Hydrological Modeling

Theo Lim

GI Studio Guest Lecture

9/16/16

Goals

- Increase familiarity with urban hydrological cycle: “Hydrologic literacy”
- Introduce advantages and shortcomings of urban hydrological modeling
- Build working knowledge of a lumped-parameter design storm model

Overview

- Why model?
- What are we trying to model?
- Approaches to modeling
- Types of models relevant to Green Stormwater Infrastructure
- Creating Hydrographs Using the SCS method
- HydroCAD demo

Why Model?

“All models are wrong, but some are useful” – George Box, statistician

What do we model?

Who is doing modeling?

When do we model?

Why Model?

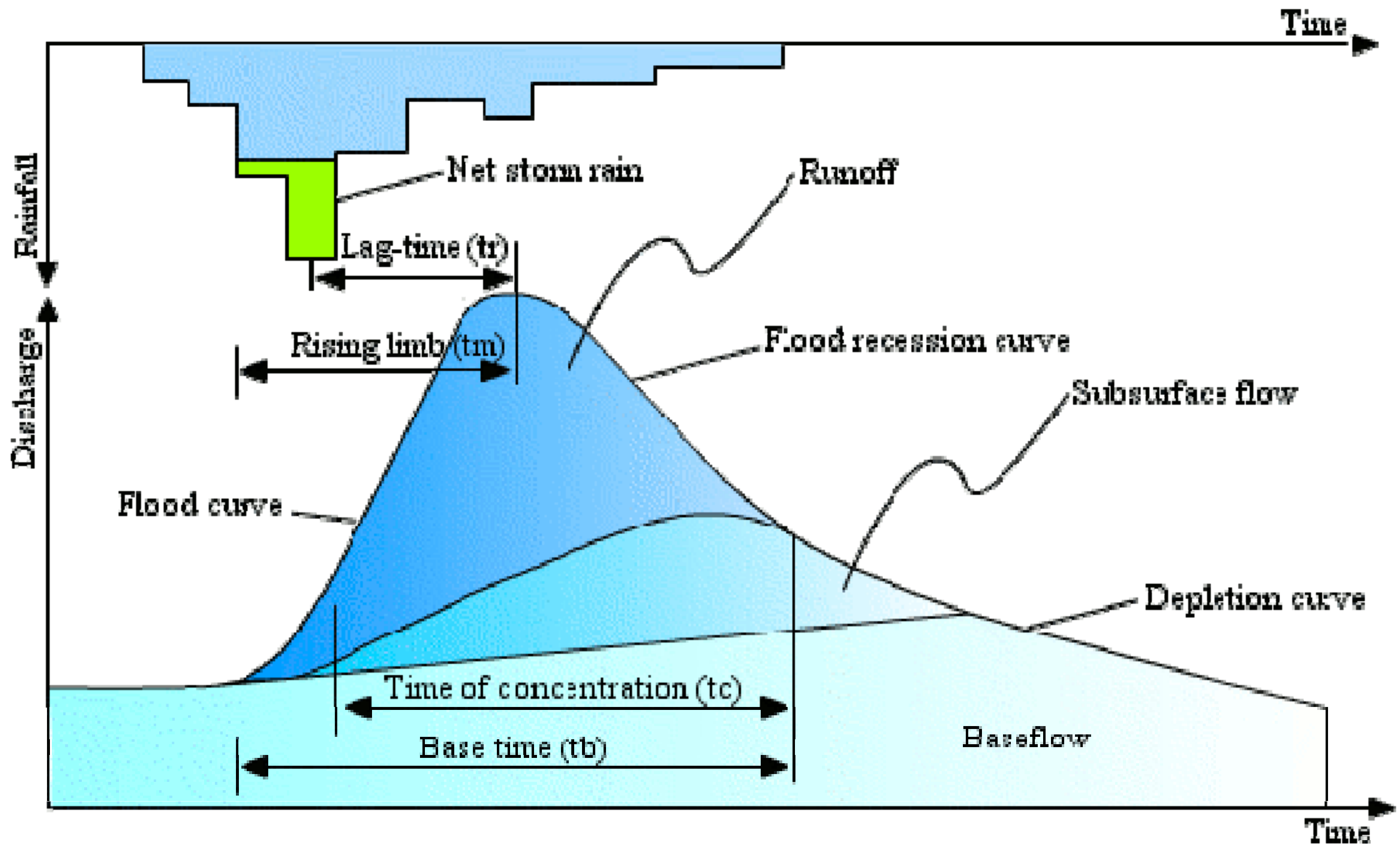
"All models are wrong, but some are useful" – George Box, statistician

Who models and when?

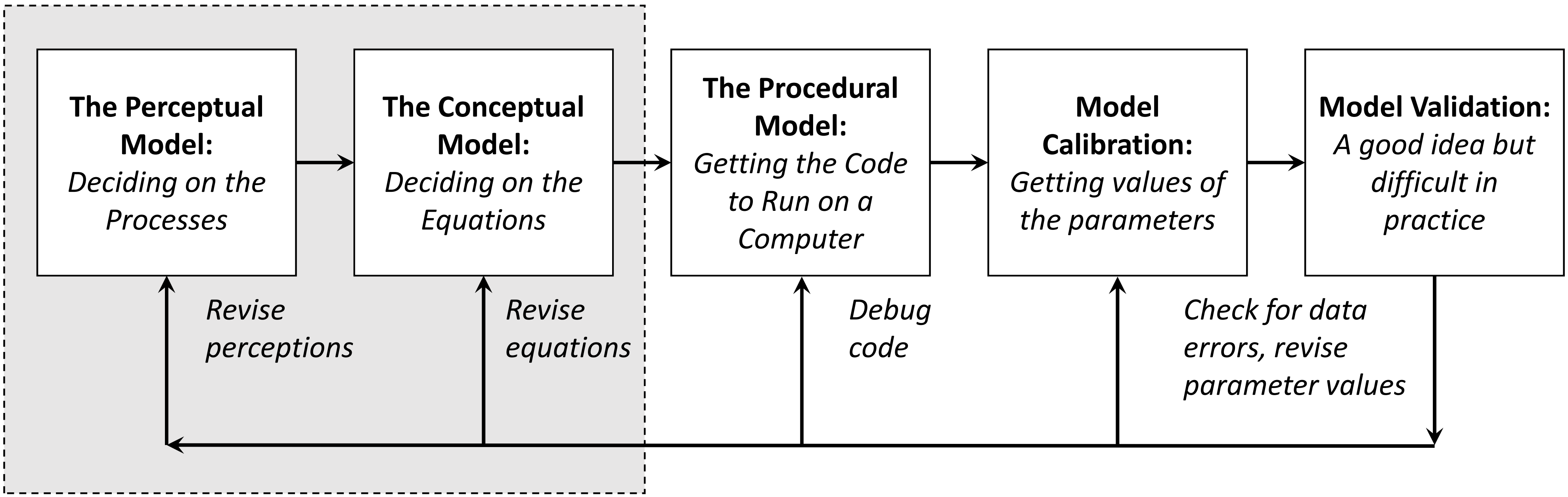
- Infrastructure managers/planners → regulatory agencies
- Infrastructure managers/planners → investment decision-making
- Site designers/developers/engineers → compliance and site permitting (usually involved after Schematic Design)
- Regional environmental planners and watershed managers → regulatory body
- Academics and researchers → publications, policies, new knowledge

Discussion: What do *we* want out of modeling?
How will *we* interact with hydrological models?

Discussion: What do we want out of modeling?

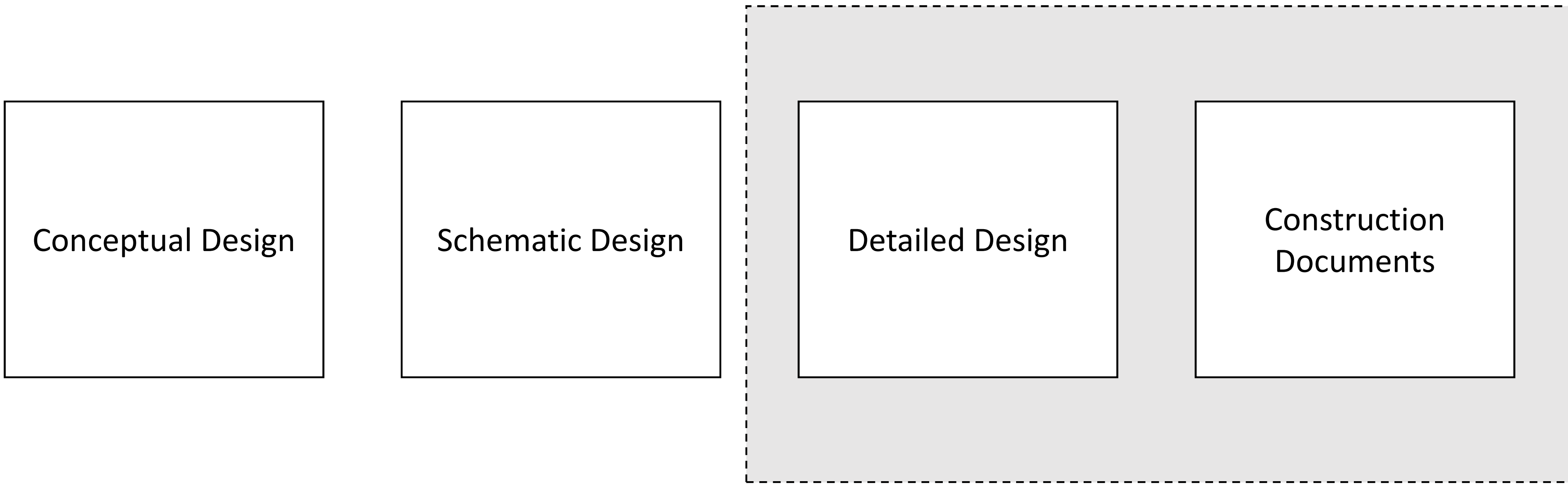


The Overall Modeling Process



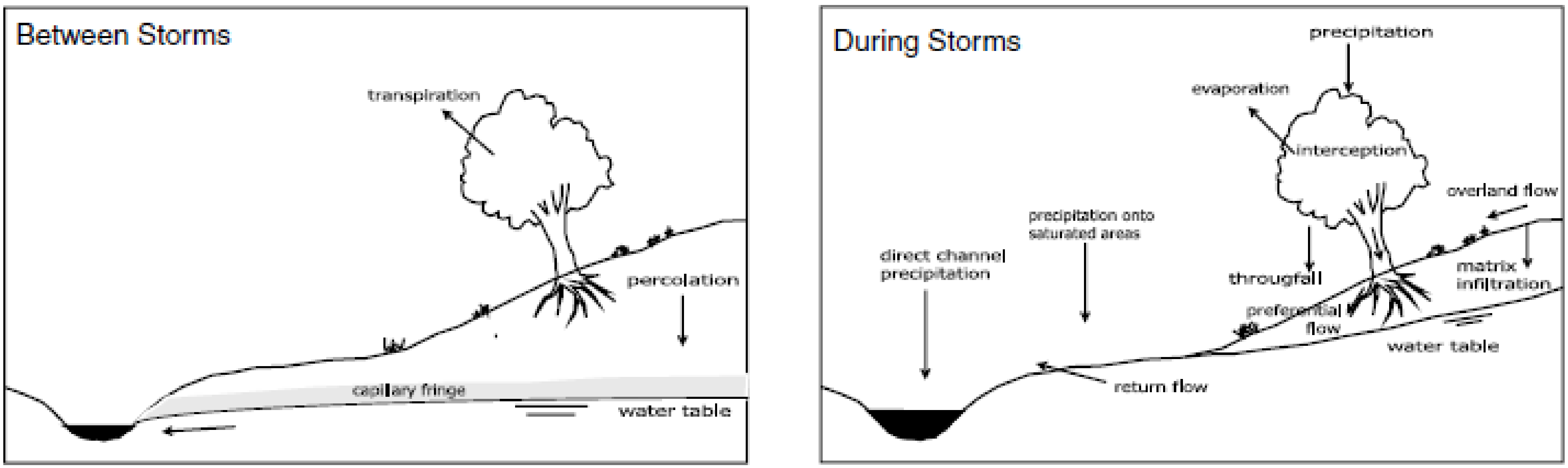
Adapted from Beven 2012

Modeling in the Site Design Process



What are we trying to model?

