfaces are soft and decrease stromwater runoff, which filters out pollutants and sediments before they arrive in downstream waters.
Diagram courtesy of the Integration and Application Network (ian.umces.edu), University of Maryland Center for Environmental Science. Source: Chesapeake and Atlantic Coastal Bays Trust Fund, 2013. Stormwater Management: Reducing Water Quantity and Improving Water Quality. IAN press, newsletter publication.

Source: U.S. Department of Environmental Protection

Figure 5. How Green Infrastructure Works

http://phci.rutgers.edu/wp-content/uploads/2016/07/Hoboken-Stormwater-HIA_FinalReport_v9-19-16.pdf

City of Hoboken, New Jersey
Proposed Stormwater Management Plan
Health Impact Assessment (HIA)

Final Report

Last Revised: 9/19/2016

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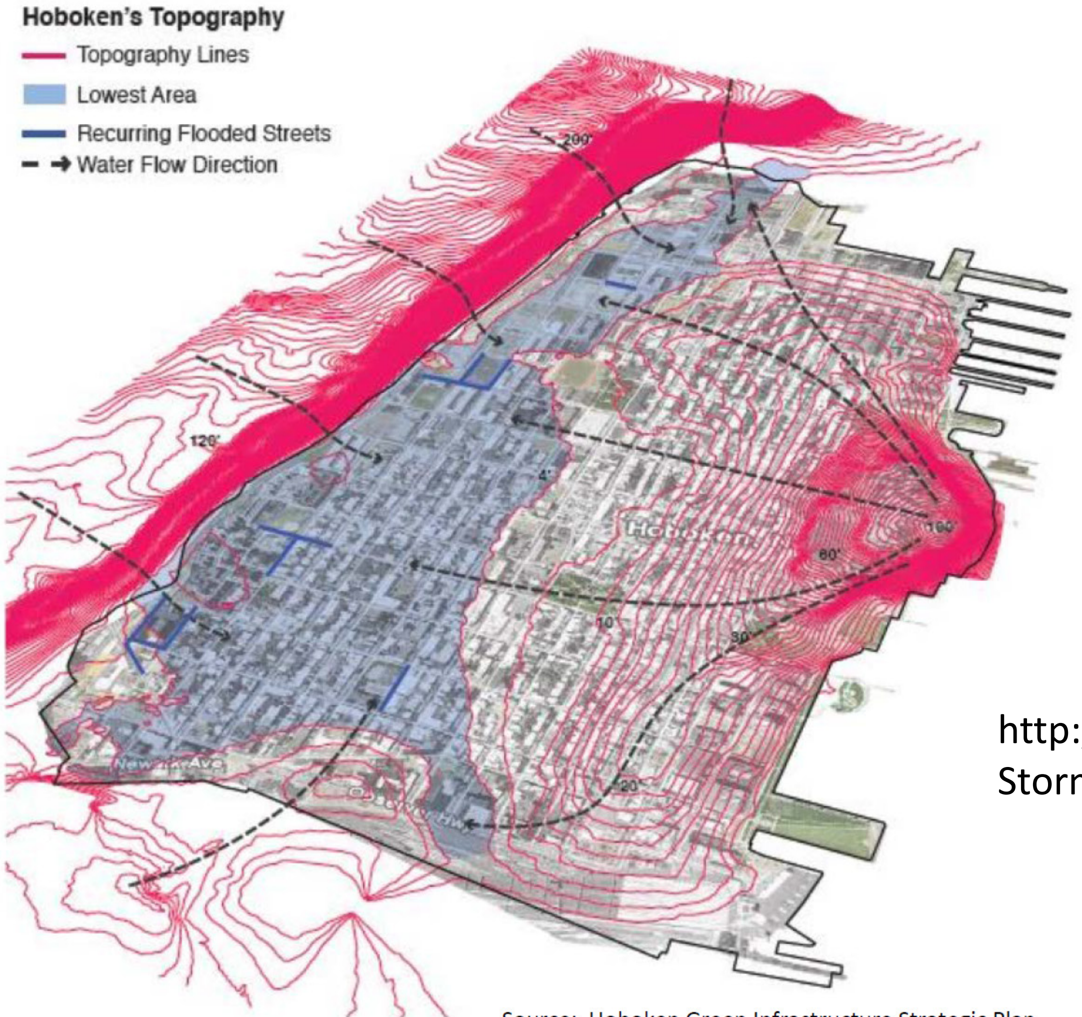
ACKNOWLEDGEMENTS

The authors would like to thank the many individuals and organizations that provided input to and feedbac
the study design, research protocols, and draft report. In particular Amber Lenhart from The Health Impact Project, a collaboration of the Robert Wood Johnson Foundation and The Pew Charitable Trusts, James Dills
from the Georgia Health Policy Center at Georgia State University and Teri Jover of New Jersey Future. Additionally, we thank Jeanne Herb and Dr. Karen Lowrie at Rutgers University. We would especially like to thank the many stakeholders who participated in this process, including the HIA Advisory Committee that included the following individuals:

- Marty Anderson, Hoboken Green Team
- Christina Butieb Bianco, Hudson Regional Health Commission
- Chris Brown, City of Hoboken, Planning Department
- Deborah Costa, FEMA
- Jamaal Cummings, FEMA
- Elizabeth Fassman-Beck, Steven's Institute of Technology
- Marisa Muscchio Gerke and Dominique Tornabe, HOPES CAP
- Francesca Giarratana, Hudson County Planning Department
- Jennifer Gonzalez, Hoboken Green Team
- Joseph Hurley, Hudson County OEM
- Rabi Kieber, USEPA Region 2
- Joann Lowry, FEMA
- Marianne Luhrs, FEMA
- Stephen Marks, City of Hoboken, Administration
- Fred Pocci, North Hudson Sewage Authority
- Frank Sasso, City of Hoboken, Health Departmer
- Caleb Stratton, City of Hoboken, Planning Department
- Nancy Tarantino, City of Hoboken, Health Department
- Dana Wefer, Hoboken Housing Authority

http://phci.rutgers.edu/wp-content/uploads/2016/07/Hoboken-Stormwater-HIA_FinalReport_v9-19-16.pdf

Flooding in Hoboken



Source: Hoboken Green Infrastructure Strategic Plan

Figure 1. Hoboken Topography Overlaid with Water Flow & Recurring Flooded Streets

http://phci.rutgers.edu/wp-content/uploads/2016/07/Hoboken-Stormwater-HIA_FinalReport_v9-19-16.pdf

Flooding in Hoboken May 31, 2015

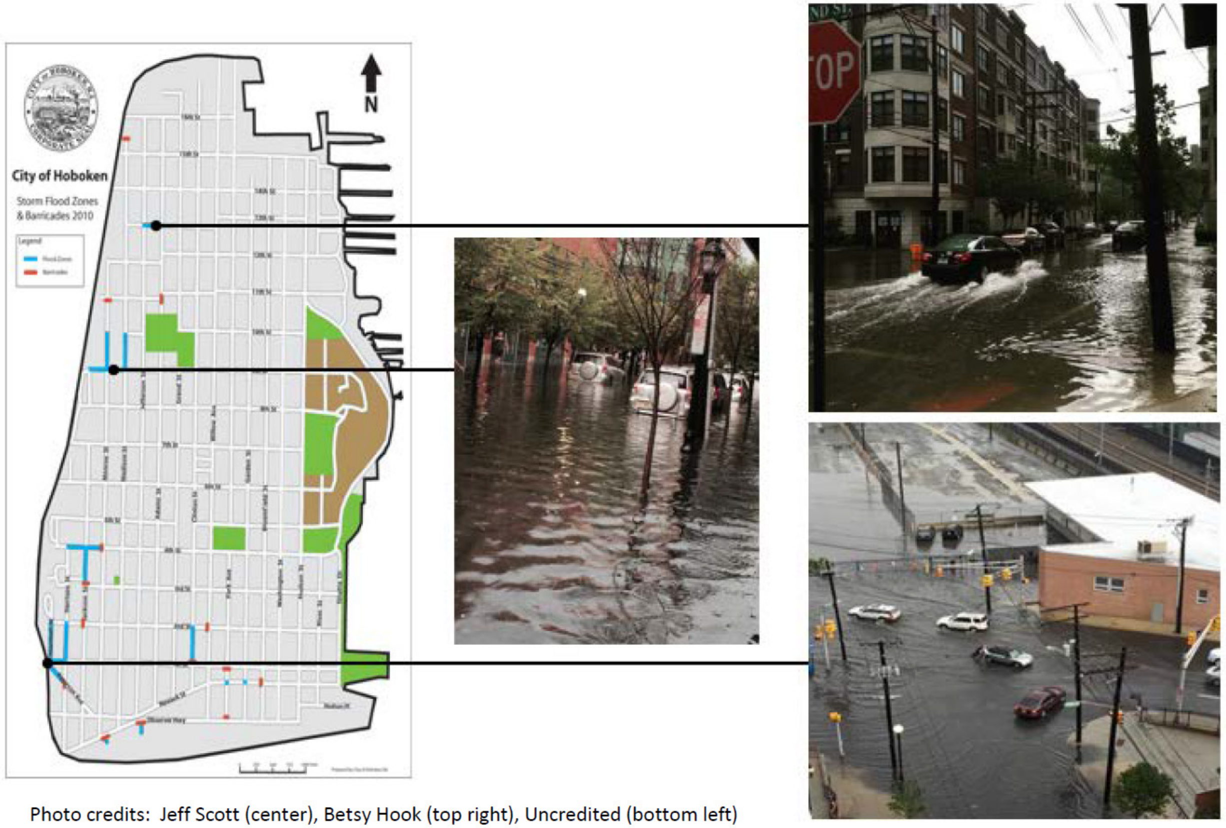
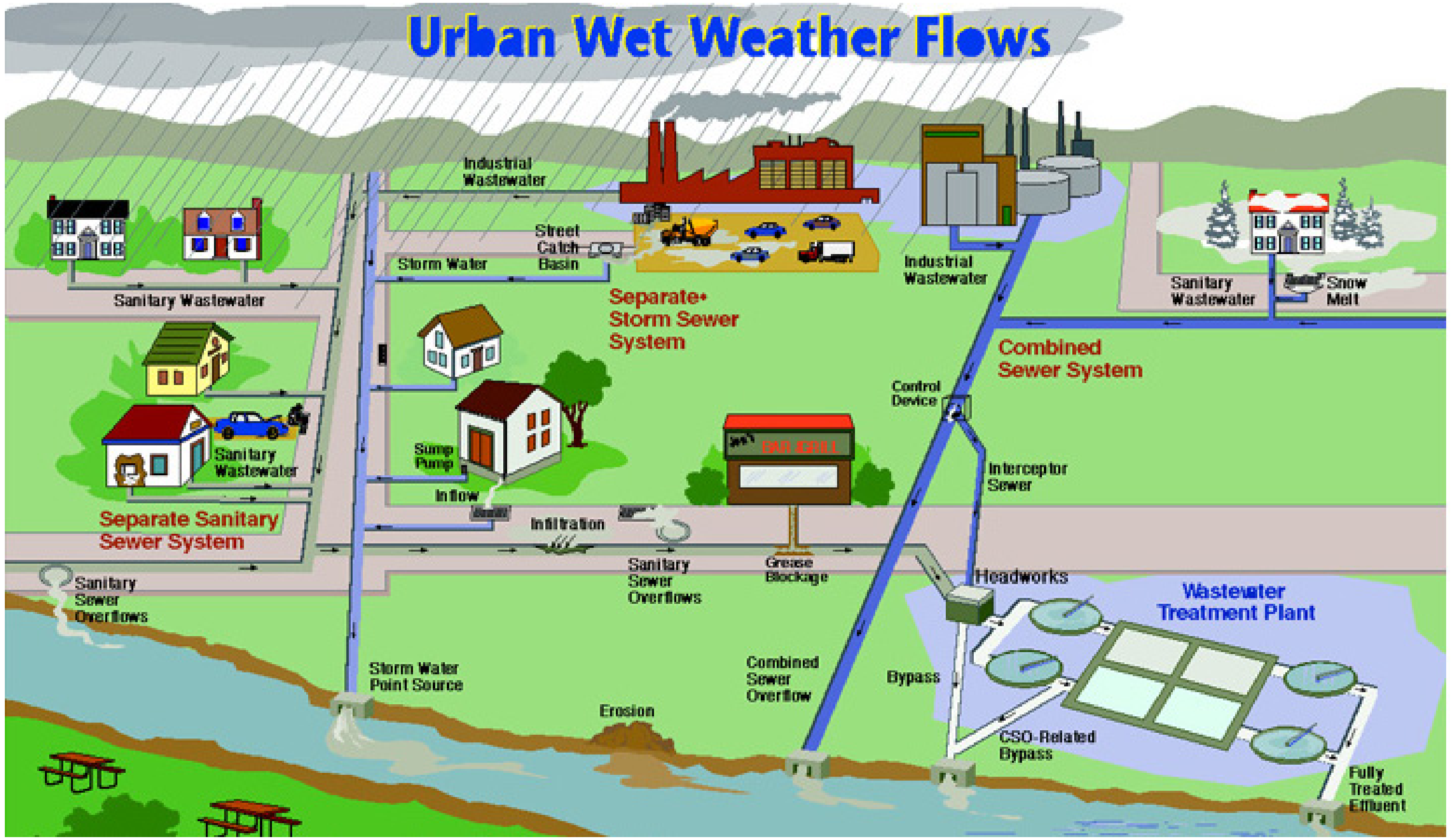


