



# An Introduction to the Storm Water Management Model (SWMM)

Michelle Simon  
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<https://www.epa.gov/waterdata/surface-water-quality-modeling-training>

# Speaker Introduction

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20 Years Superfund Site Technical Support

Working with SWMM since 2010

New EPA Technical POC for SWMM  
(after the retirement of Lew Rossman  
April 2017)



# Disclaimer

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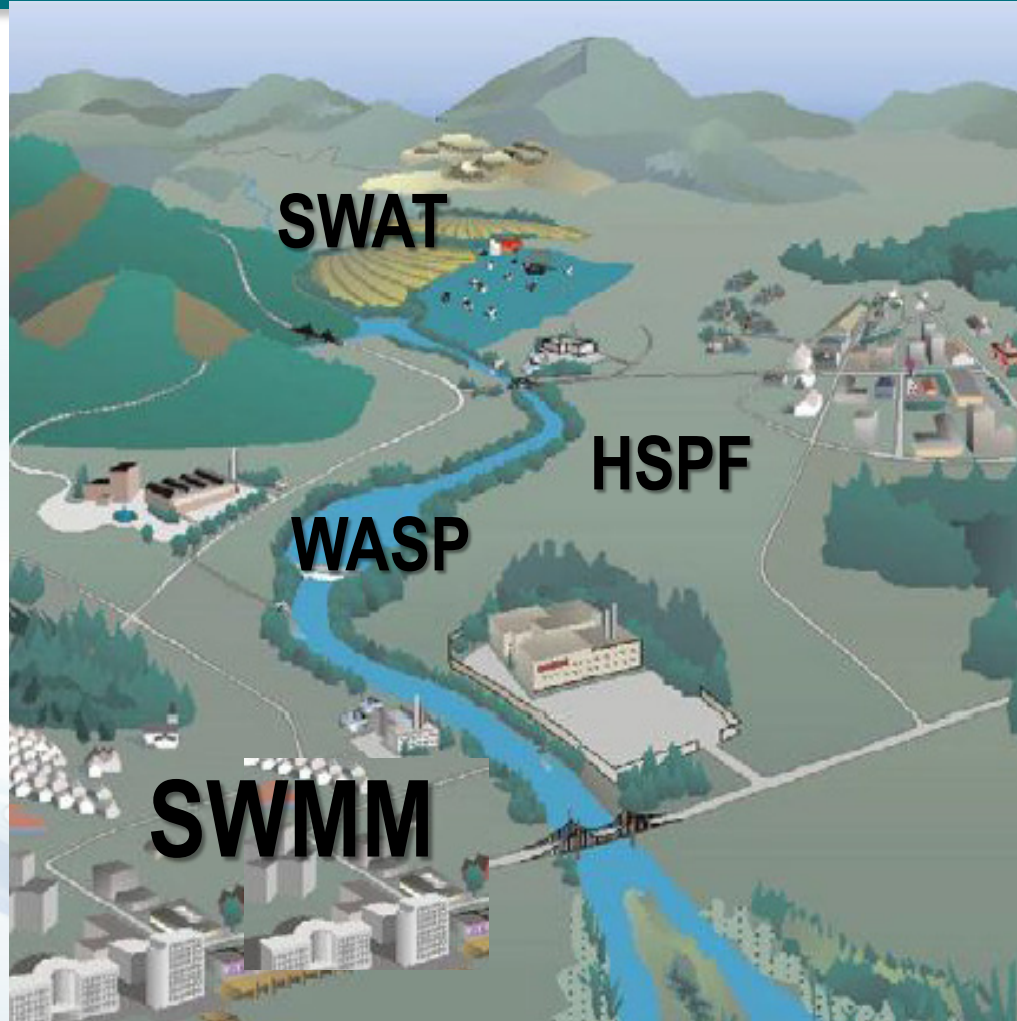
# Outline

## Storm Water Management Model

- What is SWMM?
- Processes Modeled by SWMM
- Demonstration of SWMM
- Low Impact Development (LID)
- National Stormwater Calculator
- Location of Data
- Technical Support
- Discussion & Questions