Dominant processes in un-urbanized catchments in humid climates

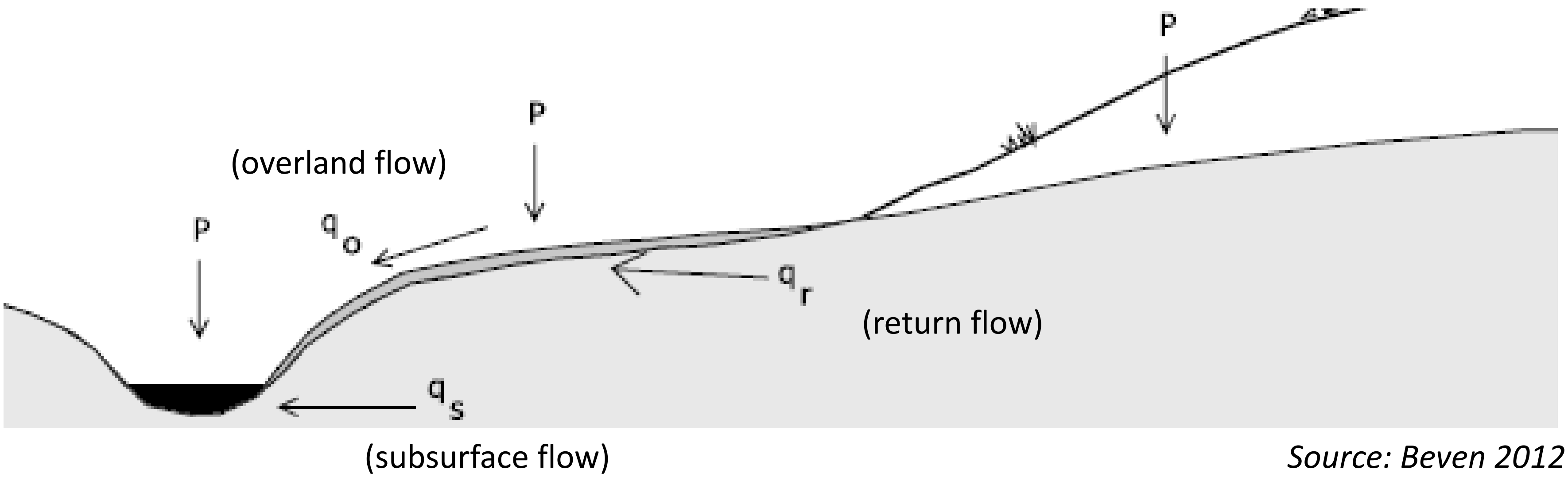


Source: Beven 2012

What are we trying to model?

Dominant processes in un-urbanized catchments in humid climates

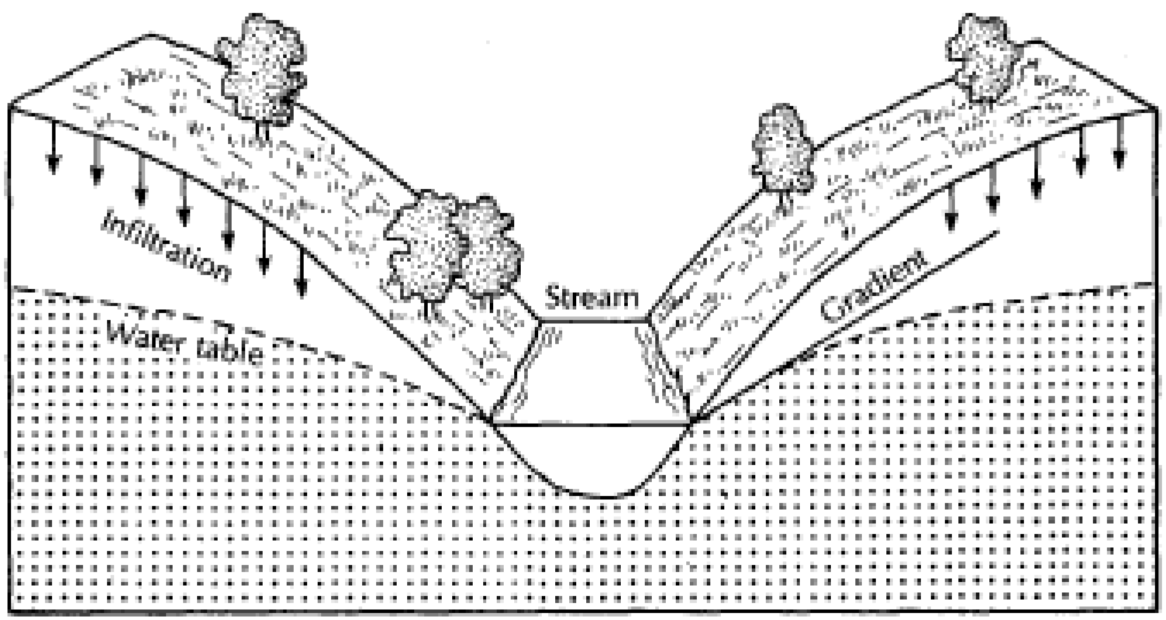
Note: "Q" is the conventional variable for flow [L^3 T^{-1}]



Source: Beven 2012

What are we trying to model?

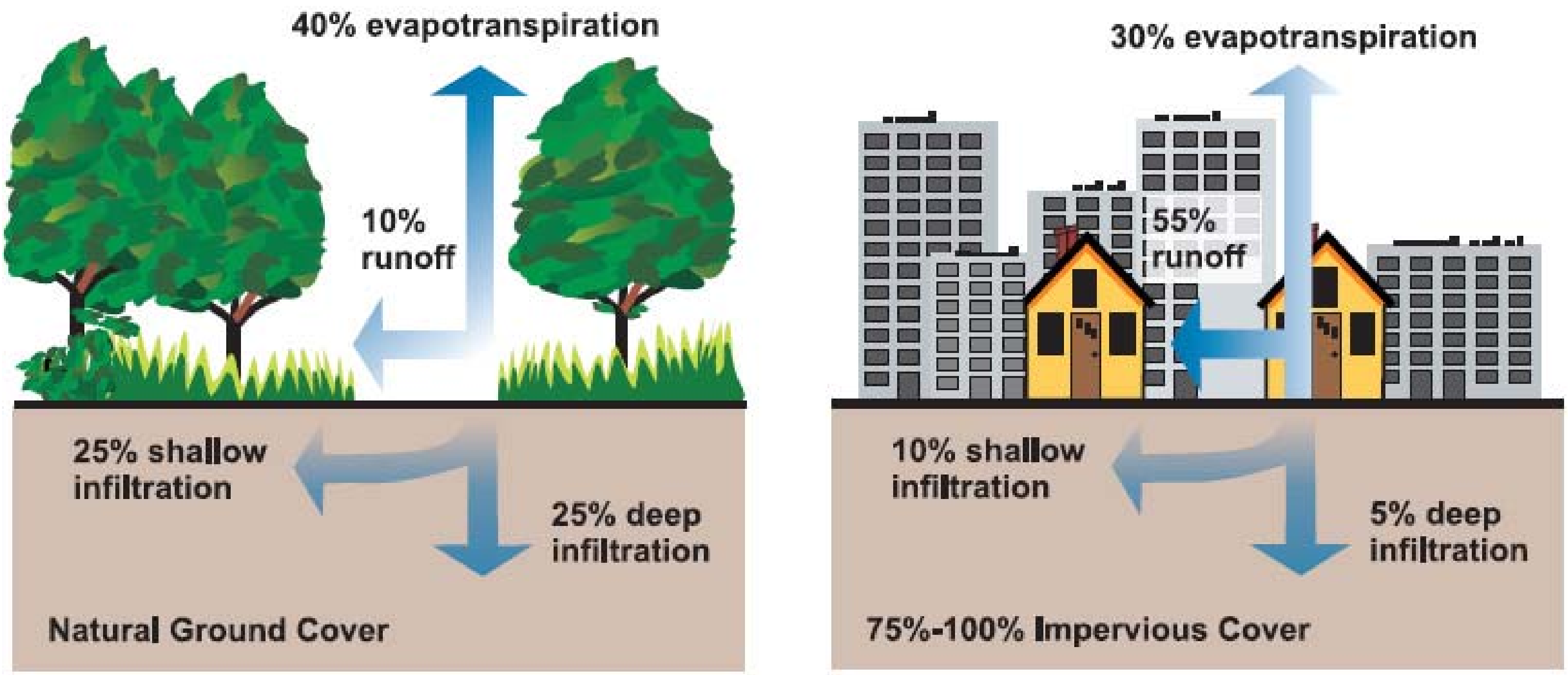
Dominant processes in un-urbanized catchments in humid climates



Source: Fetter 2001

What are we trying to model?

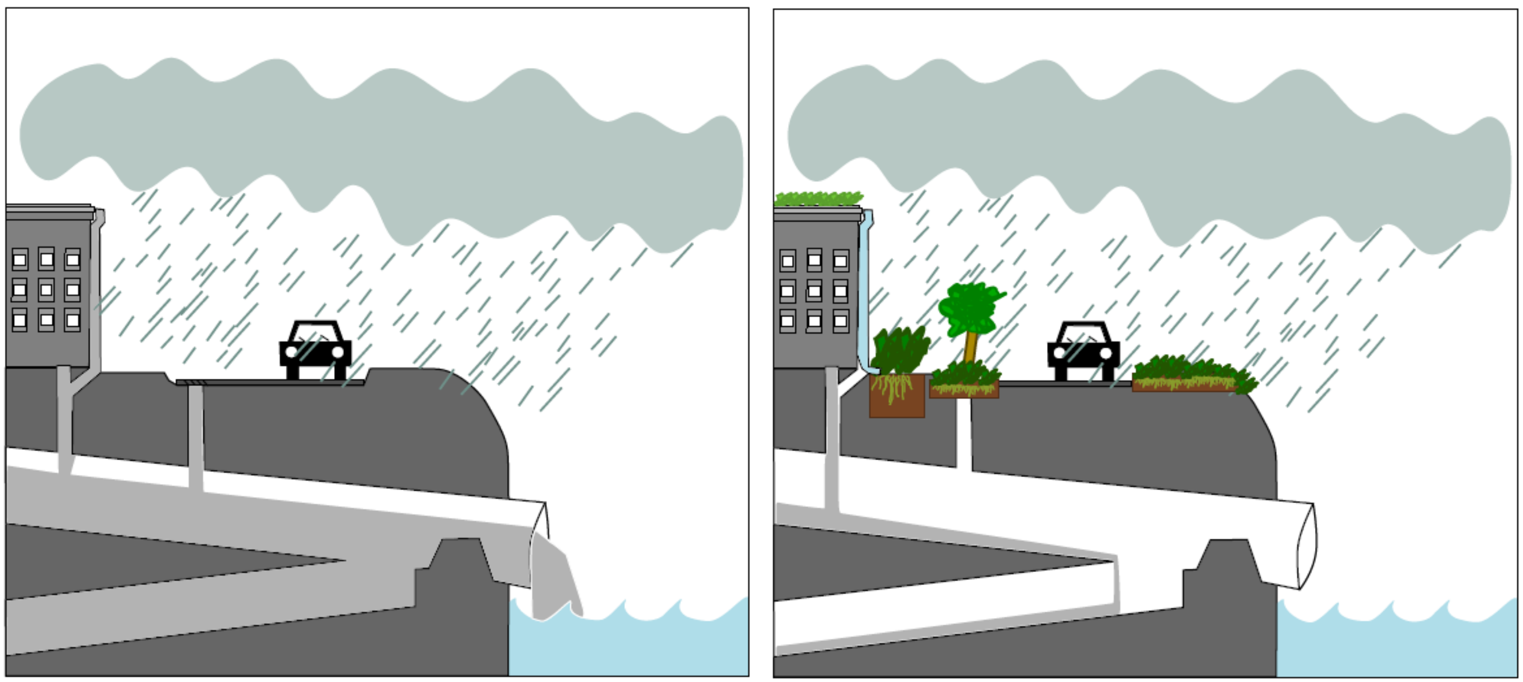
Dominant processes in URBANIZED catchments in humid climates



Source: US EPA 2003

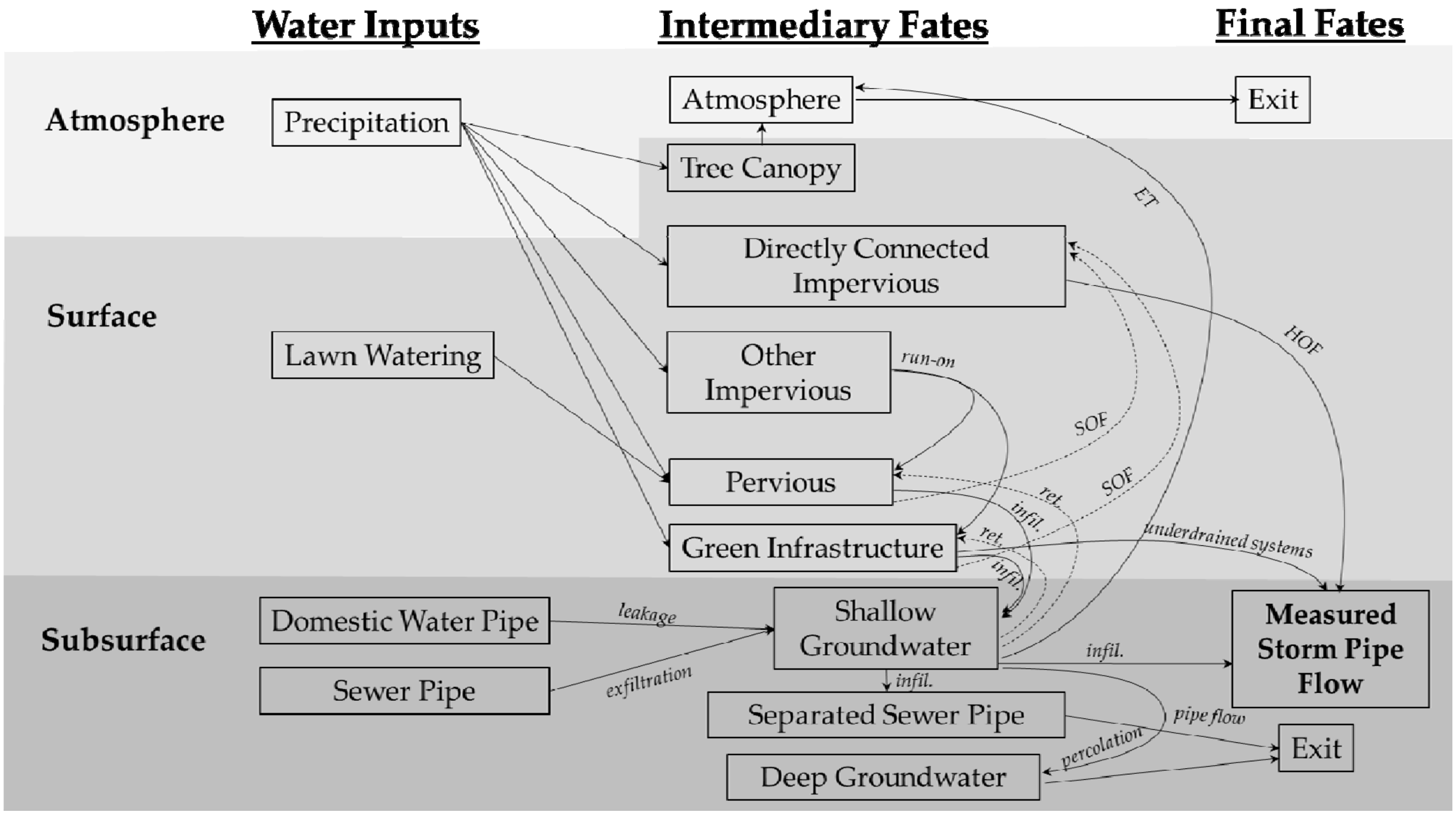
What are we trying to model?