Photo credits: Jeff Scott (center), Betsy Hook (top right), Uncredited (bottom left)

Figure 3. Flooding in Hoboken, May 31, 2015

http://phci.rutgers.edu/wp-content/uploads/2016/07/Hoboken-Stormwater-HIA_FinalReport_v9-19-16.pdf

What is SWMM?



SWMM is a public domain, distributed, dynamic hydrologic - hydraulic - water quality model used for continuous simulation of runoff quantity and quality from primarily urban areas.

What is SWMM Used For?

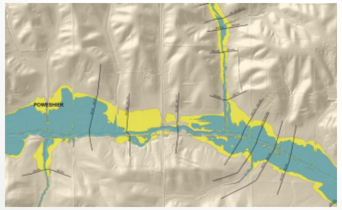
Design and sizing of drainage system components.

Control of combined and sanitary sewer overflows.

Modeling Inflow & Infiltration in sanitary sewer systems.

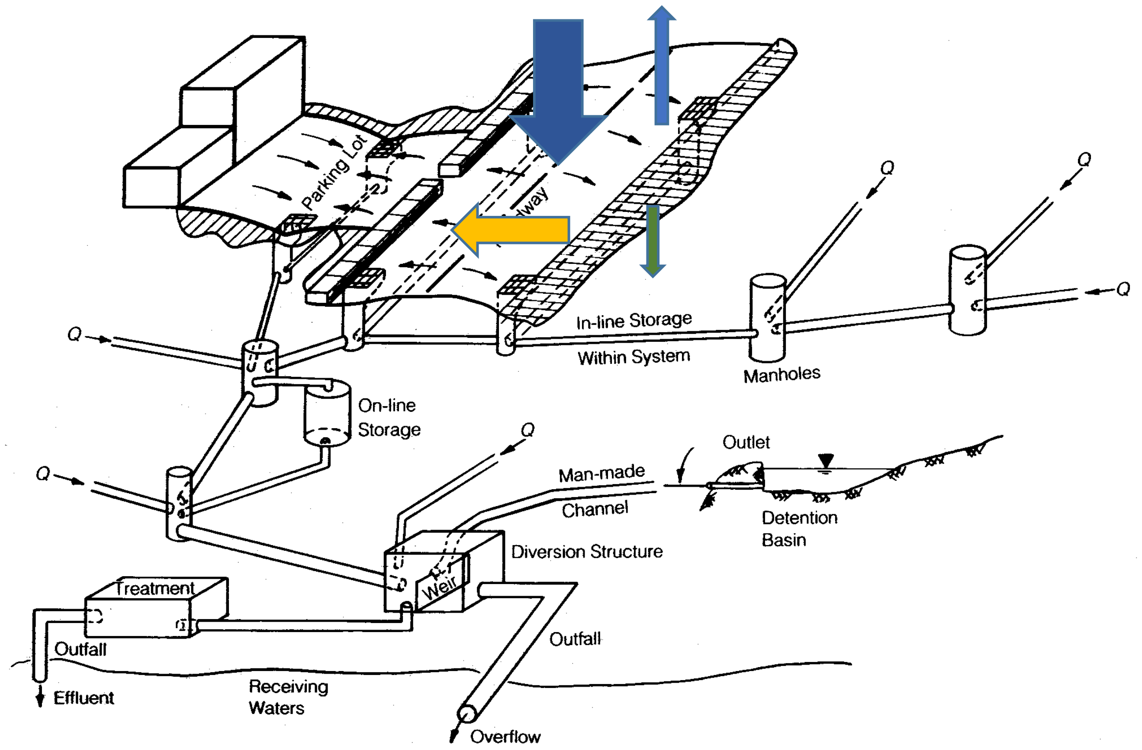
Generating non-point source pollutant loadings for load allocation studies.

Evaluating green infrastructure for sustainability goals.



Flood plain mapping of natural channel systems.

How does SWMM Model?



SWMM is a **distributed**, **dynamic rainfall-runoff** simulation model used for **single event** or long-term (**continuous**) simulation of runoff quantity and quality from **primarily urban** areas.

Hydrology – Governing equations

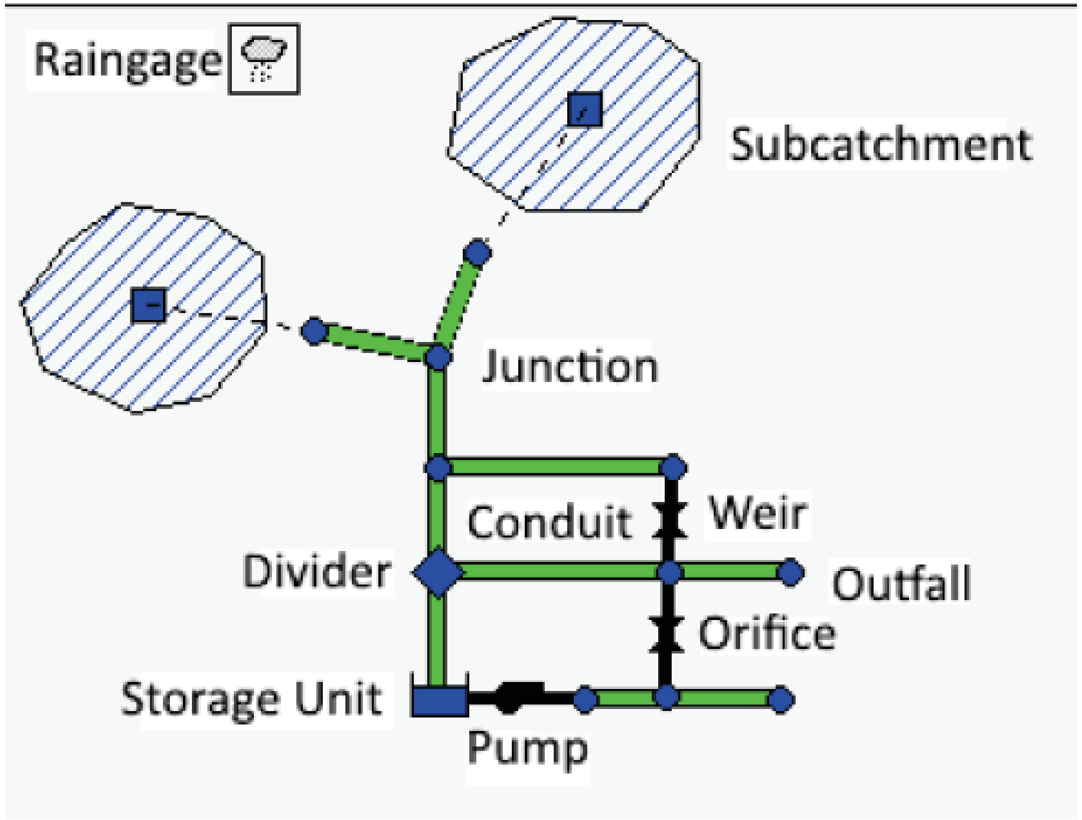
$$\frac{\partial d}{\partial t} = i - e - f - q$$

where:

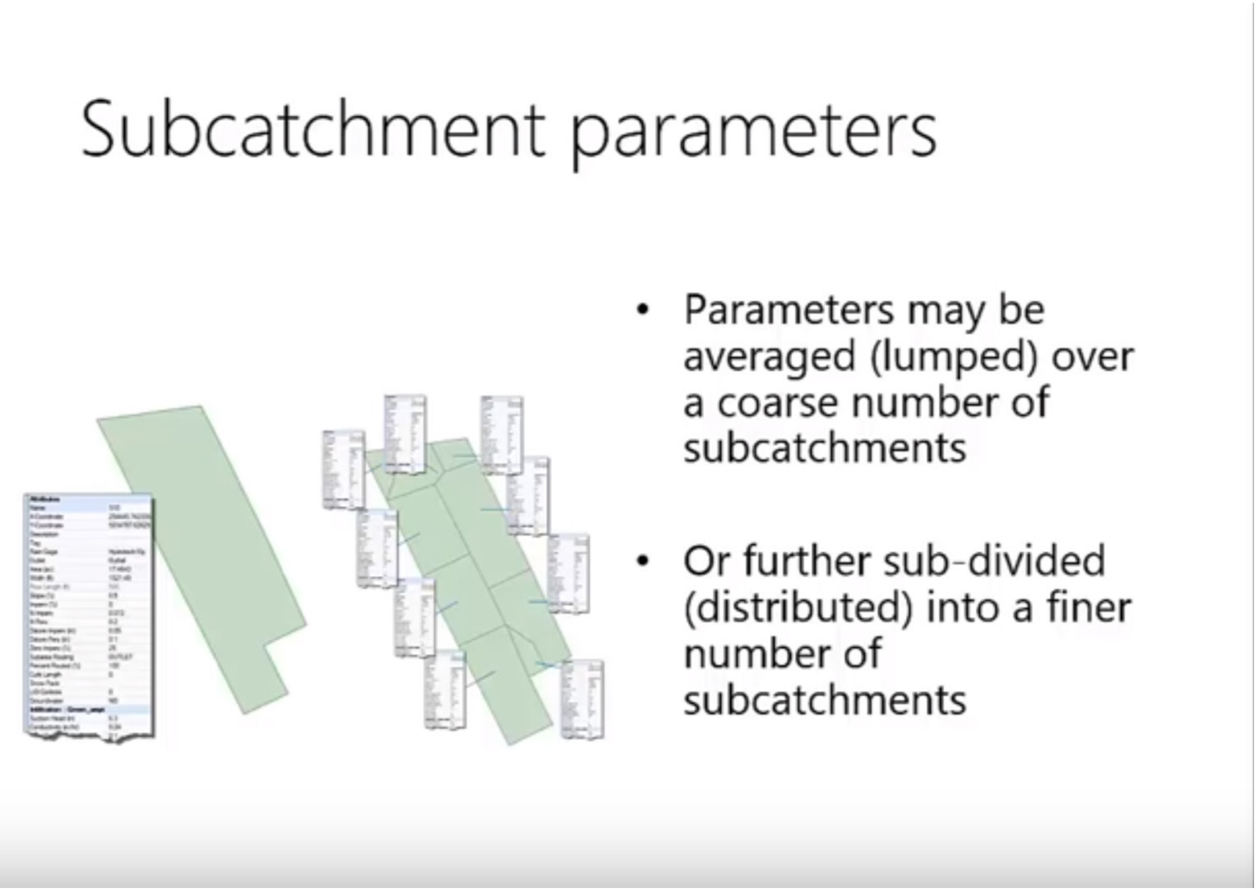
i	=	rate of rainfall + snowmelt (ft/s)
e	=	surface evaporation rate (ft/s)
f	=	infiltration rate (ft/s)
q	=	runoff rate (ft/s).
d	=	depth (ft)
t	=	time (s)

SWMM Hydrology Reference Manual Equation 3-1

SWMM's Conceptual Model

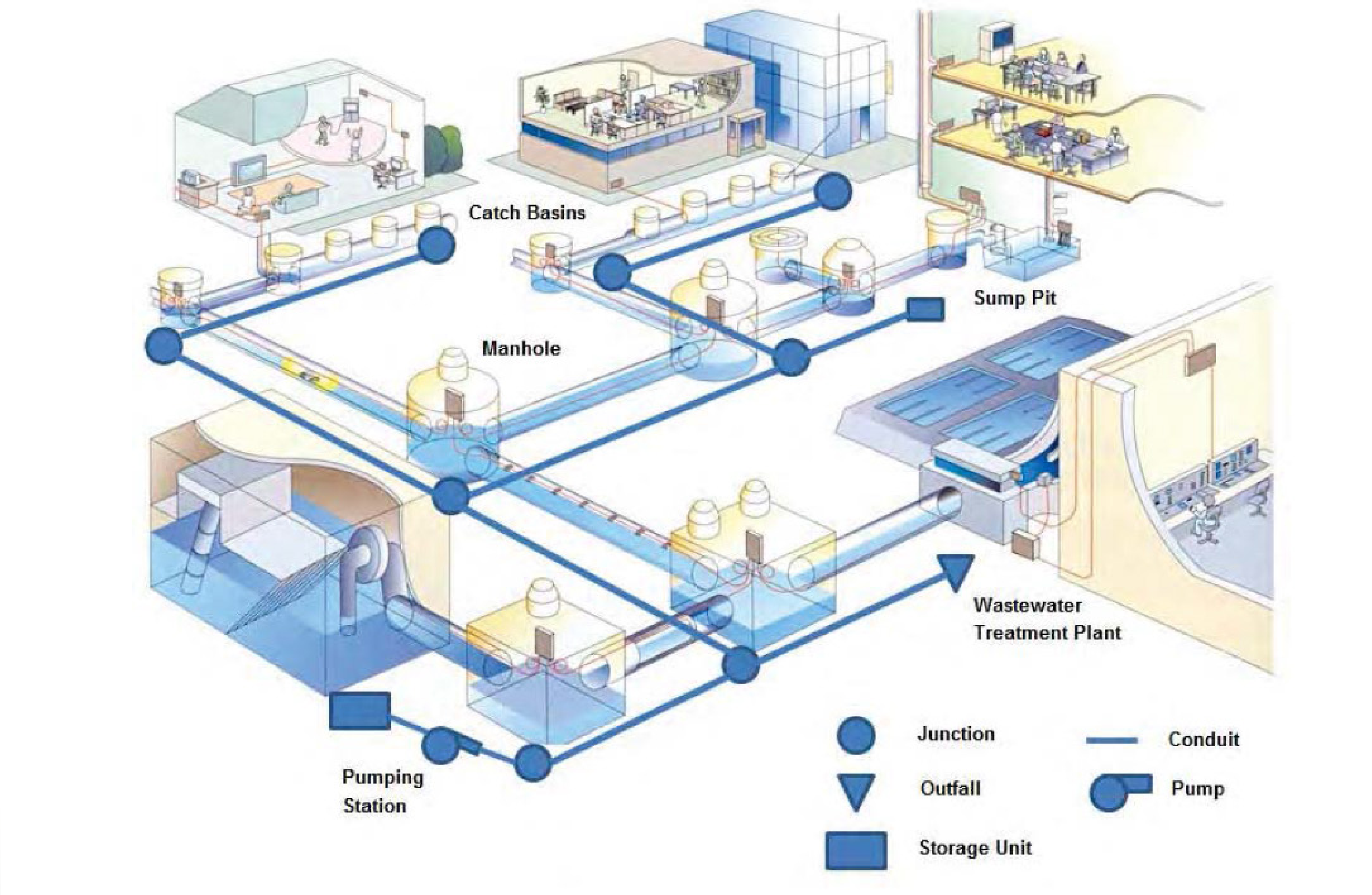


Idealized Subcatchment
(Courtesy of Rob James, CHI Water, www.openswmm.org)



https://www.youtube.com/watch?v=HZnX_GsABUA

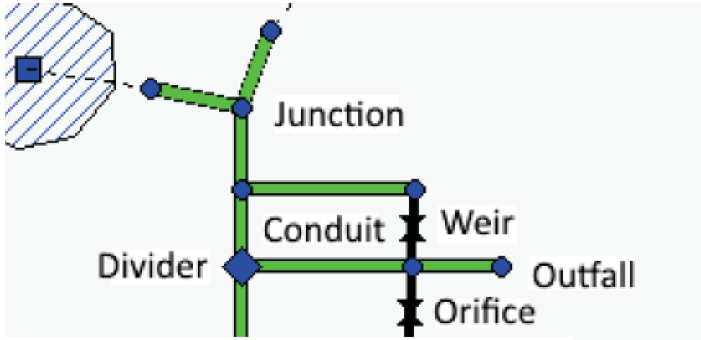
Hydraulic Model



Hydraulic Governing Equations
https://www.youtube.com/watch?v=ziWy5qbVIWo

Continuity – also used in EPANET

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} =$$



where

x	=	distance (ft)
t	=	time (sec)
A	=	flow cross-sectional area (ft^2)
Q	=	flow rate (cfs)

SWMM Hydaulics Reference Manual Equation 3 - 1

Hydraulic Governing Equations

Momentum – also used in EPANET

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2/A)}{\partial x} + gA\frac{\partial H}{\partial x} + gAS_f = 0$$

H	=	hydraulic head of water in the conduit ($Z + Y$) (ft)
Z	=	conduit invert elevation (ft)
Y	=	conduit water depth (ft)
S_f	=	friction slope (head loss per unit length)
g	=	acceleration of gravity (ft/sec^2)