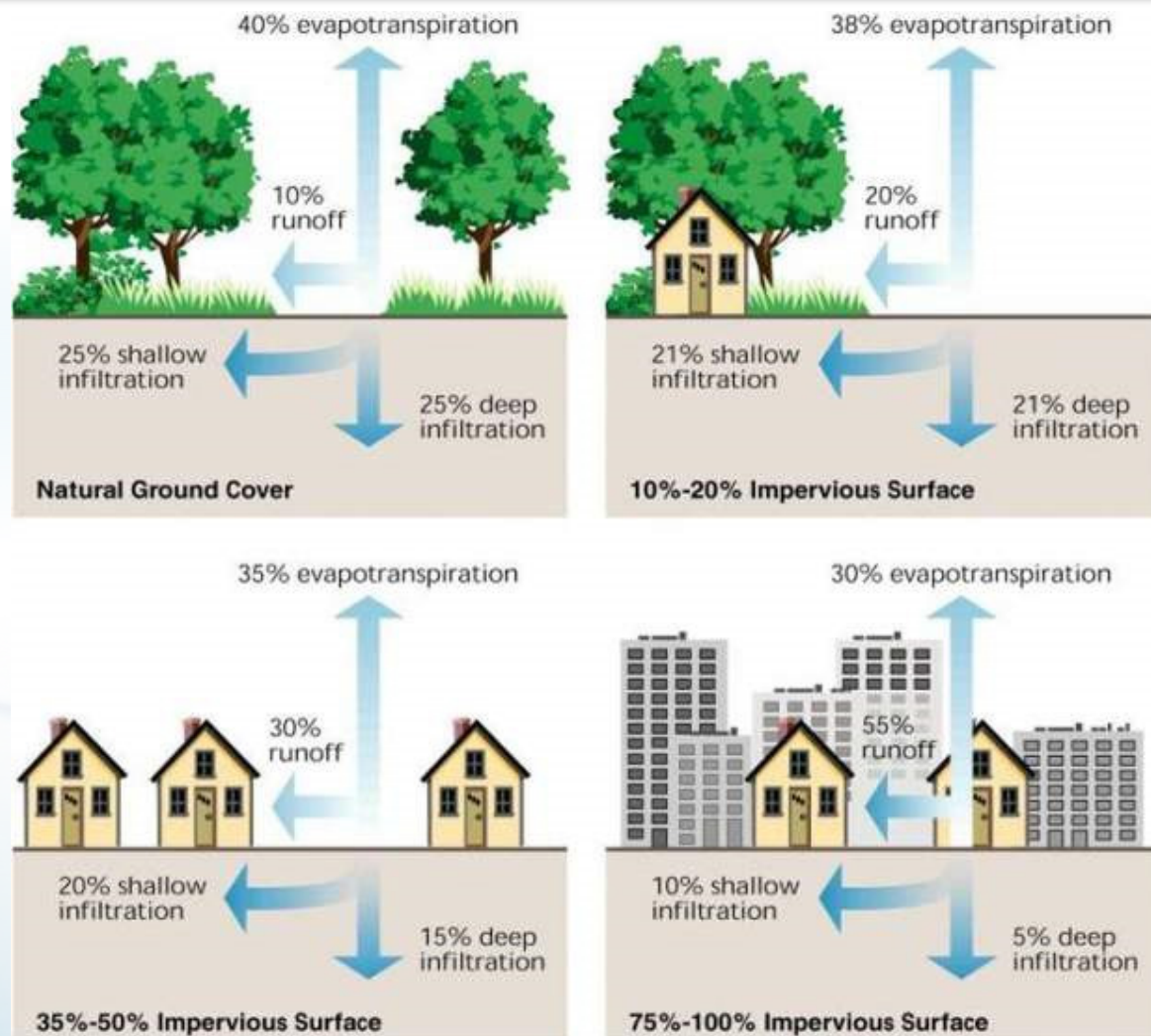
# How SWMM, HSPF, SWAT, and WASP Relate



<https://cfpub.epa.gov/watertrain/pdf/modules/WshedModTools.pdf>

<https://www.aquaterra.com/resources/pubs/fiftyyearwatershedconferencePrograms.php>