Dominant processes in URBANIZED catchments in humid climates



Source: Lim 2014

Elements of the Urban Hydrologic Cycle



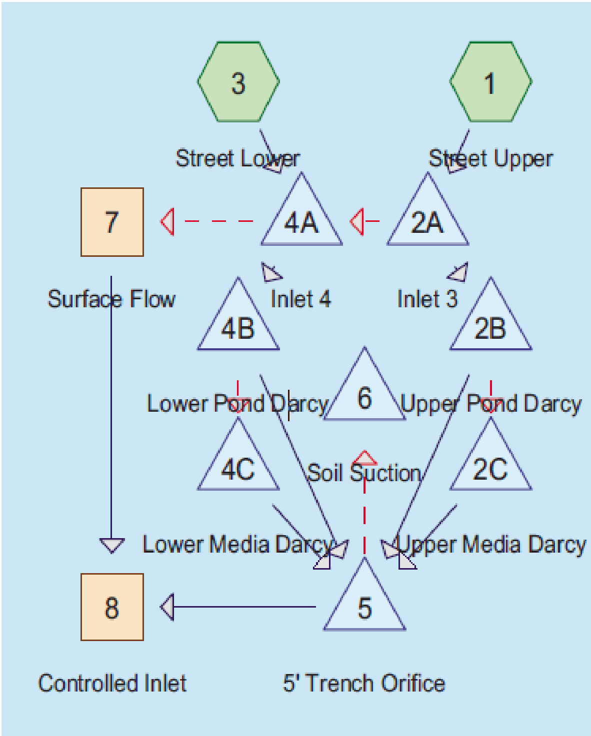
Source: Lim 2015

Approaches to Modeling

LUMPED: Treats catchment as a single unit, state variables represent catchment averages over the entire area

DISTRIBUTED: Discretizes catchment into grid cells, state variables are assigned to each grid and related to each other through physical process equations, sometimes called “process-based” or “physically-based” models

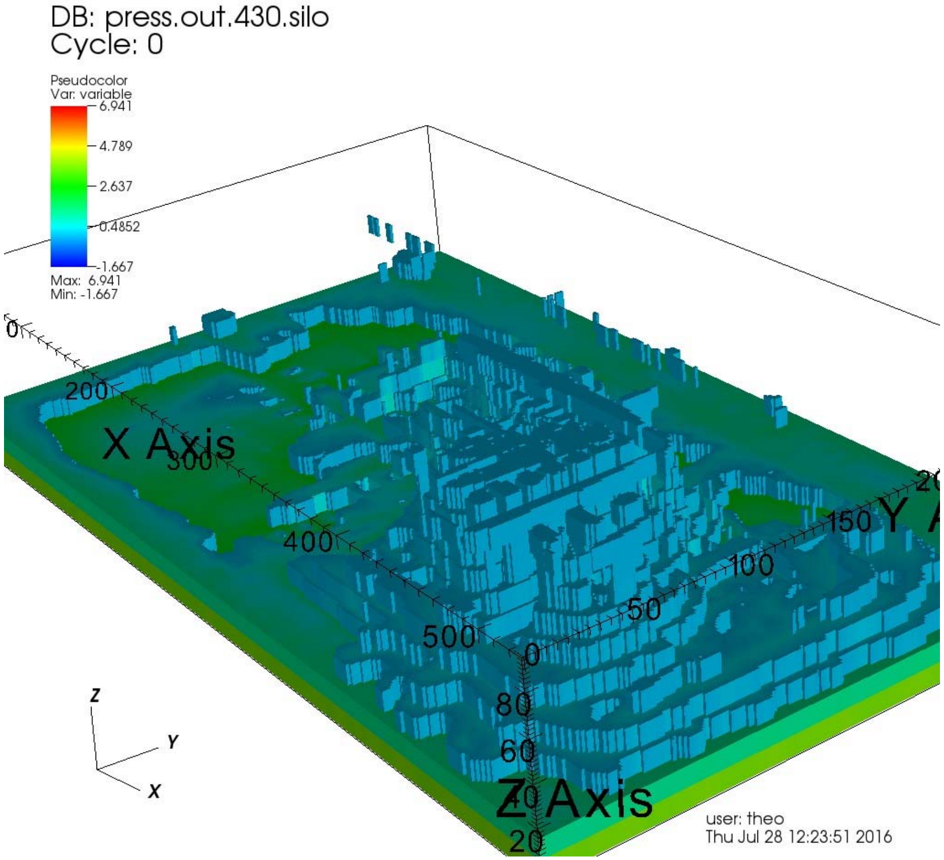
Approaches to Modeling



HydroCAD is an example of a **lumped parameter**, edge-node model. Each node represents a "catchment" with its own storage, porosity, conductivity etc parameters

Source: Lucas 2010

Approaches to Modeling



ParFlow-CLM is an example of a **fully-distributed**, finite-difference model model. In this example, the horizontal gridding is 1.5m x 1.5m, with variable dz discretization in the z dimension. Continuous solutions to Richards equation for the pressure field are solved using a numerical solver, called KINSOL.

Source: Lim 2016

Approaches to Modeling

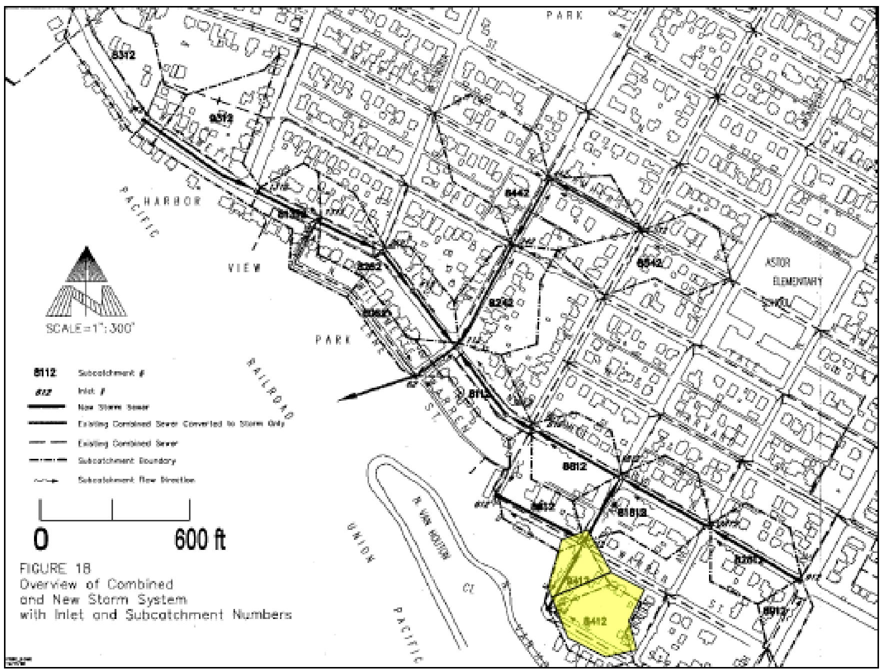


Figure 3-6 Fisk B catchment, Portland, Oregon (Portland BES, 1996).

SWMM is generally classified as a lumped parameter model, but what would happen if you make the "catchments" really small?

Source: Rossman 2015

Approaches to Modeling

BOTTOM-UP: This is primarily what we have been talking about and what most people are referring to when they talk about “hydrological modeling.” Modelers are interested in running simulations given known relationships between parameters (equations), given some actual or hypothetical scenarios.

TOP-DOWN: Another approach to determining if our perceptual models of hydrological function are supported by empirical evidence. When might we take a top-down modeling approach?

Approaches to Modeling

- More on top-down modeling later…
- Back to bottom-up types now…

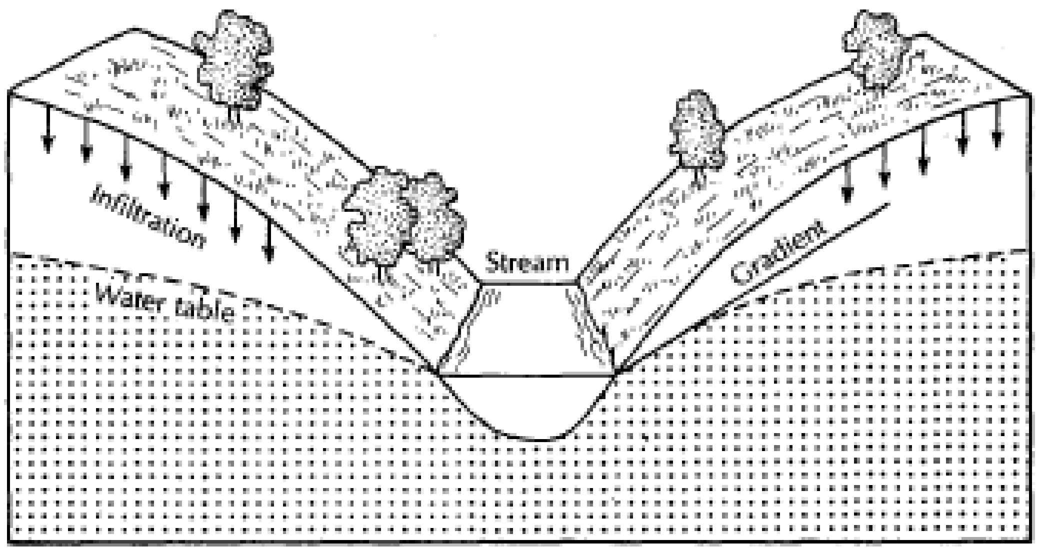
Approaches to Modeling

	Key Concepts	Examples
Rainfall-runoff calculation	Peak flow Q = CiA	The Rational Method
Hydrologic	Rainfall-runoff simulation plus reservoir/channel routing (TIME and SPACE)	TR-55, HEC-HMS (SCS method), ParFlow, RHESYS
Hydraulic	Flow rates, and flow velocities through waterways, structures and pipes	HEC-RAS
Combined Hydrologic-Hydraulic	Hydrologic outputs used as inputs to hydraulic model	SWMM, HydroCAD
Water Quality	Mass loading, dispersion, advection, etc	WASP

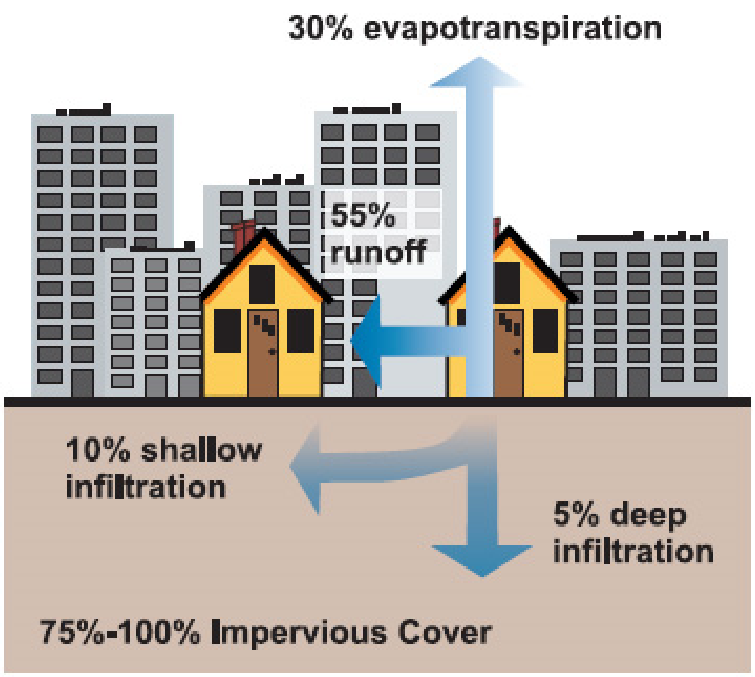
http://stormwater.pca.state.mn.us/index.php/Available_stormwater_models_and_selecting_a_model

Re-focus: What are we trying to model?