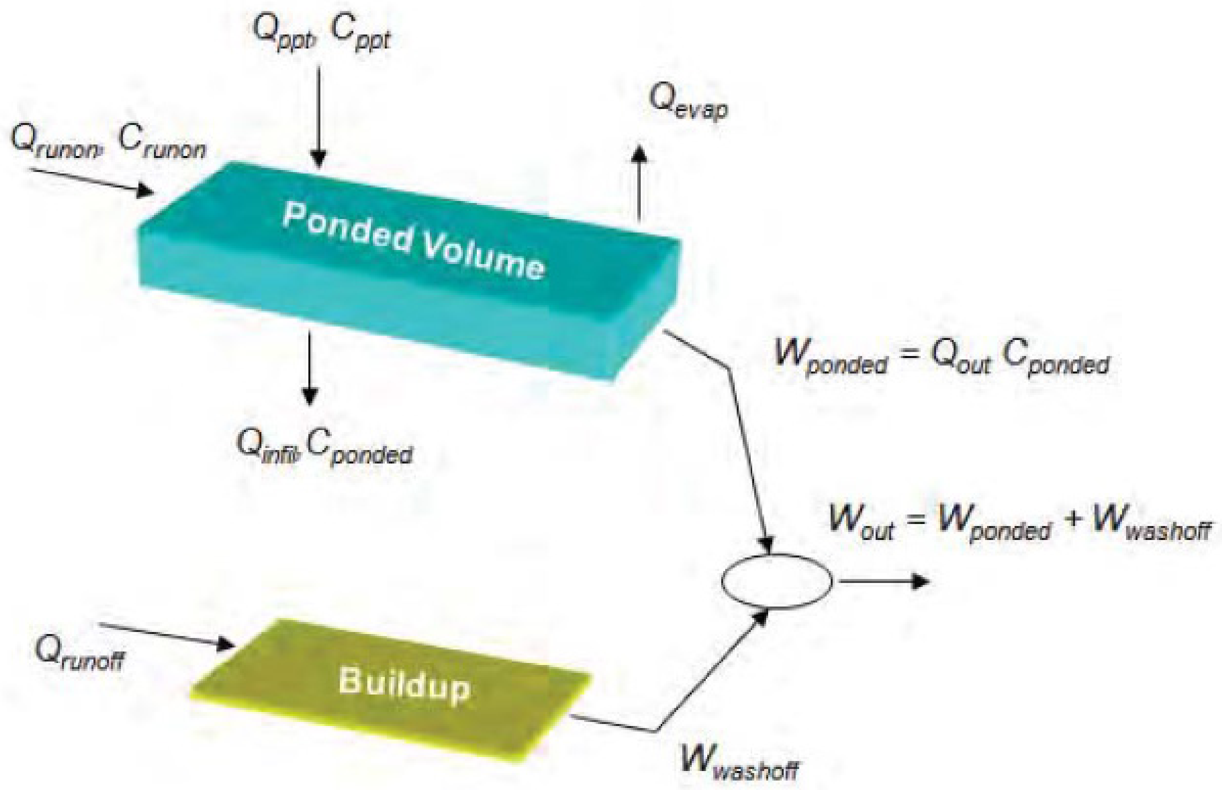
SWMM Hydraulics Reference Manual Equation 3 - 2

Level of sophistication

1. Steady Flow Routing
2. Kinematics Wave Routing
3. Dynamic Wave Routing

SWMM Hydraulics Reference Manual Equation 3-1

Water Quality - Pollutant Buildup and Wash-off



Types of Low Impact Development Storm Control Measures that SWMM can model

Disconnection

Infiltration Basin

Rain Garden

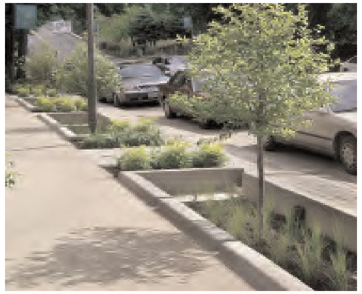
Cistern

Infiltration Trench

Green Roof

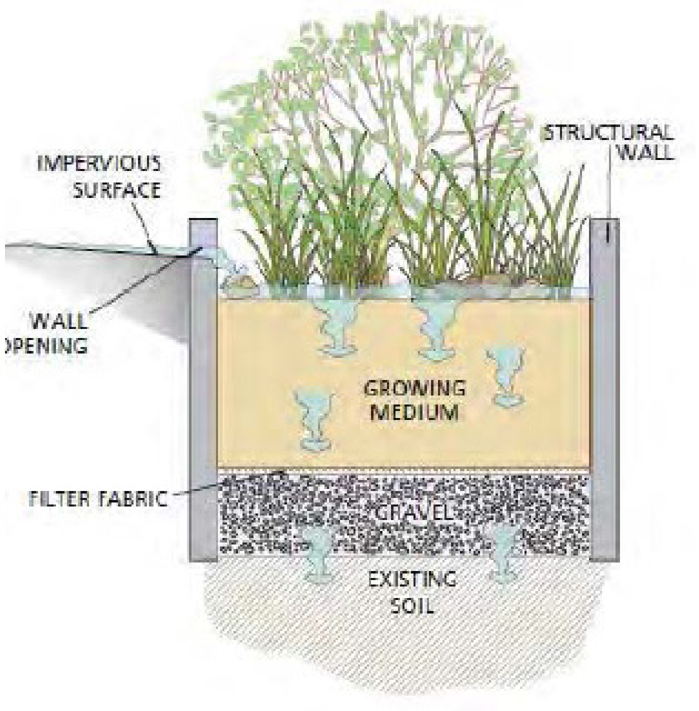
Porous Pavement

Vegetative Swale

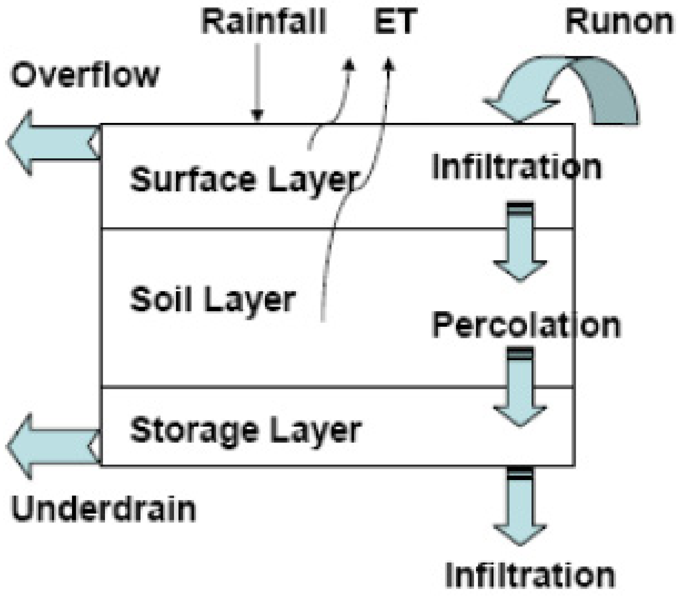


Street Planter

Green Infrastructure Subcatchment



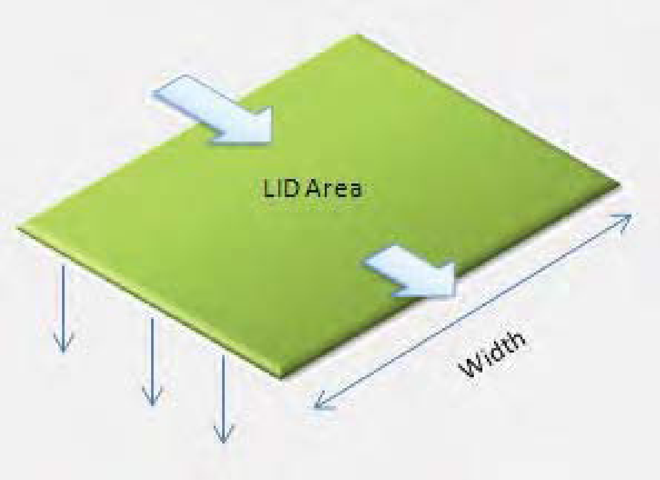
(A)



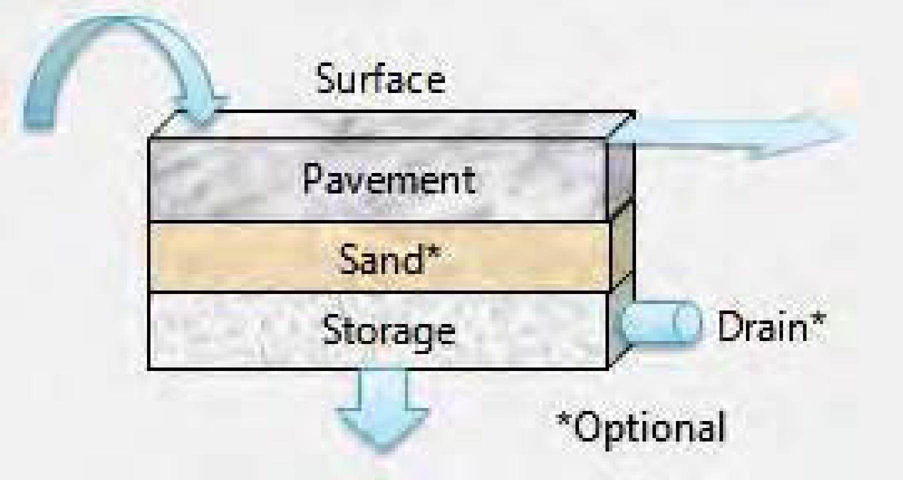
(B)

$$\frac{\partial c}{\partial t} = -\frac{\partial (uc)}{\partial x} + \frac{\partial}{\partial x}\left(D\frac{\partial c}{dx}\right) + r(c)$$

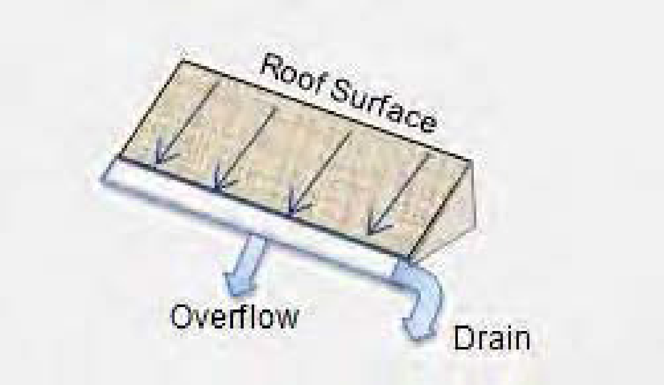
More Green Infrastructure Subcatchments



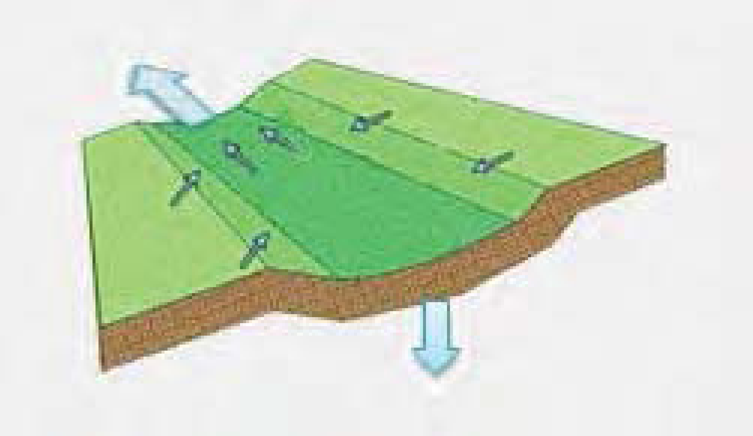
Green Roof



Permeable Pavement



Roof Disconnection



Vegetative Swale

Infiltration

- **Ho**

$$F(t_p) = \int_0^{t_p} f_p dt = f_\infty t_p + \frac{(f_0 - f_\infty)}{k_d}\left(1 - e^{-k_d t_p}\right)$$