# Urbanization Changes the Hydrologic Cycle

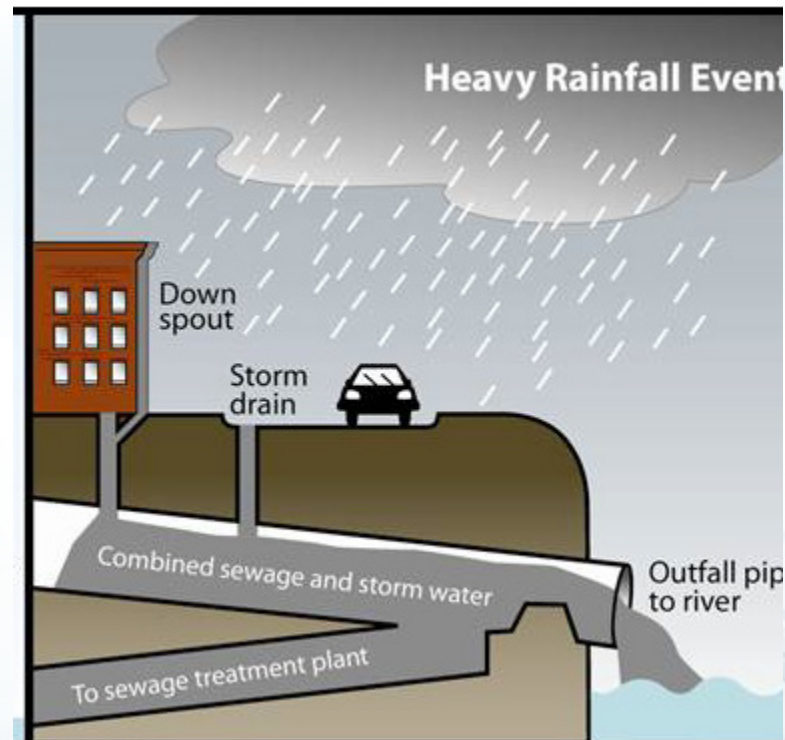


- Soils and vegetation are replaced with impervious surfaces
- Impervious surfaces are connected to dense drainage networks
- Runoff drains directly into streams, lakes, wetlands, and coastal waters
- Even small storms generate significant runoff

# 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 e coli, metals, PAHs, and other pollutants.
- **Reduced groundwater** recharge impacts water supplies.





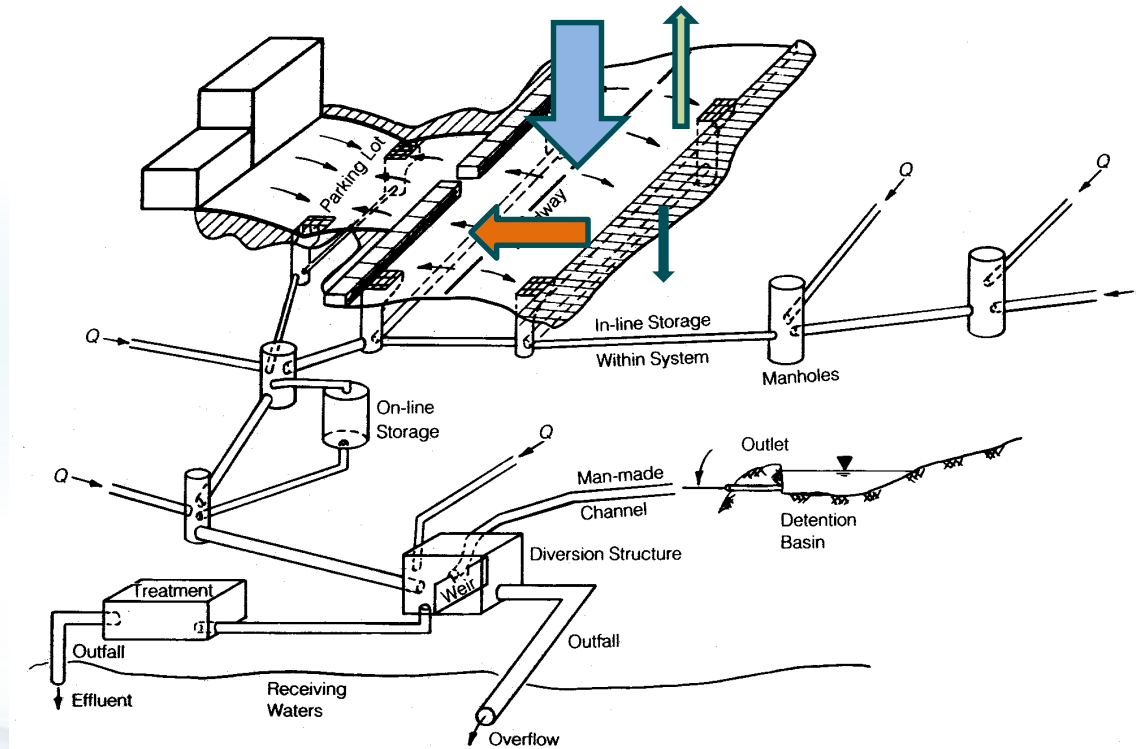
# What is SWMM?