Dominant processes in in response to rainfall



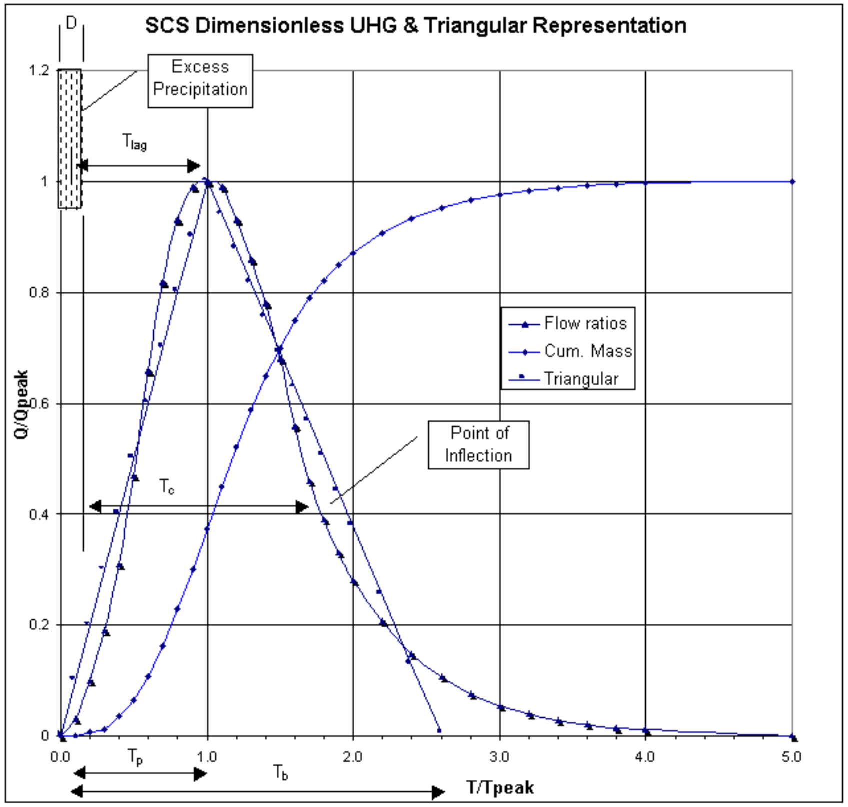
Source: Fetter 2001



Source: US EPA 2003

Back to: What are we trying to model?

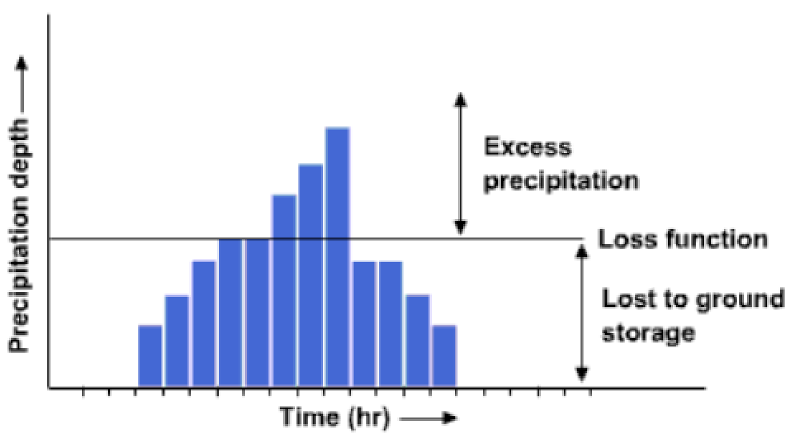
Dominant processes in in response to rainfall

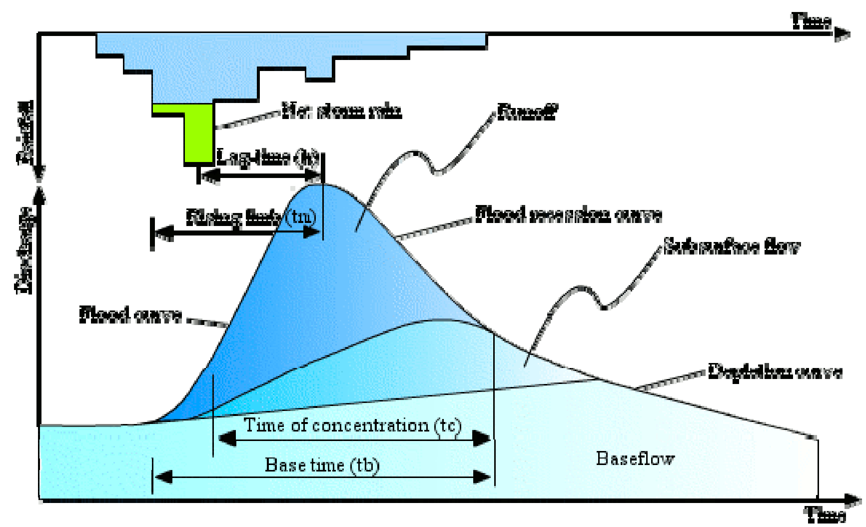


Infiltration and Surface Runoff

- Logic:

Precipitation Rate (Timing of a Volume)	Infiltration Capacity Models, sometimes called "loss models", or "initial abstraction"	Precipitation Excess (a Volume)	Timing of Runoff, or creating of a streamflow hydrograph (Timing of the Volume)

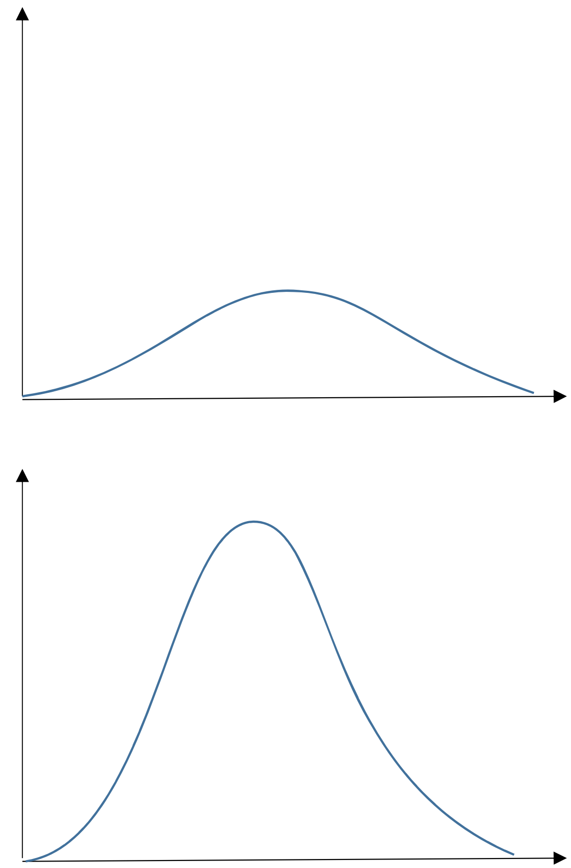




Infiltration and Surface Runoff

Thoughts on hydrographs

- What would be the effect of steeper slopes in the catchment area?
- What would be the effect of rougher surfaces?
- What would the effect of an elongated basin shape be?



Runoff Curve Number

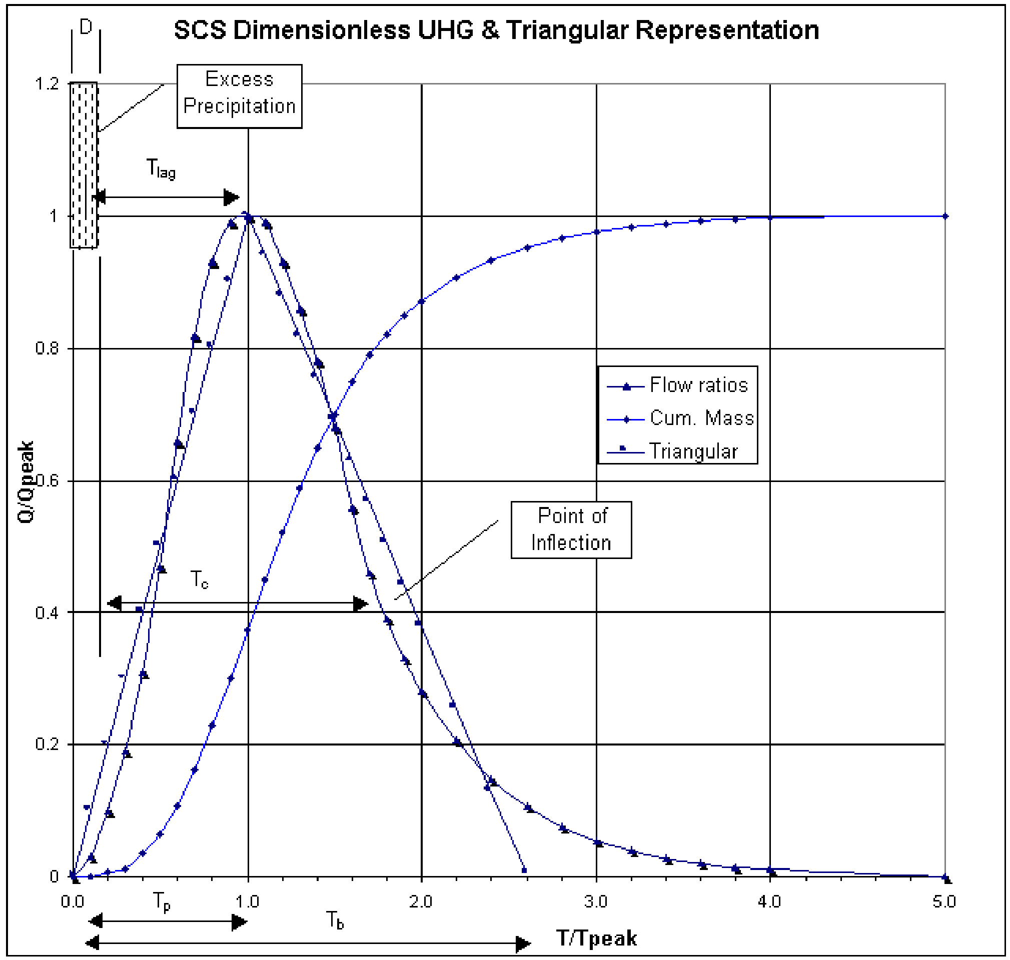
- For calculating direct runoff from rainfall excess

Peak, Peak Delay, Volume-Based Designs

1. Detention Ponds

The Unit Hydrograph

- This is like the “normal distribution” of surface runoff models
- Constructed from empirical data averaging the area and precipitation-normalized hydrographs from many (un-developed), small watersheds
- Easy to compute from geographic parameters -> define “lag time”
- Nice curvilinear shape



The Unit Hydrograph

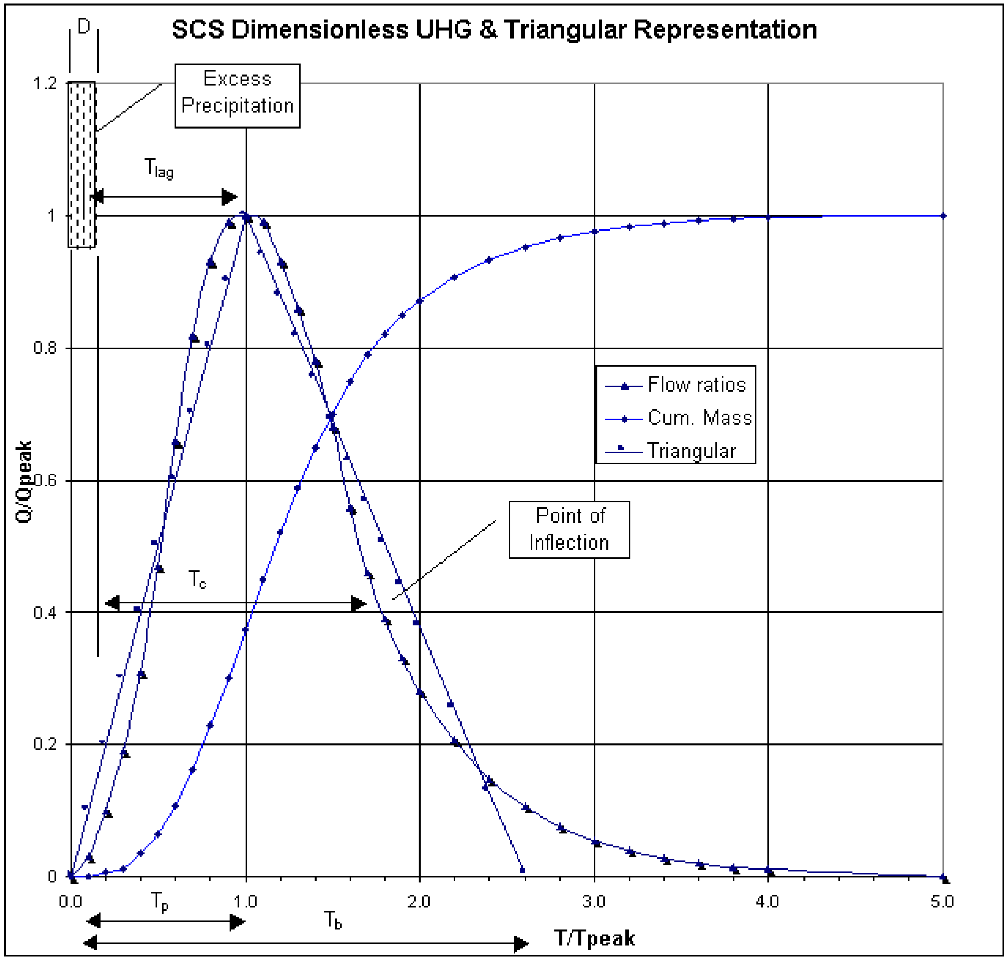
- Time lag is calculated from geomorphic characteristics of the catchment area

$$t_L = \frac{L^{0.8}(S+1)^{0.7}}{1900Y^{0.5}}$$

L = Hydraulic length (ft)