- **Modified Horton**

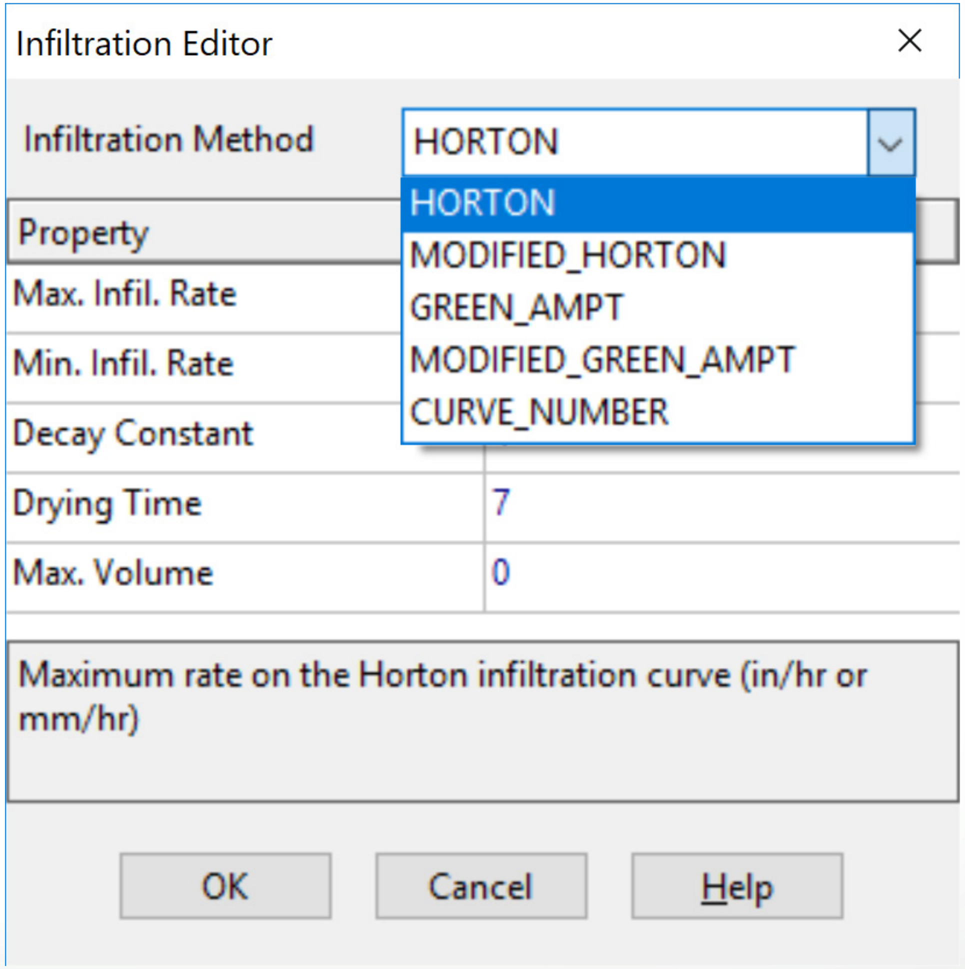
$$f_p = f_\infty + (f_0 - f_\infty)e^{-k_d t}$$

- **Green_Ampt, Modified Green_Ampt**

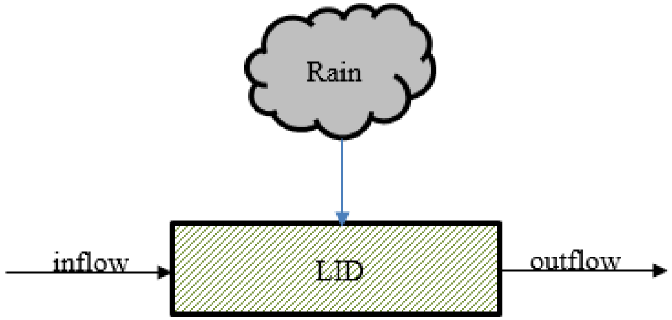
$$F = K_s + \psi_s \theta_d ln\left(1 + \frac{F}{\psi_s \theta_d}\right)$$

- **Curve_Number**

$$S_{max} = \frac{1000}{CN} - 10$$



Types of LIDs Hydrology Tested



Rain Garden/Bioretention

Infiltration Trench

Green Roof

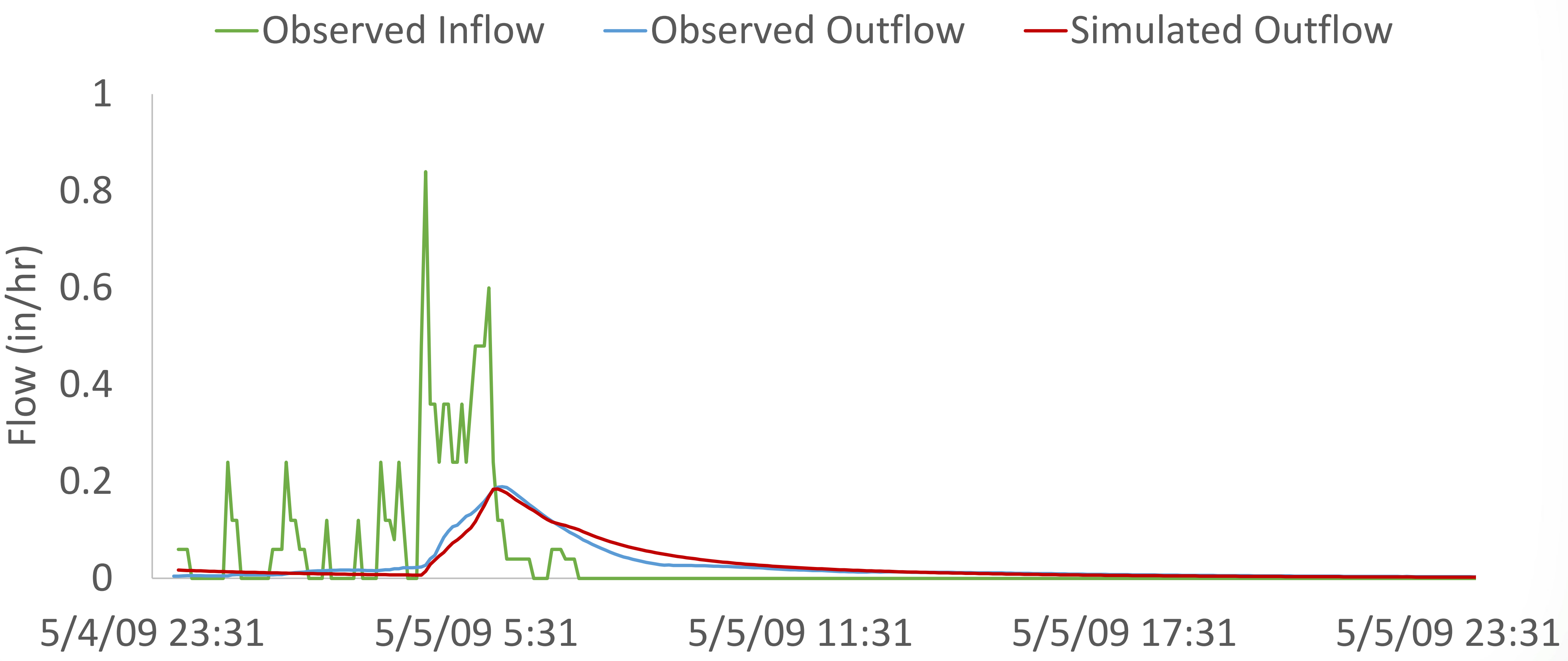
Porous Pavement

Vegetative Swale

LID Studies used for testing

LID Type	Research Organization Location	Name of Project	Reference
Bio-retention	North Carolina State University, NC	Graham Bio-Retention	(Passeport et al. 2009)
Rain Garden	Villanova University, PA	Villanova BTI Rain Garden	(Lord 2013)
Infiltration Trench	Villanova University, PA	Villanova Infiltration Trench	(Emerson 2008)
Vegetated Swale	University of Maryland, Savage, MD	UMD BioSwale	(Davis et al. 2012)
Vegetated Swale	Washington State Department of Transportation, King County, WA	Washington DOT BioSwale	(Maurer 2009)
Green Roof	City of Portland, OR	Hamilton Ecoroof	(Hutchinson et al. 2003) (She and Pang 2010)
Green Roof	City of Seattle, WA	EOC Green Roof	(Cardno TEC. 2012)
Green Roof	City of Seattle, WA	FS10 Green Roof	(Cardno TEC. 2012)
Porous Pavement	North Carolina State University, Kingston, NC	Boone Porous Pavement	(Wardynski et al. 2013)