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.

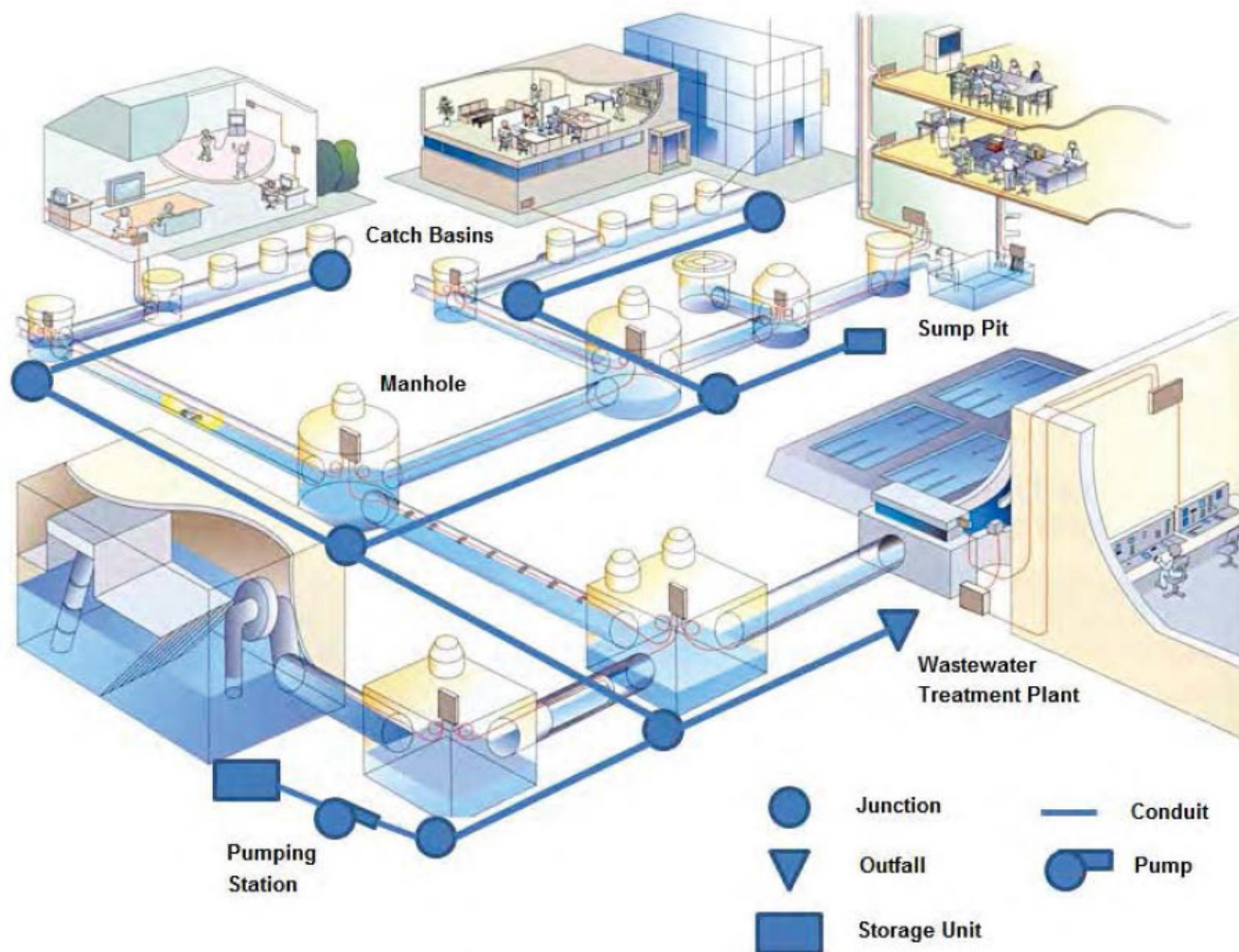


# How does SWMM Model?



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**.