Y = slope (%)

S = potential max retention (inches)



Calculating Peak Discharge

$$t_L = \frac{L^{0.8}(S+1)^{0.7}}{1900Y^{0.5}}$$

$$t_c = \frac{5}{3}t_L$$

$$t_P = 0.67t_c$$

$$P_e = Q$$

$$q_p = \frac{484AQ}{t_p}$$

Pe = Precipitation excess = 1” in UH case
Q = total runoff depth = 1” in UH case
A = watershed area (mi^2)
q_p = peak discharge (ft^3/s)

General Desc	Peaking Factor	Limb Ratio
Urban areas; steep slopes	575	1.25
Typical SCS	484	1.67
Mixed urban/rural	400	2.25
Rural, rolling hills	300	3.33
Rural, slight slopes	200	5.5
Rural, very flat	100	12.0

Getting Storage (S) from the Curve Number (CN)

$$S = \frac{1000}{CN} - 10$$

- Look CN up in a table. (https://en.wikipedia.org/wiki/Runoff_curve_number)
- CN ranges from 30 (low runoff potential) to 100 (high runoff). Paved parking lots are 98.
- It's a function of land cover/vegetation and soil type
- Can do a weighted average if several types within contributing area

Create a Unit Hydrograph Mini-Lab

Q1: For **one inch of rainfall excess**, what peak discharge would we expect to see from a medium density watershed with the following characteristics:

Area = 3 sq mi
Hydraulic Length = 1.2 miles
Average Slope = 3%
Land Cover: 1/3 Poor condition grass in Hydrologic Group A, 2/3 parking lot
Peaking Factor = 484

Q2: Use the provided spreadsheet to estimate discharge at time = 100 min

Q3: What should CN be to lower the peak cfs per inch of rainfall to 721?

SCS Method Tradeoffs

PROS

- Computationally efficient
- Can be adjusted with peaking factor, limb ratio, and CN to calibrate to observed data
- Very widely used
- Good for “quick checks”

CONS

- Linearity assumption: assumes that 2” of rainfall excess produces a peak discharge twice as large as 1” of rainfall excess
- Ie, response is independent of rainfall intensity
- Ie, rainfall excess is uniformly distributed throughout the catchment.
- No physical mechanisms represented. Cannot assign sensitivity in the model, if some condition changes in the watershed, won’t be able to calibrate
- Assumes overland surface runoff

A Top-Down Model Example for Urbanized Watersheds

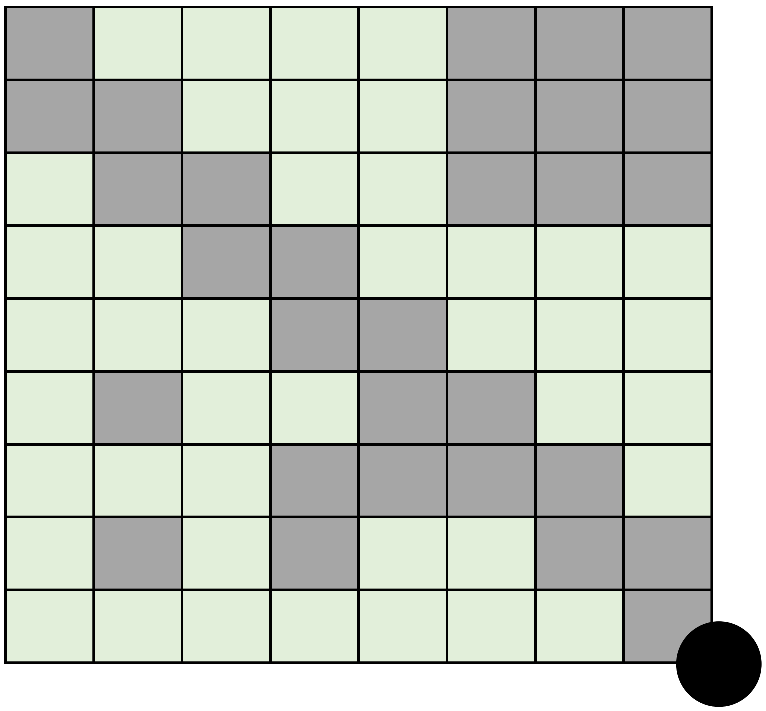
Premise: Do not assume CN, Peaking Factor, Land Cover/vegetation type, and instead look at the relationship between rainfall depth and average runoff depth for many storms, and across many watersheds.

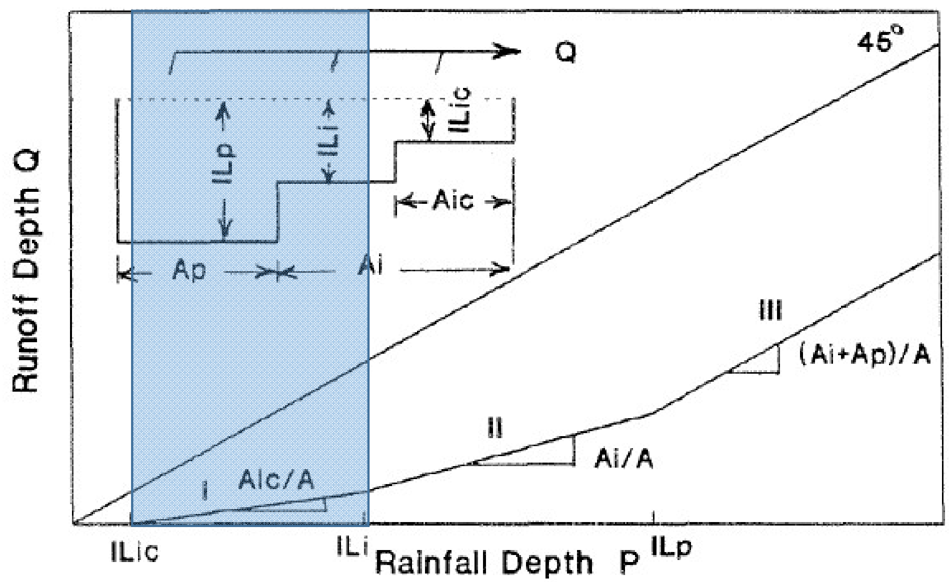
Instead: characterize the relationship between rainfall depth and runoff depth, and see what watershed characteristics best explain nonlinearity

A Top-Down Model Example for Urbanized Watersheds

Motivation: Many assume that hydraulic connectivity in urbanized watersheds (ie, flashy response) is primarily determined by imperviousness preventing infiltration into subsurface. Is this true?

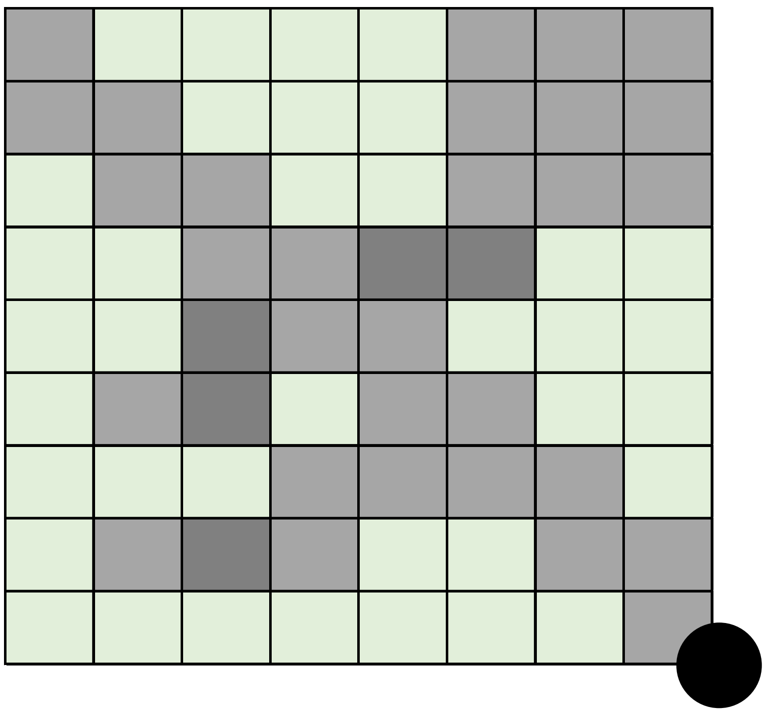
Simple Conceptualization of Changing Contributing Area

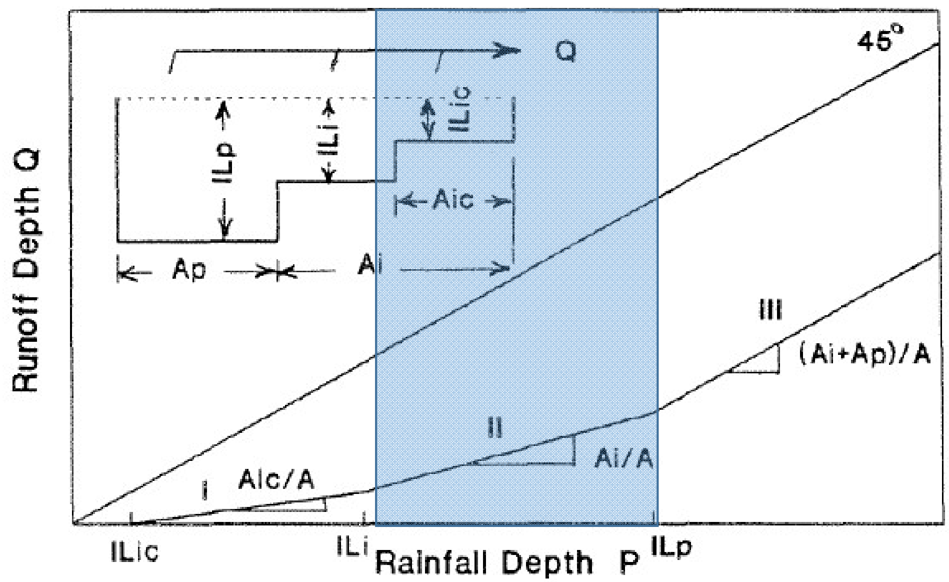




Boyd, et al 1994

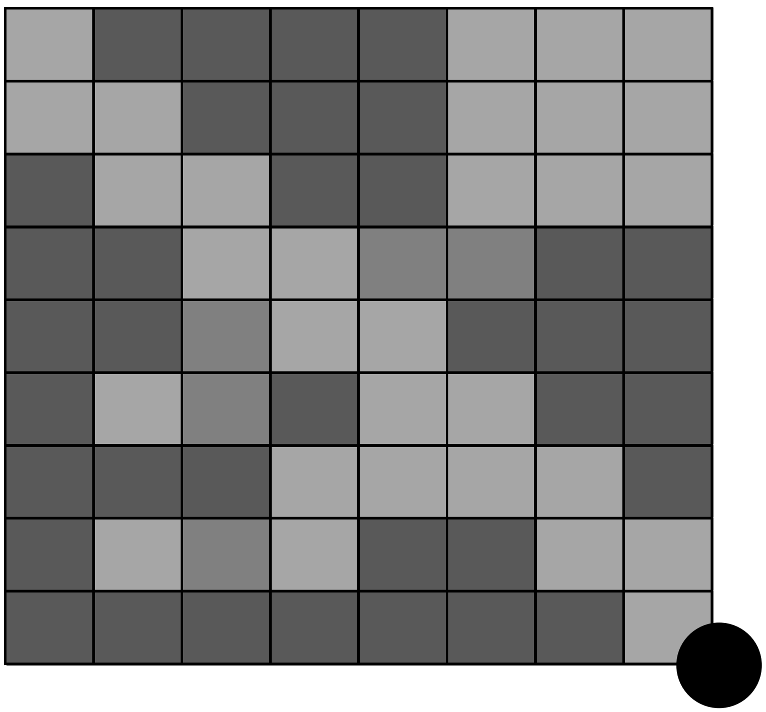
Simple Conceptualization of Changing Contributing Area