Seattle ECO Green Roof Hydrograph



Goodness of Fit

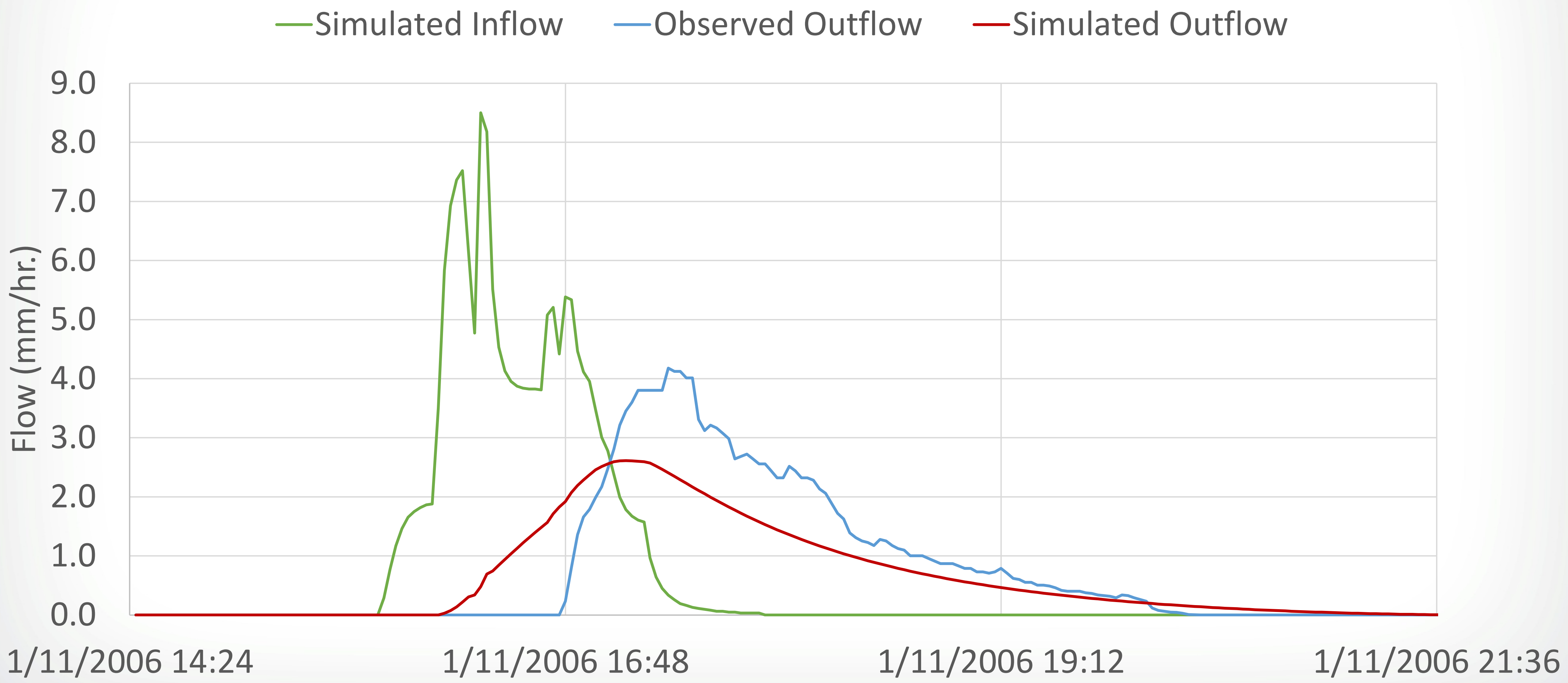
Coefficient of Determination

$$R^2 = \left(\frac{\sum_{i=1}^{n} (O_i - O^{mean})(P_i - P^{mean})}{\sqrt{\sum_{i=1}^{n} (O_i - O^{mean})^2} \sqrt{\sum_{i=1}^{n} (P_i - P^{mean})^2}} \right)^2$$

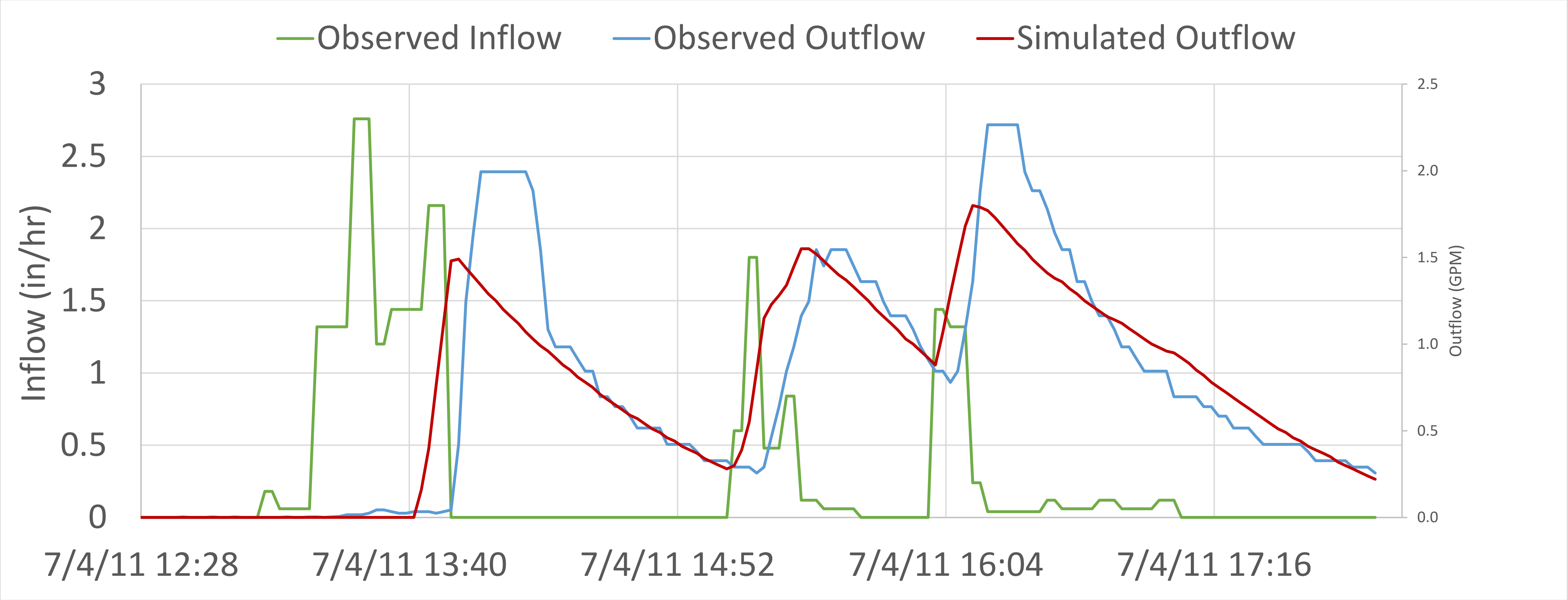
Nash-Sutcliffe Efficiency Statistic

$$N - S = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - O^{mean})^2}$$

Hydrograph from *UMD Bioswale* analysis depicting early outflow start-time



Boone Porous Pavement hydrograph depicting early outflow start-time

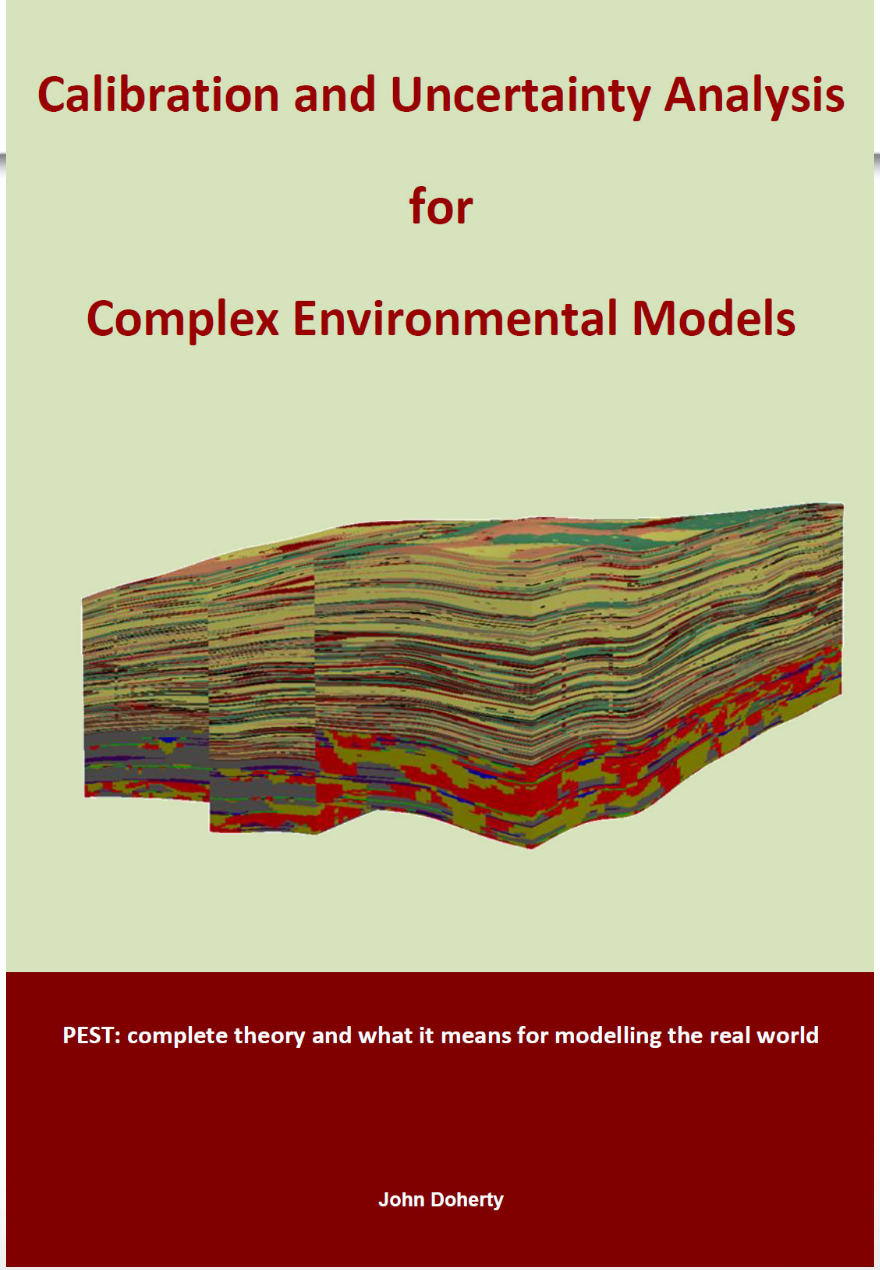


Multi-event Calibration Method

	Storm 1	Storm 2	Storm 3	Storm 4	Average
	Calibration NSE	NSE	NSE	NSE	Storm 1 Calibration AVG NSE
	NSE	Calibration NSE	NSE	NSE	Storm 2 Calibration AVG NSE
	NSE	NSE	Calibration NSE	NSE	Storm 3 Calibration AVG NSE
	NSE	NSE	NSE	Calibration NSE	Storm 4 Calibration AVG NSE