# Hydraulic Model



# 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.

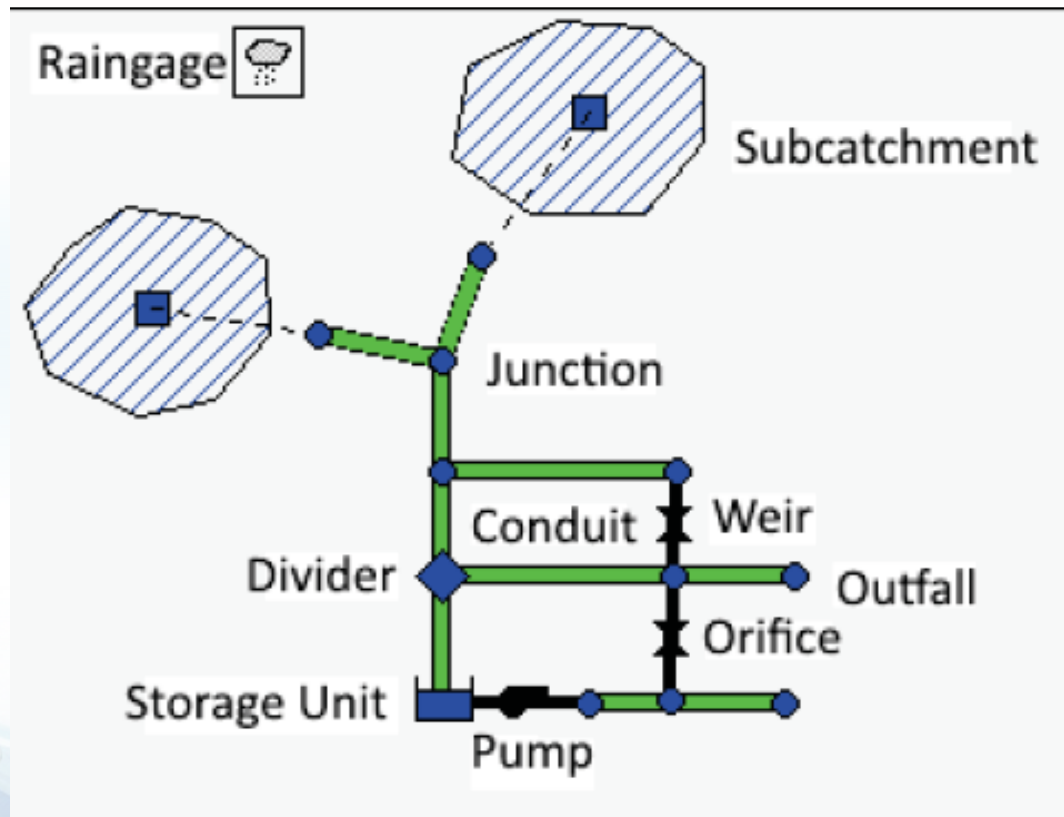


Evaluating green infrastructure for sustainability goals.



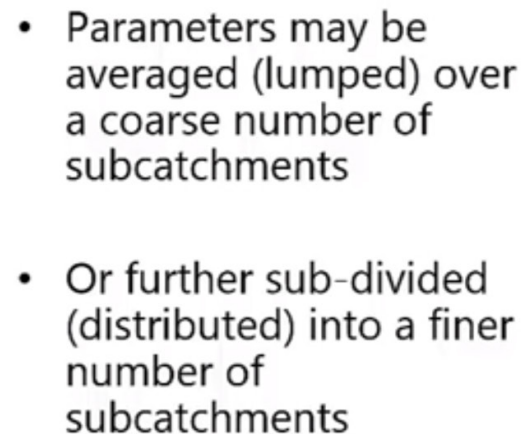
Flood plain mapping of natural channel systems.

# SWMM's Conceptual Model





## Subcatchment parameters



14

# 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).

Hydrology Reference Manual Equation 3-1

# Hydraulic Governing Equations

- Continuity

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0$$

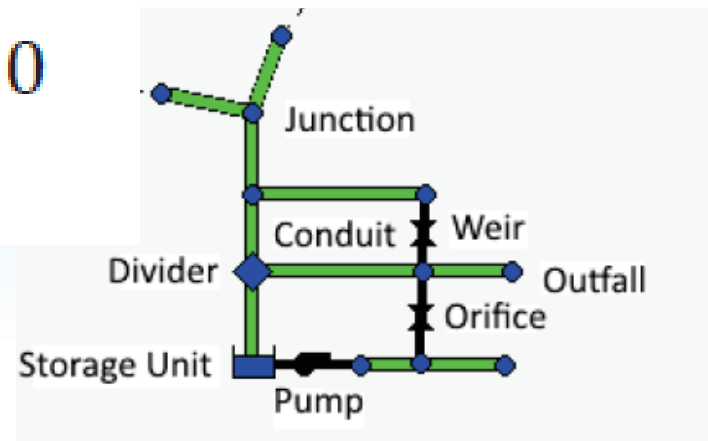
where

$x$  = distance (ft)