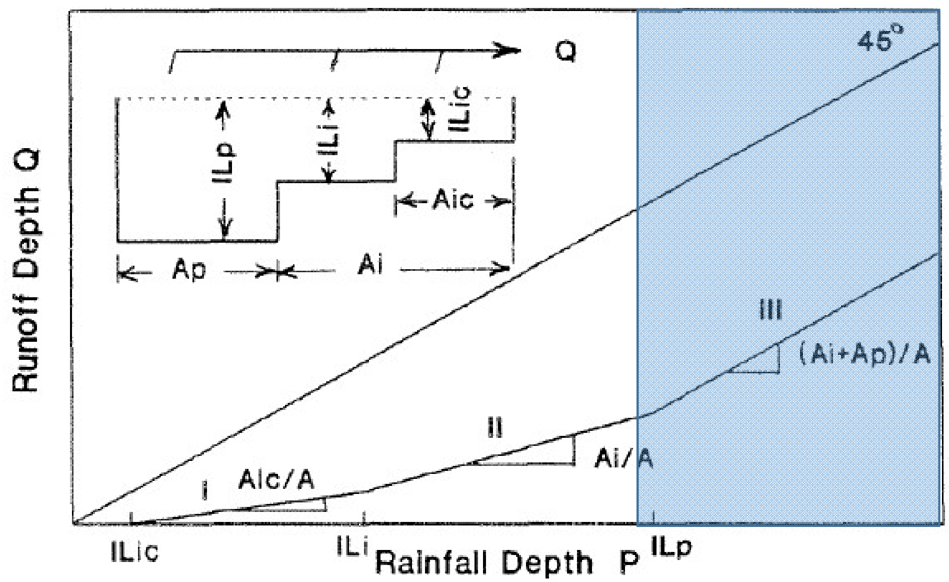




Boyd, et al 1994

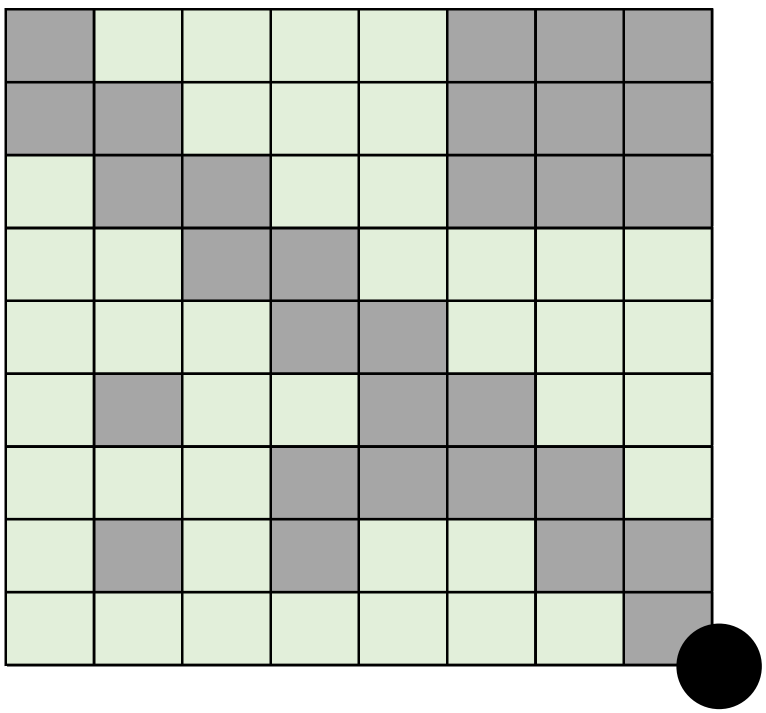
Simple Conceptualization of Changing Contributing Area