PEST

http://www.pesthomepage.org/

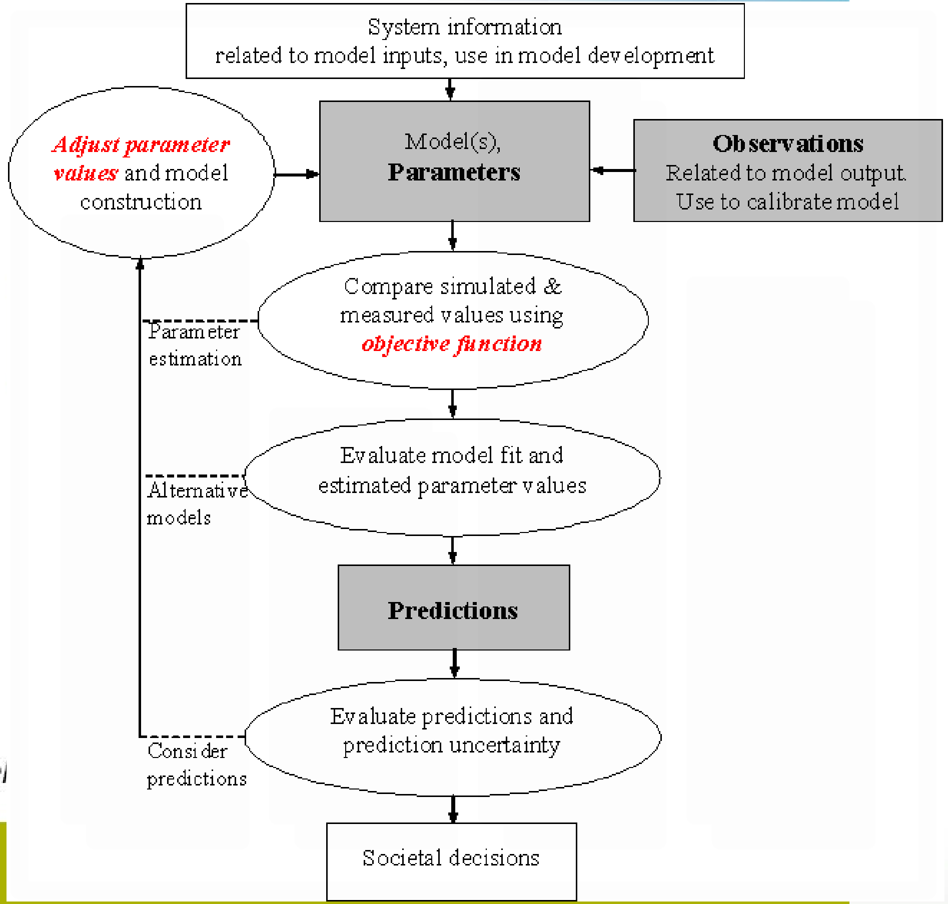


How PEST Works

PEST
(Parameter Estimation Software)

PEST is a nonlinear parameter estimation package capable of estimating parameters for any computer model. It solves a nonlinear least squares problem and minimizes the differences between the model's outputs and field measurements such as the calculated and measured discharges.

PEST adapts to the model



PEST program
5/3/2015 Pag.11

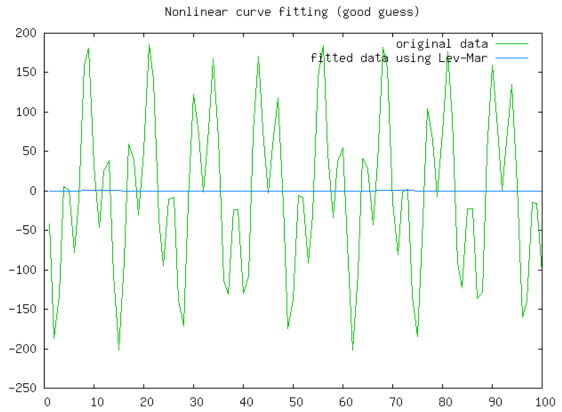
https://www.google.com/search?q=parameter+estimation+images&tbm=isch&tbo=u&source=univ&sa=X&ved=2ahUKEwik0dbkzbHeAhVyTt8KHW6TDR0QsAR6BAgFEAE&biw=1680&bih=941#imgrc=FbdsdbiAFfzVvM: J. Doherty 2007

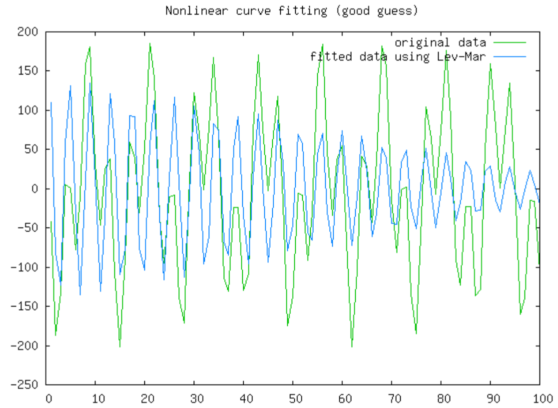
Parameter Estimation Algorithm

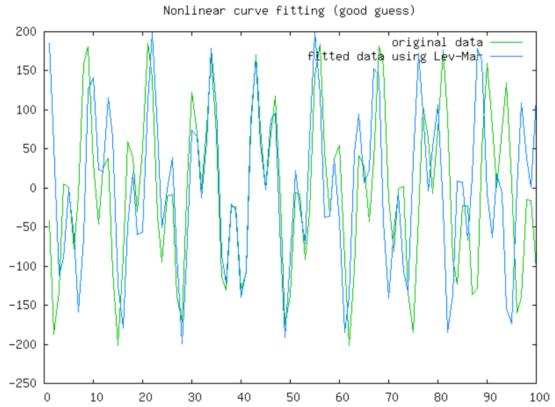
Levenberg–Marquardt algorithm (LMA or just LM), AKA damped least-squares (DLS)

$$f(x) = \frac{1}{2}\sum_{j=1}^{m} r_j^2(x)$$

$$\nabla^2 f(x) = J(x)^T J(x)$$





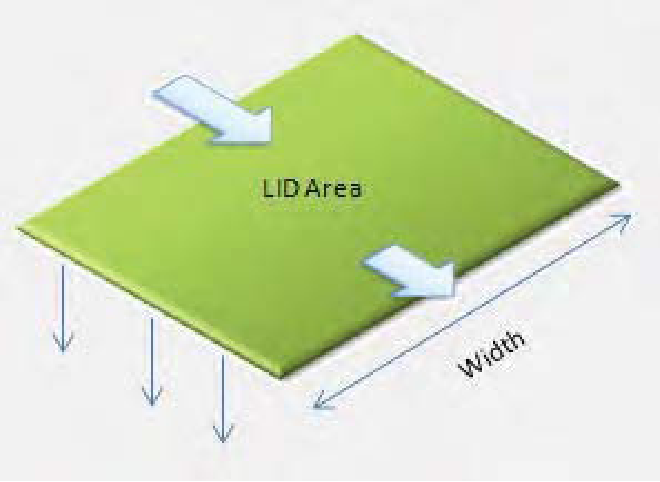


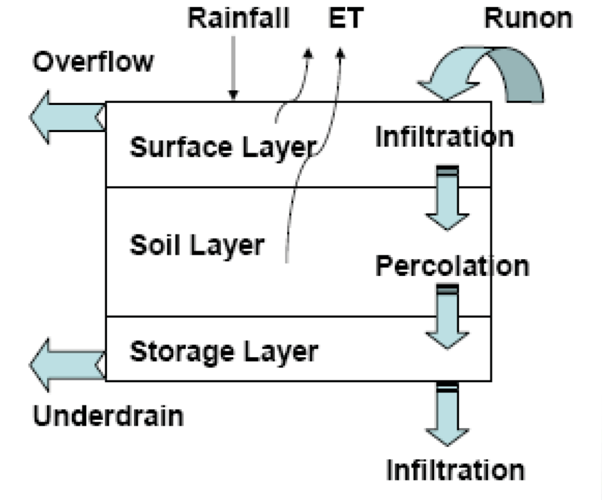
https://en.wikipedia.org/wiki/File:Lev-Mar-best-fit.png

$y = a\cos(bX) + b\sin(aX)$

Parameters for a SWMM LID Green Roof

Parameter
Maximum Freeboard, inches (D_1)
Surface Void Fraction (ϕ_1)
Soil Layer Thickness, inches (D_2)
Soil Parameters:
Porosity (ϕ_2)
Field Capacity (θ_{FC})
Wilting Point (θ_{WP})
Plant Available Water (θ_{FC} - θ_{WP})
Saturated Hydraulic Conductivity, in/hr (K_{2S})
Wetting Front Suction Head, inches (ψ_2)
Percolation Parameter (HCO)
Drainage Layer Thickness, inches (D_3)
Drainage Layer Void Fraction (ϕ_3)
Drainage Layer Roughness (n_3)
Capture Ratio (R_{LID})





Most Sensitive Parameters

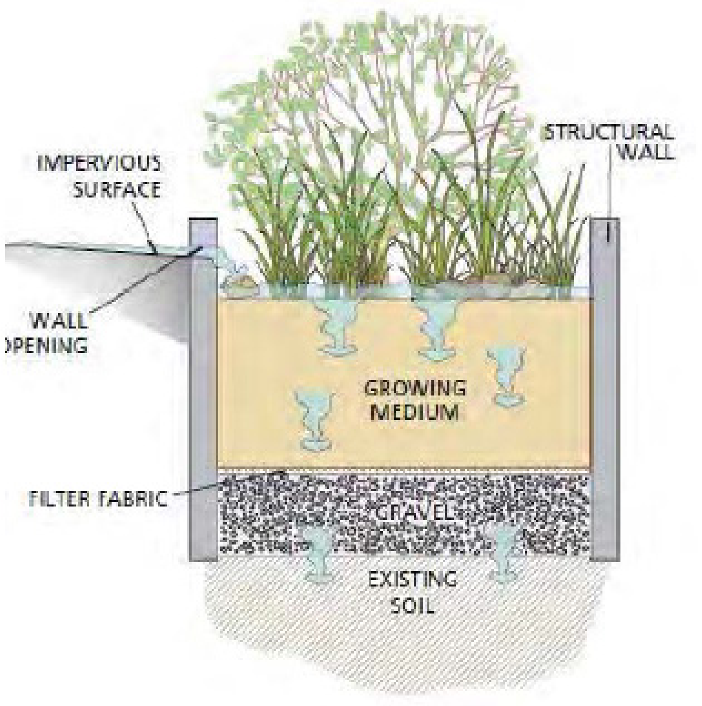
1 = most sensitive
7 = least sensitive

Parameter		Rank
LID Usage	Width (ft.)	7
	Initial Saturation	5
Soil	Porosity	4
	Field Capacity	2
	Wilting Point	1
Drainage Mat	Void Ratio	3
	Roughness	6