$t$  = time (sec)

$A$  = flow cross-sectional area (ft<sup>2</sup>)

$Q$  = flow rate (cfs)



# Governing Equations

- Momentum

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

$H$  = 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<sup>2</sup>)



# Assumptions

- Assumes varied, unsteady flow (Saint Venant Equations)
- Level of Sophistication
  - Steady Flow Routing
  - Kinematics Wave Routing
  - Dynamic Wave Routing

# Dynamic Wave Routing

Used for

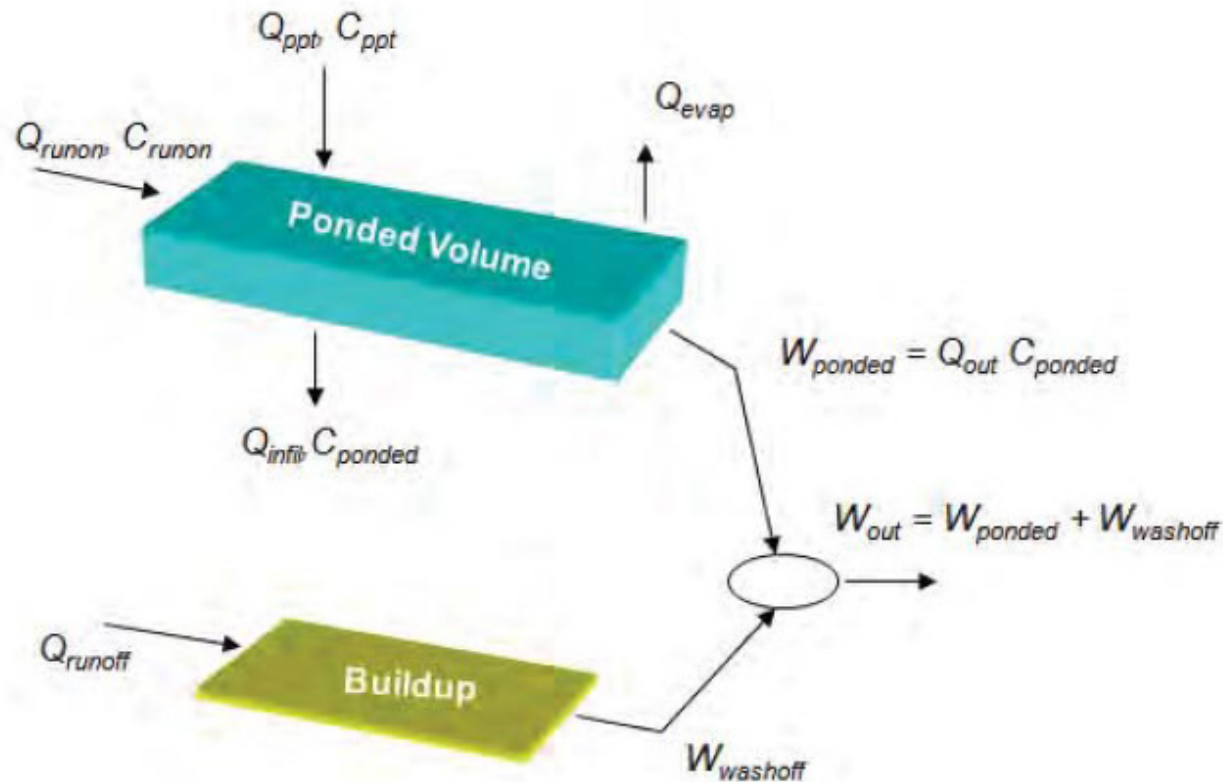
- Branched or looped networks
- Backwater due to tidal or other conditions
- Free-surface flow
- Pressure flow or surcharge
- Flow reversals