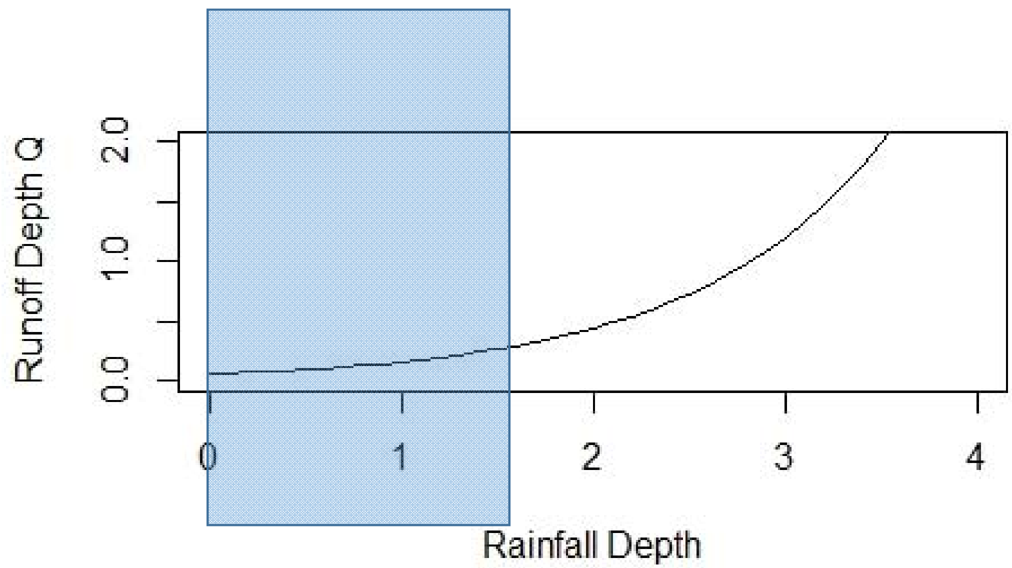




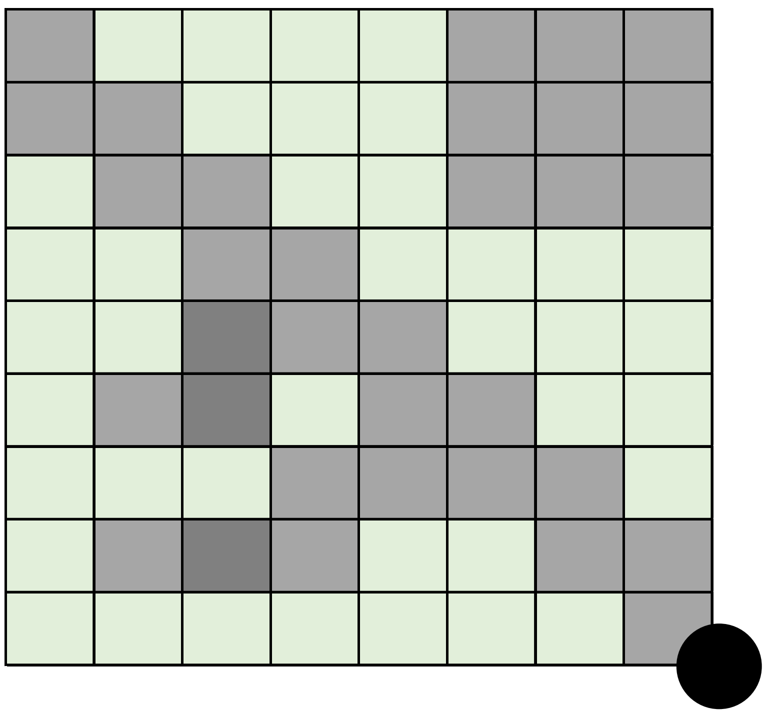
Boyd, et al 1994

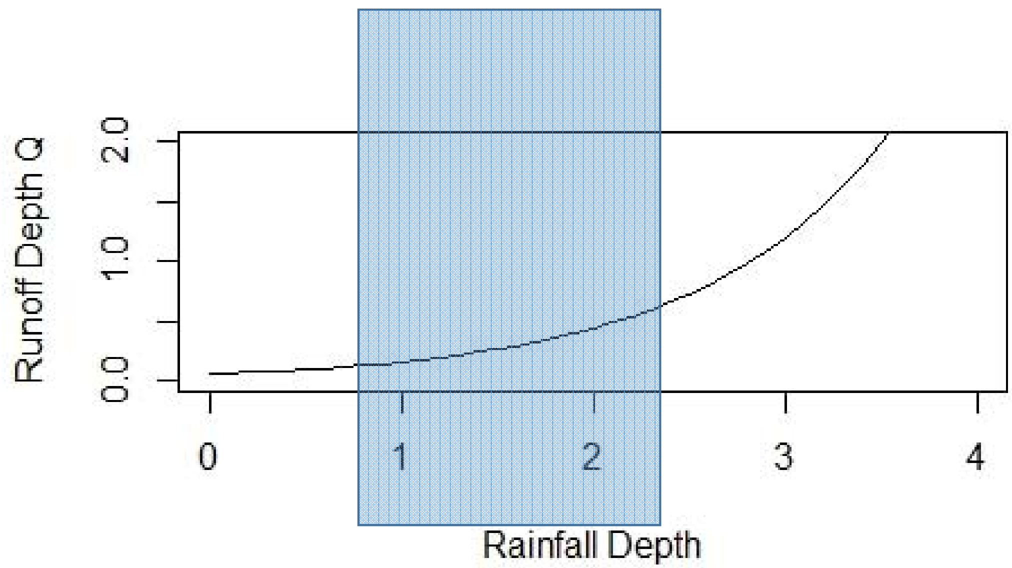
Nuance: probably more continuous



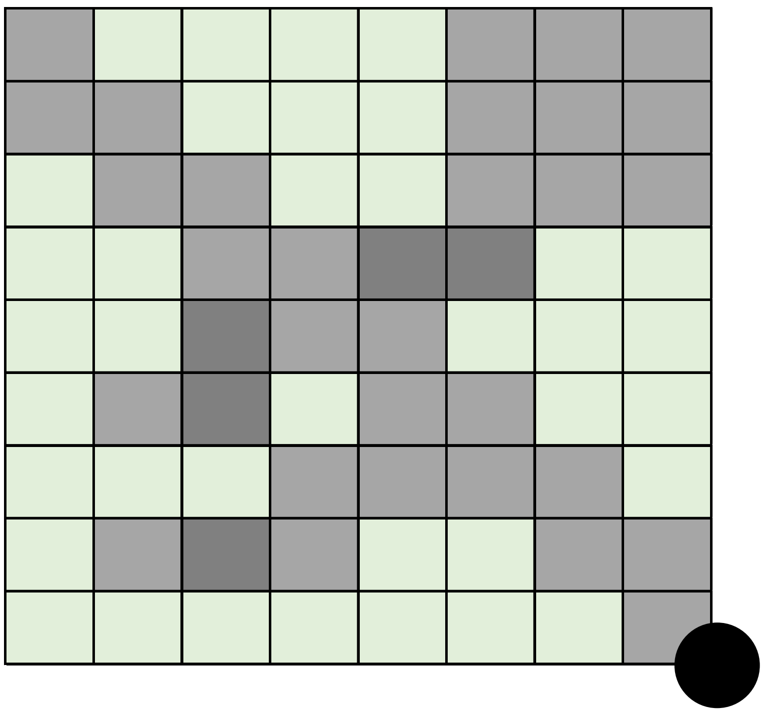


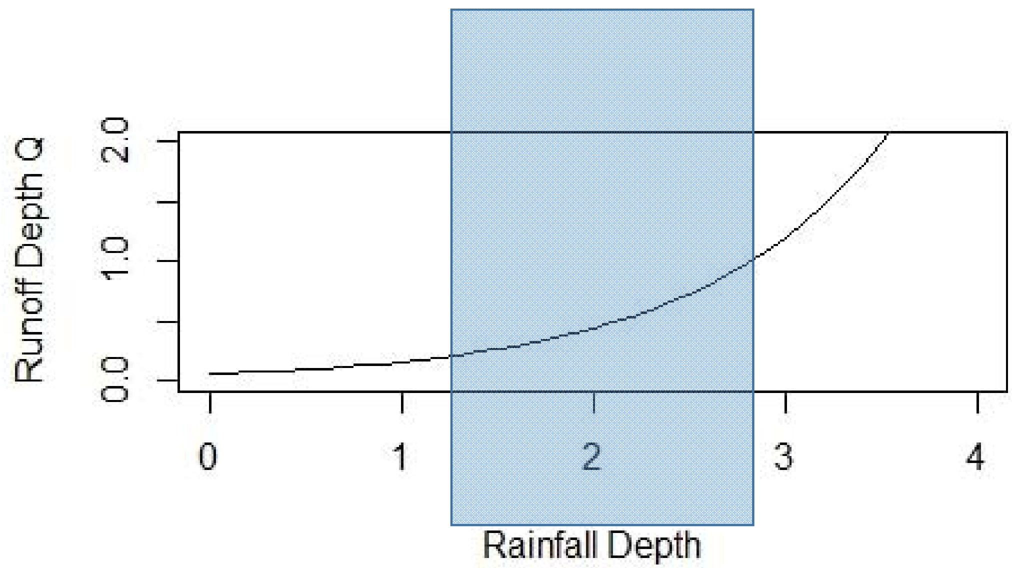
Nuance: probably more continuous



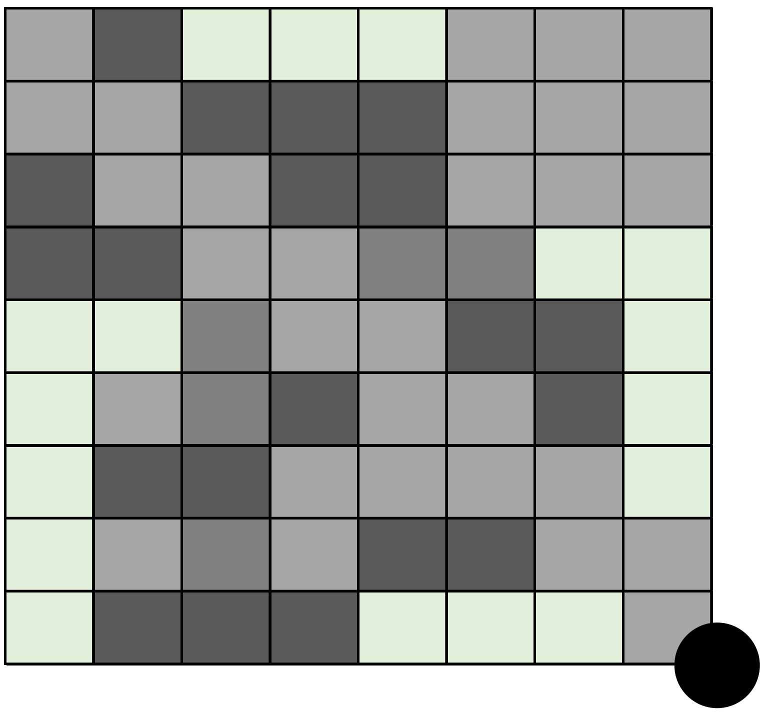


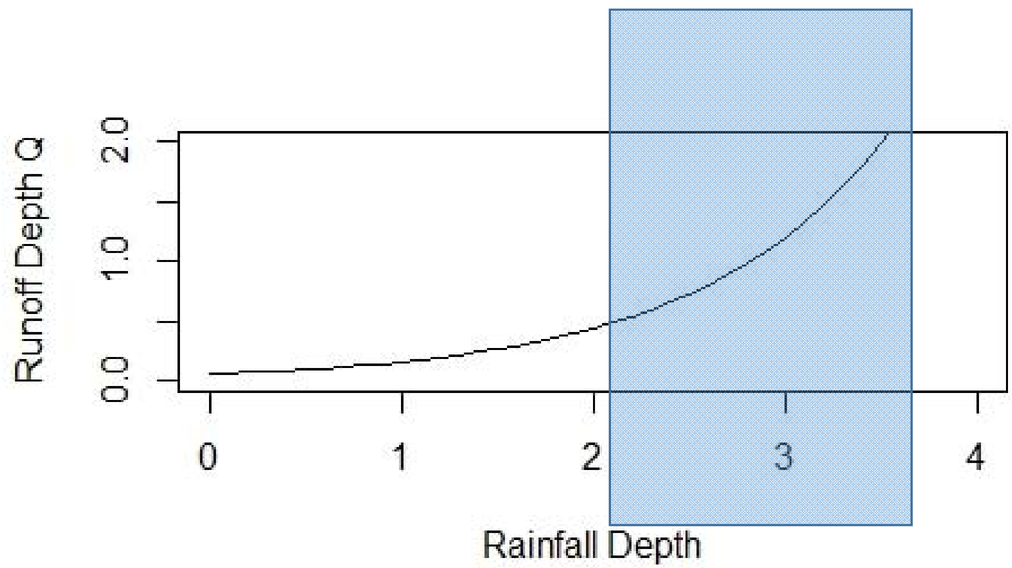
Nuance: probably more continuous



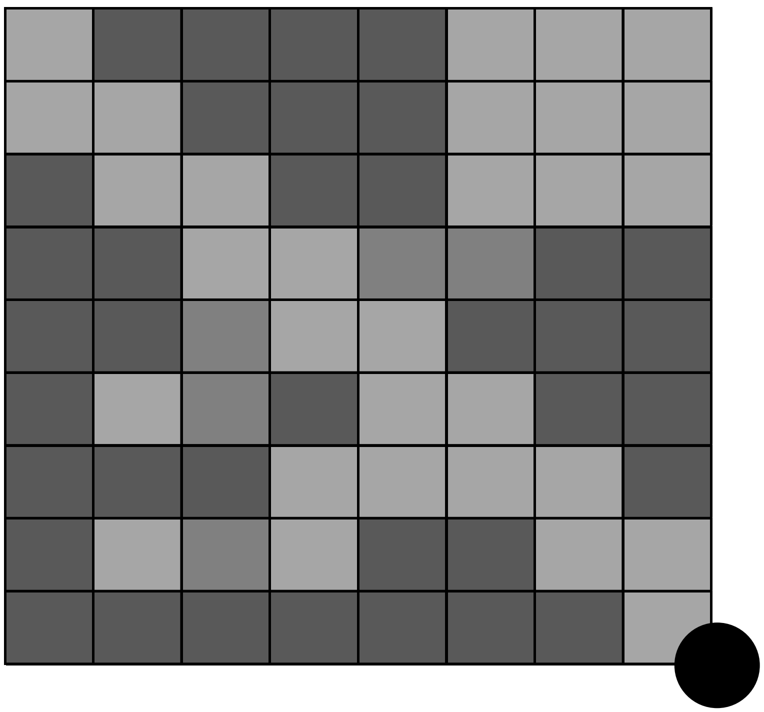


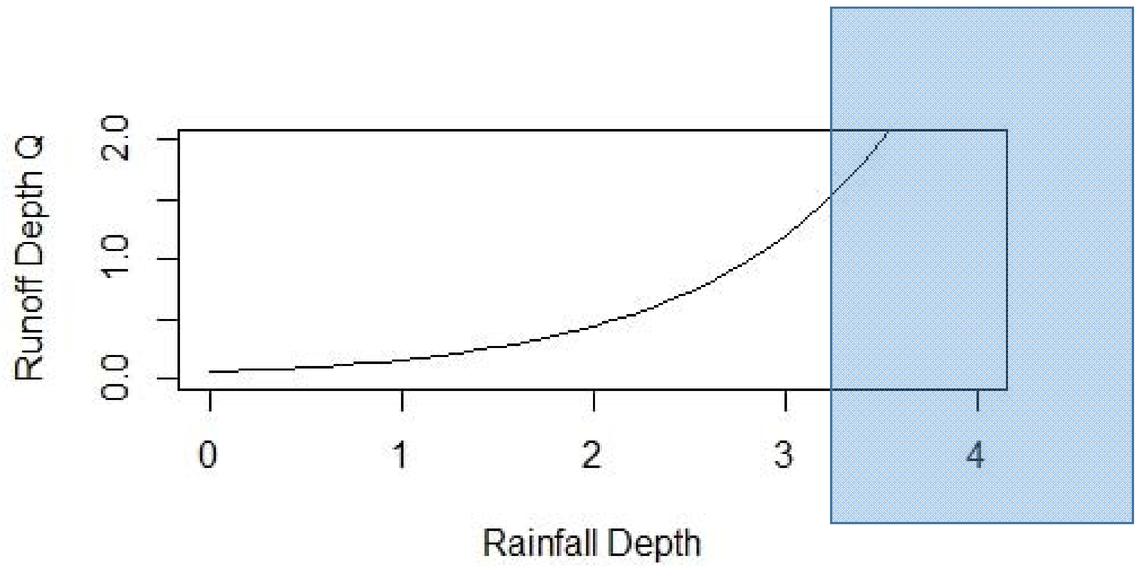
Nuance: probably more continuous





Nuance: probably more continuous



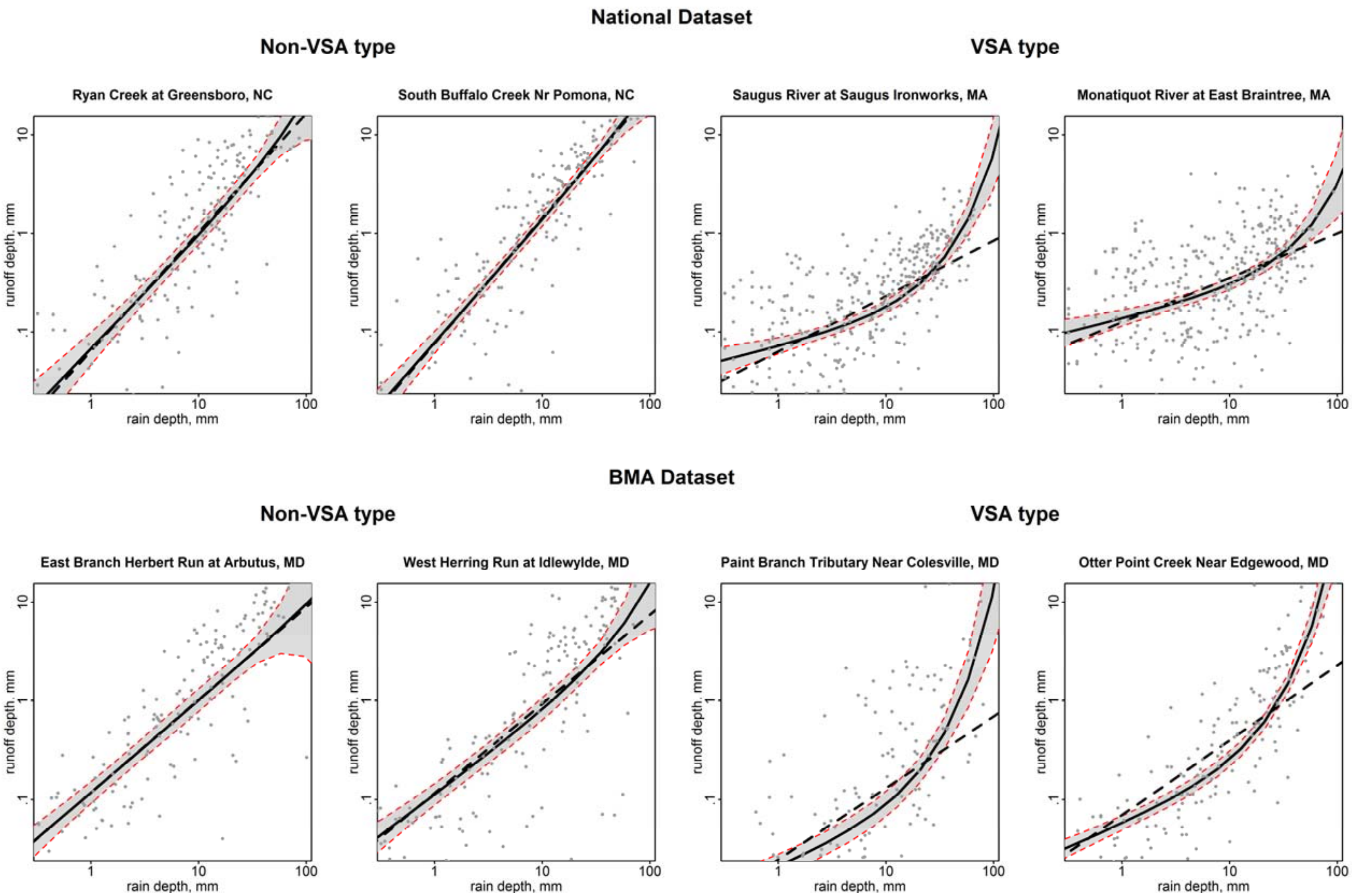


A Top-Down Model Example for Urbanized Watersheds

Non-linear response = less “flashy flows”. Contributing areas are becoming connected only as storm size increases; not all at once. (There is distributed “storage” in the watershed)

Logic:

Detect nonlinear response over many rainfall events for many catchments → Determine what factors best predict nonlinear response: is it low levels of impervious surface?



Source: Lim, 2016

FIGURE 5: Example plots of linear and nonlinear relationships between rainfall and runoff (log transformed). Gray areas represent 90% confidence interval of model fit with both linear and nonlinear terms included, using robust standard estimates. The solid line is the *predicted relationship with both linear and* nonlinear terms included. The dashed line is the predicted relationship with only the linear term included

TABLE 2. Results of logistic regression of percent undeveloped land and other controls on probability of VSA-type response

	MODEL 1A: Undeveloped Land			MODEL1B: Undeveloped Land + Morphologic and Meteorological Controls				MODEL1C: Undeveloped Land + Development Characteristics + Morph/Met Controls			
Panel A: National Dataset (n = 91)											
	Estimate	Effect on Odds (%)	t-statistic [(a)]	Estimate	Effect on Odds (%)	t-statistic	VIF	Estimate	Effect on Odds (%)	t-statistic	VIF
Undeveloped Land (%)	0.034	3.476	1.327 .	0.053	5.488	2.392 *	1.324	0.066	6.842	1.233	6.981
Total Impervious Area (%)								0.012	1.249	0.133	14.579
Developed Open Space (%)								-0.032	-3.154	-0.502	6.655
Distance to CSO (m)								0.000	0.000	0.535	1.965
Ret/Det SW Infrastructure (binary)								0.301	35.081	0.459	1.483
Average Slope (%)				-0.441	-35.682	-2.225 *	1.370	-0.298	-25.763	-1.332	1.670
Average Annual Precipitation (cm/yr)				0.038	3.892	1.964 *	1.159	0.036	3.692	1.456	1.694
Catchment Area (km^2)				0.002	0.152	0.448	1.143	0.000	0.015	0.036	1.547
Intercept	0.516	67.566	0.185	-3.160	-96	-1.491		-3.270	-96	-0.694	
McFadden's R^2	0.038			0.124				0.143			
Count-based R^2 (above mean)	0.560			0.670				0.692			

Table 3. Results of logistic regression of development types and other controls on probability of VSA-type response