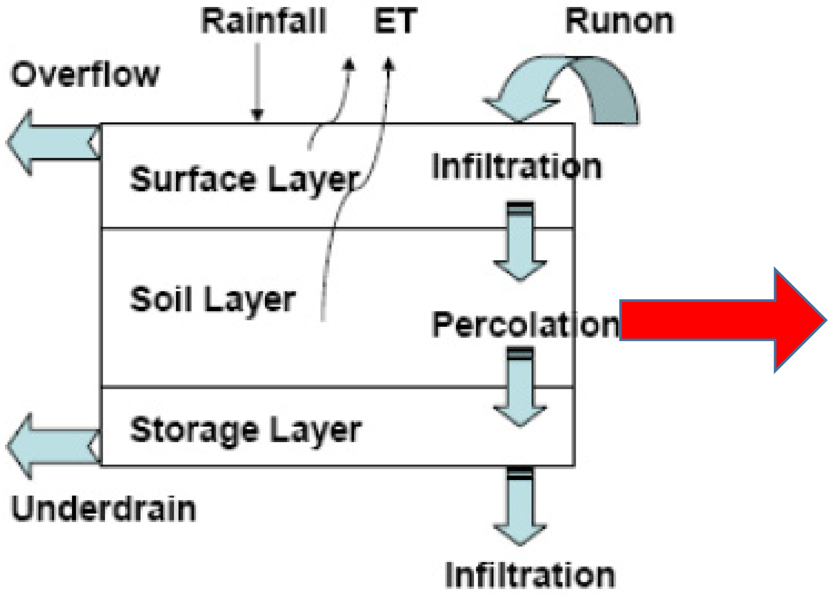
LID Module Performance Summary Table

LID Name	Average NSE Value	Average r^2 Value
Graham Bio-retention	0.86	0.93
Villanova BTI Rain Garden	0.86	0.96
Villanova Infiltration Trench	0.65	0.67
UMD BioSwale	0.78	0.87
Washington DOT BioSwale	0.70	0.91
Hamilton Ecoroof	0.92	0.90
EOC Green Roof	0.94	0.97
FS10 Green Roof	0.93	0.84
Boone Porous Pavement	0.74	0.89

SWMM LID Modeling Weakness



(A)



(B)

Conclusions

- PEST is a useful tool for parameter estimation
- SWMM LID can model hydrology with
  - NSE ranging from 0.65- 0.94
  - R^2 ranging from 0.67 – 0.97
- SWMM LID Module does not account for lateral exfiltration which is important for deep, narrow, LIDs, such as Infiltration Trenches
- EWRI LID Group was formed to improve scientific underpinnings of SWMM
- Next step – test water quality and LID aggregations

Questions?

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Most Recent ORD Publications

Niazi, M., C. Nietch; Mahdi Maghrebi; N. Jackson; B. R. Bennett; M. Tryby; and A. Massoudieh (2017). "Storm Water Management Model: Performance Review and Gap Analysis." *Journal of Sustainable Water in the Built Environment*

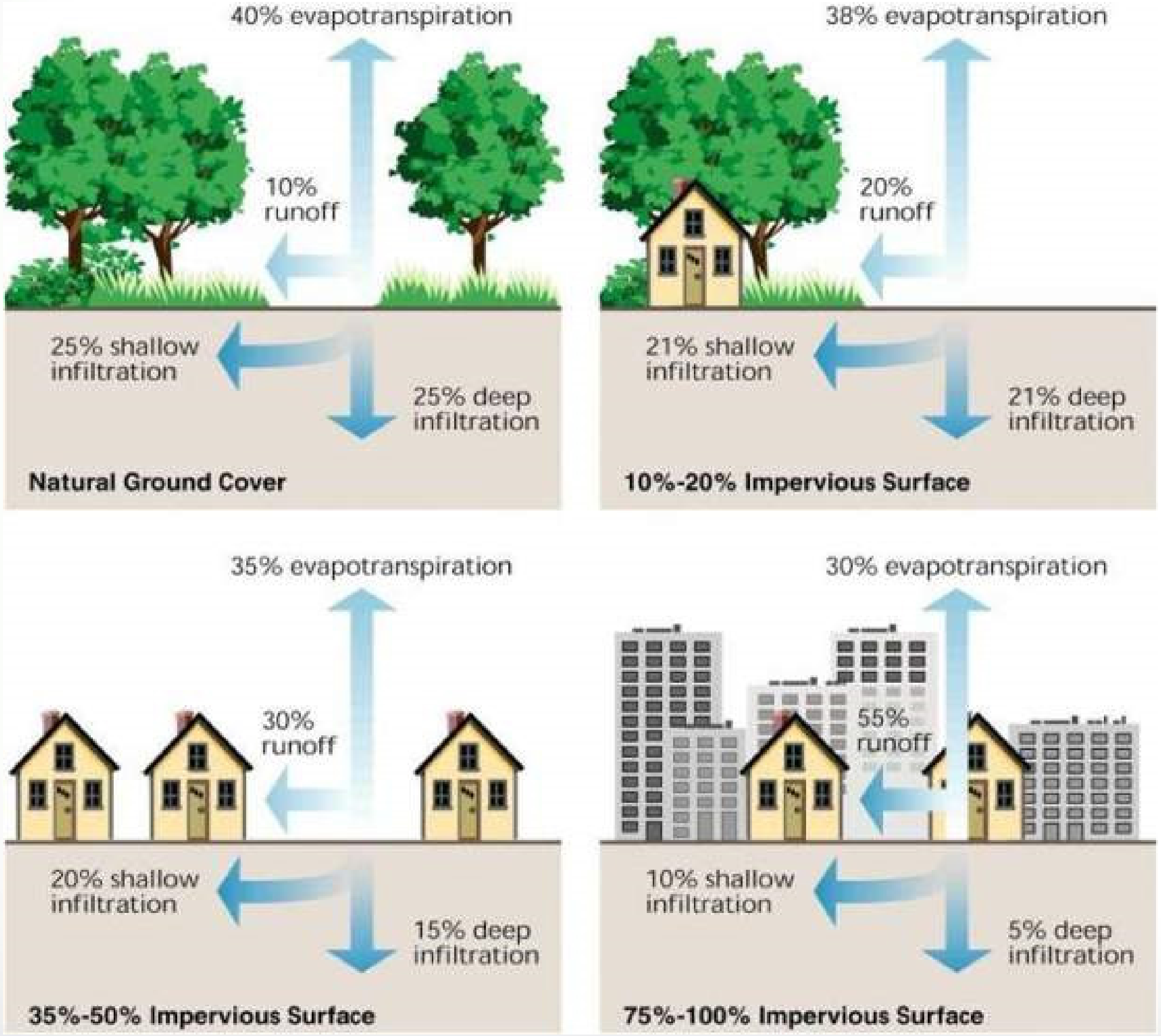
Platz, M.; M. Simon; and M. Tryby (2018). "Testing of the SWMM Model's LID Modules." Submitted to *Journal of Environmental Modelling and Software*

Brad Barnhart, Heather Golden, Joseph Kasprzyk, James Pauer, Chas Jones, Keith Sawicz, Nahal Hoghooghi, Michelle Simon, Robert McKane, Paul Mayer, Amy Piscopo, Darren Ficklin, Jonathan Halama, Paul Pettus, Brenda Rashleigh.
"Embedding co-production and addressing uncertainty in watershed modeling decision-support tools: successes and challenges"
Journal of Environmental Modelling and Software 109 368-379

Hoboken Flooding Events

http://phci.rutgers.edu/wp-content/uploads/2016/07/Hoboken-Stormwater-HIA_FinalReport_v9-19-16.pdf

Urbanization Changes the Hydrologic Cycle

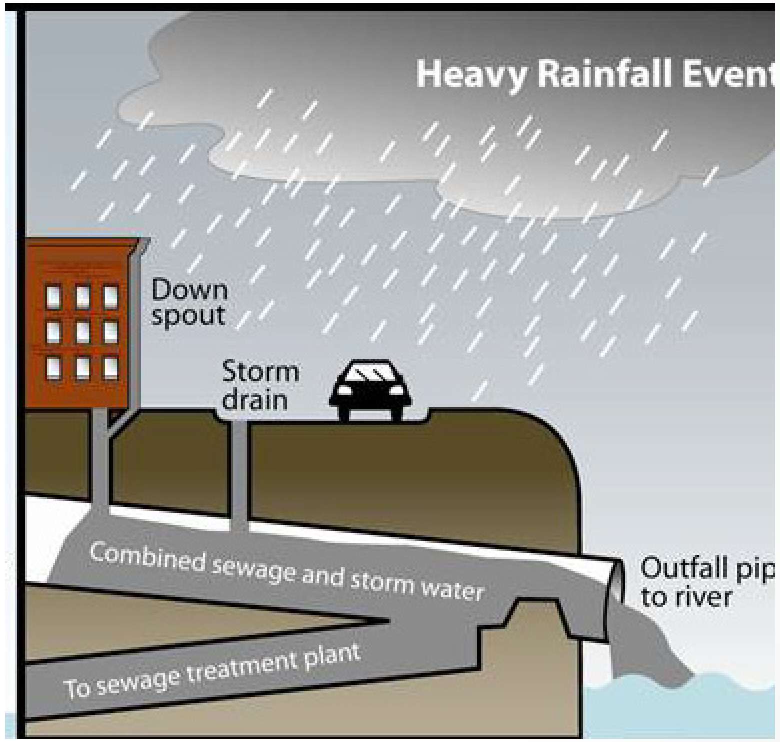


- Soils and vegetation are replaced with impervious surfaces
- Impervious surfaces are connected to dense drainage networks
- Runoff drains directly into streams, lakes, wetlands, and coastal waters
- Even small storms generate significant runoff

Urban Stormwater Impacts

Hydrologic, Geomorphic, and Biological Impacts:

- Increased stormwater volume and velocity causes flooding, erosion, and sewer overflows.



- Impaired habitat and water quality impact fisheries and shellfish harvesting due to microbials, metals, PAHs, and other pollutants.
- Reduced groundwater recharge impacts water supplies.

US Map of Combined Sewer Overflow Agreements