# Kinematic Wave

Cannot have

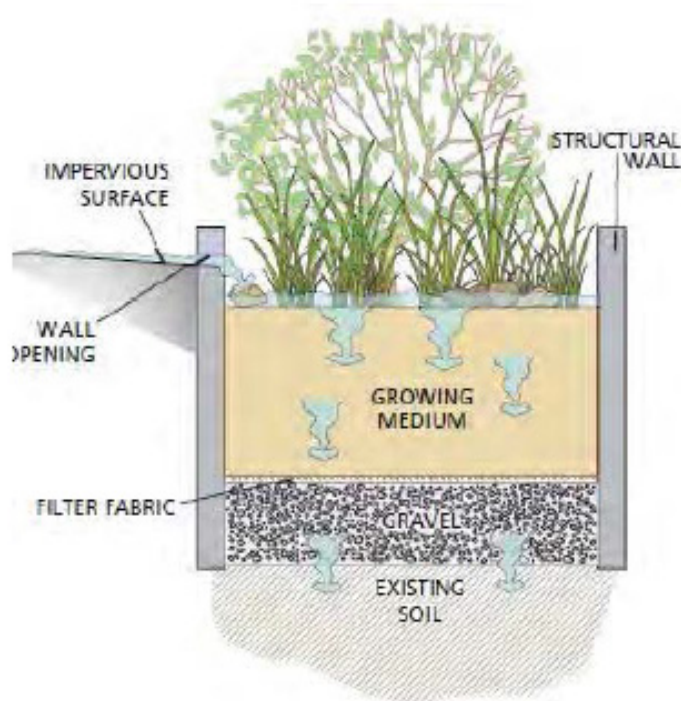
- Looped networks
- Backwater effects
- Pressure-flow conditions

# Pollutant Buildup and Washoff

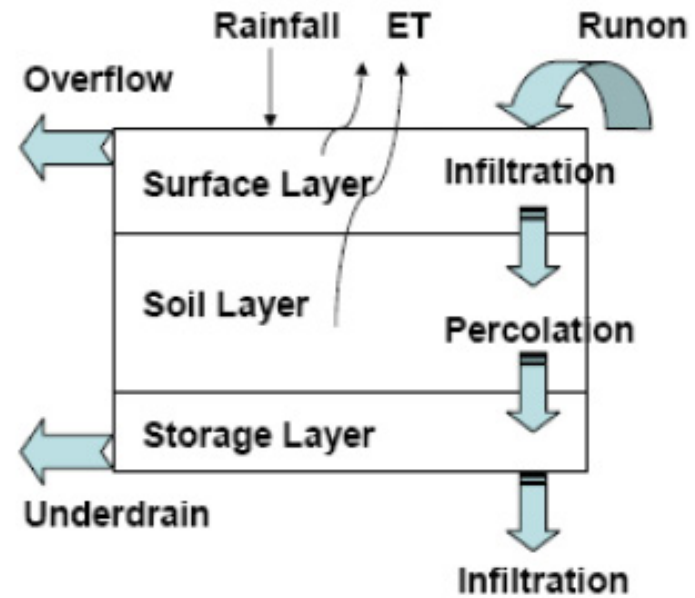




# Green Infrastructure Subcatchment



(A)



(B)

# Questions?



# Demonstration of SWMM

- Walk through
  - Hydrology
  - Hydraulics
  - Water Quality
  - Low Impact Development
- Calibration of SWMM

# SWMM Demonstration

- Go to Desktop SWMM

# Hydraulic Animation

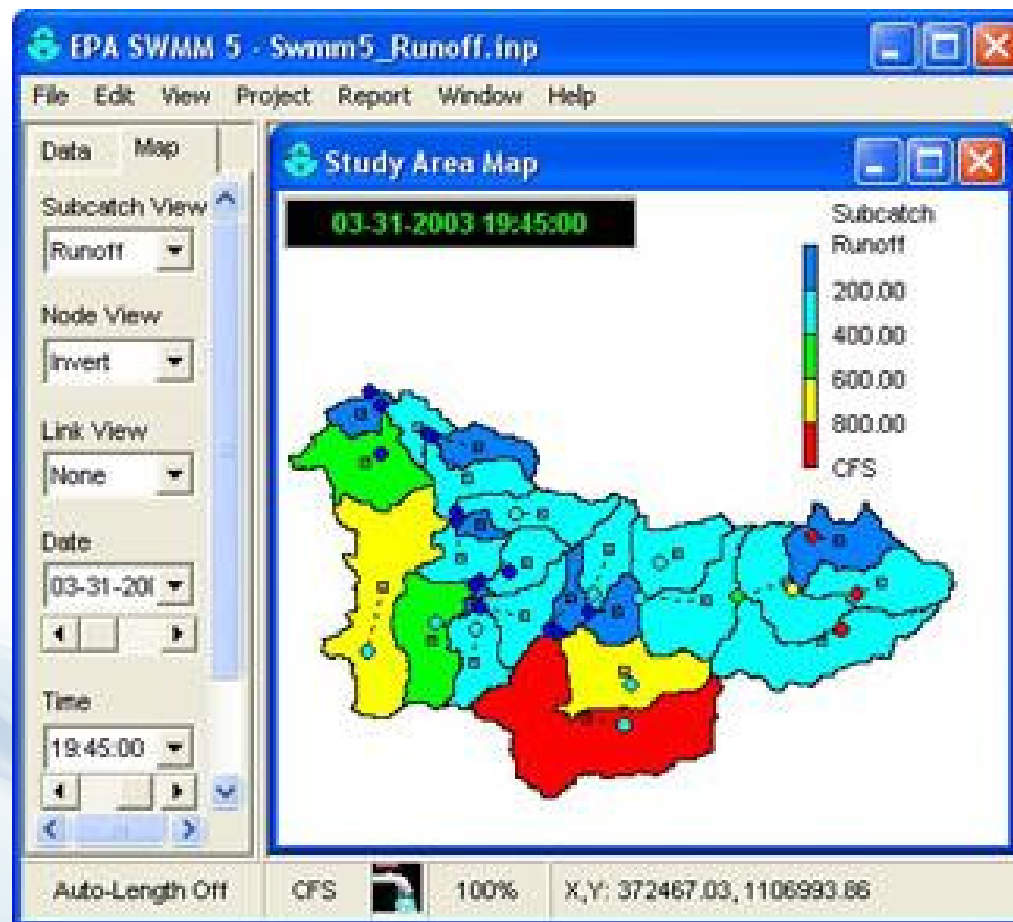
(Courtesy of Robert Dickinson, Innovyze)