Panel A: National Dataset (n = 91)	MODEL 2A: TIA				MODEL2B: TIA + Open Space				MODEL2C: TIA + Open Space + Other Development Characteristics			
	Estimate	Effect on Odds (%)	t-statistic [a]	VIF	Estimate	Effect on Odds (%)	t-statistic	VIF	Estimate	Effect on Odds (%)	t-statistic	VIF
Total Impervious Area (%)	-0.023	-2.235	-0.861	1.400	-0.083	-7.981	-2.157 *	2.724	-0.092	-8.758	-2.275 *	2.932
Developed Open Space (%)					-0.089	-8.554	-2.364 *	2.433	-0.095	-9.095	-2.449 *	2.591
Distance to CSO (m)									0.000	0.000	0.789	1.873
Ret/Det SW Infrastructure (binary)									0.120	12.776	0.190	1.411
Average Slope (%)	-0.327	-27.879	-1.613	1.509	-0.348	-29.363	-1.669 .	1.517	-0.289	-25.068	-1.304	1.656
Average Annual Precipitation (cm/yr)	0.036	3.646	1.919 .	1.177	0.052	5.319	2.465 *	1.378	0.048	4.906	2.111 *	1.457
Catchment Area (km^2)	0.003	0.350	0.290	1.066	0.002	0.222	0.668	1.094	0.001	0.055	0.134	1.529
Intercept	-1.621	-80.234	-0.781		0.881	141.303	0.362		1.472	335.976	0.547	
McFadden's R^2	0.066				0.128				0.553			
Count-based R^2 (above mean)	0.626				0.648				0.703			

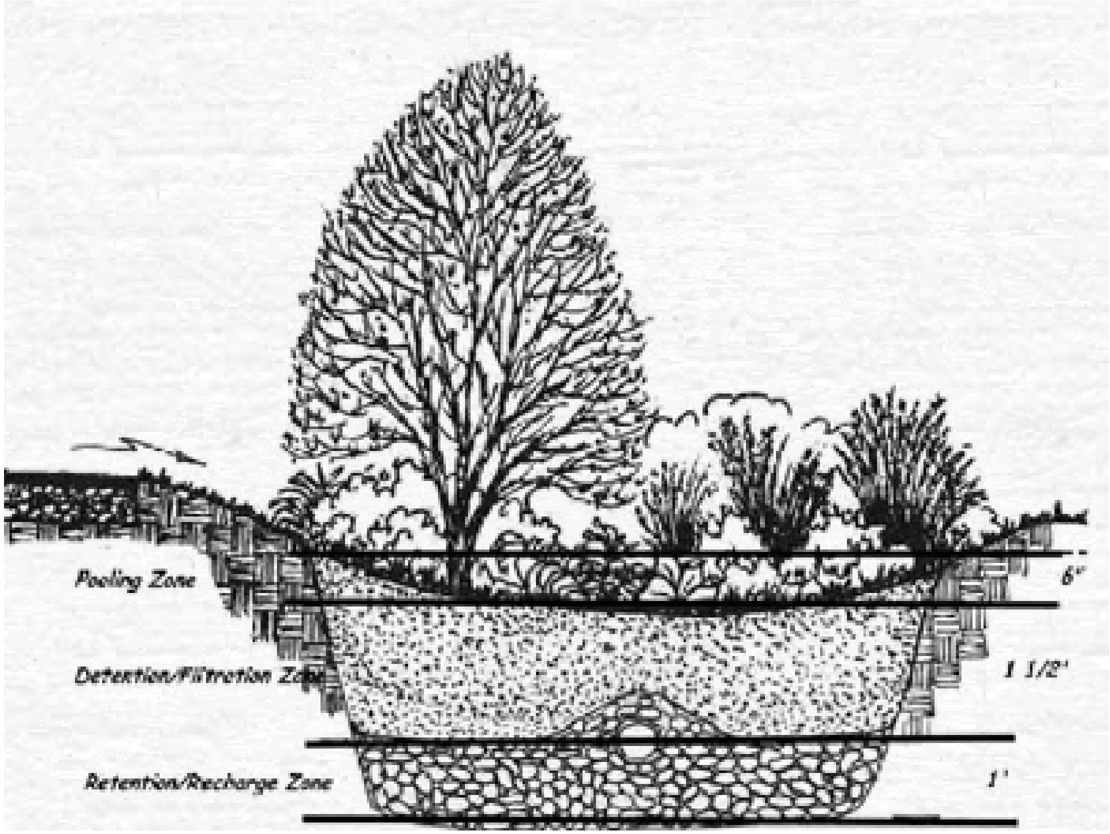
1. **Percent Undeveloped is the Best Predictor of Incremental Storage in Watershed**
2. **Low density development functions more similarly to impervious surface than undeveloped land (why?)**

HydroCAD Demo: A Rain Garden

Note: HydroCAD is not a watershed model.
It is based on modeling "ponds"
The underlying premise is a "level" pool surface, or large stone/gravel filled structures.

We typically do not have that condition with rain gardens.

Have to develop work arounds.



HydroCAD Demo: SCS 24h rain distributions

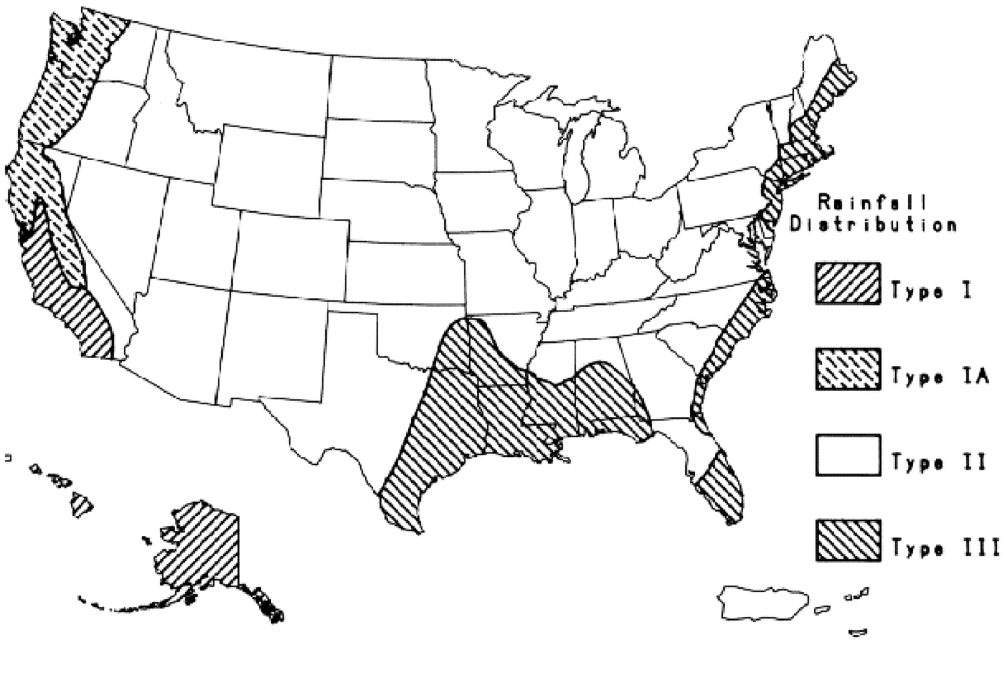
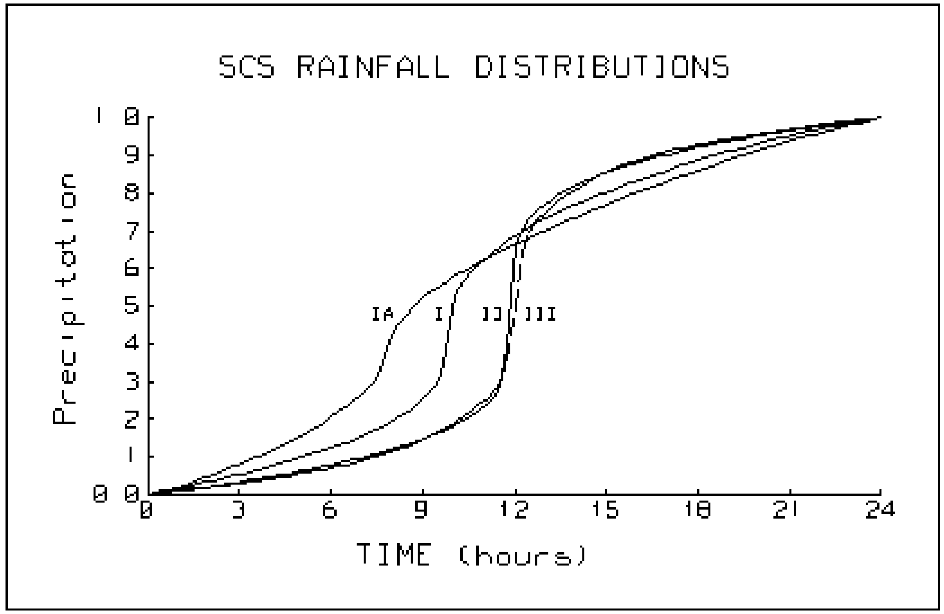
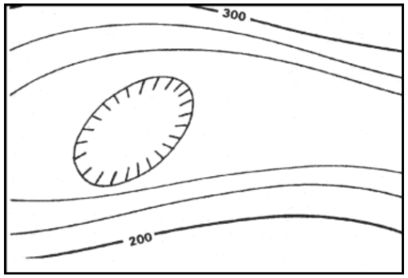


Figure B-2.—Approximate geographic boundaries for SCS rainfall distributions.



What to look for on a field site visit

- Sheet flow, shallow channelized (Rule of Thumb, 300 ft) if raining
- Mark breaklines – eg: retention wall, other sharp discontinuities in topography – dark black line
- Look for evidence of soil erosion, mark on map – squiggly line. How to stabilize?



- Mark local depressions, hills
- Mark all downspout locations
- Mark existing condition with (E)
- Jot ideas for grading improvement with (P) or different color pen
- If going during/right after rain, note where ponding occurs (X), depth, and why – blocked inlet? Pavement issue? Surface Grading? Compacted soil?

Other Design Thoughts

"Dear PoPville,

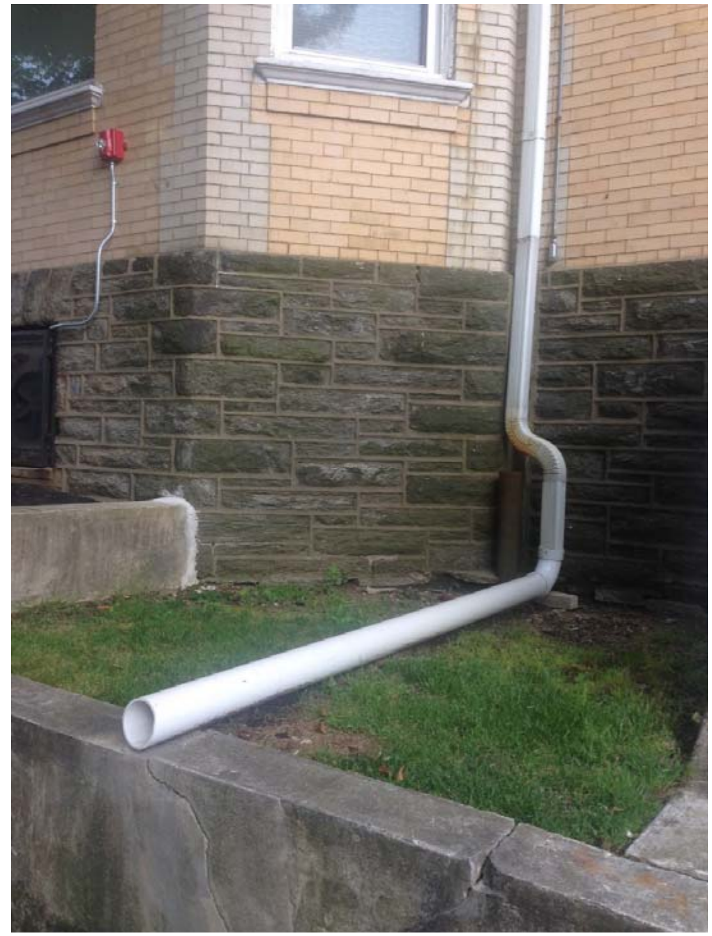
Just wanted to pass along a pretty disappointing photo. The Carter G. Woodson Park was recently completed in Shaw at a cost of over $1 million. It is a beautiful space and a great addition to the neighborhood. However, **after every storm, a sizable portion of the park floods due to poor drainage**. Many of the new plants are already showing damage. It is a shame that the landscapers didn't anticipate this problem. Hopefully, it can be fixed soon and the park can live on for many years as it was intended."

Ed. Note: When I first saw one of these giant puddles in Petworth years ago, I was confused too but was told it was perfectly normal that it was just a rain garden intended to collect water like this. Isn't this same thing?

http://www.popville.com/2015/07/whats-up-with-the-giant-puddle-at-the-new-carter-woodson-park-in-shaw/

Other Design Thoughts

A speedbump berm



A “disconnected” downspout

Data Sources

Precipitation

- Many cities have their own rainfall gage networks. Can use Theissen polygons or spline methods to interpolate basin-averaged rainfall depths/intensities
- CoCoRaHS - citizen science – network of rainfall gages
- NOAA – NCDC – large network of airport-based rain gages
- NEXRAD – radar based (continuous, rather than discrete data points)

Data Sources

Flows

- Most large cities will have monitoring within sanitary sewer/separate sewer pipes very few monitor stormwater pipes
- USGS stream gages – many are in urbanized watersheds

Soils/Subsurface

- "Urban" soils = Who knows!? Important to get: permeability (hydraulic conductivity, and/or infiltration rates)
- Groundwater table level
- Bedrock? Clay lenses?

Vegetation

- Land cover type (NLCD ~ 30 m resolution) , anything better? Try UVM