# Storm Water Management Model

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



# SWMM Webpage, continued

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

## Downloads

Date	Description
03/30/2017	<a href="#">Self-Extracting Installation Program for SWMM 5.1.012 (EXE)</a> (5 MB)
12/11/2014	<a href="#">SWMM-CAT Download Version 1</a> (4 MB)
03/30/2017	<a href="#">List of SWMM 5 Updates and Bug Fixes (TXT)</a> (1 pg, 132 K)
03/30/2017	<a href="#">Source Code for the SWMM 5.1.012 Computational Engine (ZIP)</a> (375 K)
03/30/2017	<a href="#">Source code for the SWMM 5.1.012 graphical user interface (ZIP)</a> (2 MB)
09/07/2016	<a href="#">SWMM 5.1 Interface Guide (ZIP)</a> (47 K)
05/25/2005	<a href="#">Utility for converting SWMM 4 data files to SWMM 5 files (EXE) Version 1.2</a> (2 MB)

# SWMM Webpage, continued

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

## Documentation

Date	Title
09/30/2015	<a href="#">SWMM 5.1 User's Manual</a>
09/01/2014	<a href="#">SWMM-CAT User's Guide</a>
01/29/2016	<a href="#">SWMM Reference Manual Volume I—Hydrology</a>
08/07/2017	<a href="#">SWMM Reference Manual Volume II—Hydraulics</a>
09/08/2016	<a href="#">SWMM Reference Manual Volume III—Water Quality</a>
01/31/2017	<a href="#">SWMM Technical Fact Sheet</a>
07/06/2010	<a href="#">SWMM Applications Manual (ZIP)</a> (7 MB)
09/19/2006	<a href="#">Quality Assurance Report for Dynamic Wave Flow Routing (ZIP)</a> (3 MB)

# Storm Water Management Model Reference Manual

## Volume I – Hydrology (Revised)





# Storm Water Management Model Reference Manual

## Volume II –Hydraulics



# Storm Water Management Model Reference Manual

## Volume III – Water Quality



# SWMM Reference Manuals

## 4.4 Green-Ampt Method

The Green-Ampt equation (Green and Ampt, 1911) has received considerable attention in recent years. The original equation was for infiltration with excess water at the surface at all times. Mein and Larson (1973) showed how it could be adapted to a steady rainfall input and proposed a way in which the capillary suction parameter could be determined. Chu (1978) has shown the applicability of the equation to the unsteady rainfall situation, using data for a field catchment. The Green-Ampt method was added into SWMM III in 1981 by R.G. Mein and W. Huber (Huber et al., 1981).

### 4.4.1 Governing Equations

The Green-Ampt conceptualization of the infiltration process is one in which infiltrated water moves vertically downward in a saturated layer, beginning at the surface (Figure 4-5). In the wetted zone the moisture content  $\theta$  is at saturation  $\theta_s$ ; while the moisture content in the un-wetted zone is at some known initial level  $\theta_i$ .

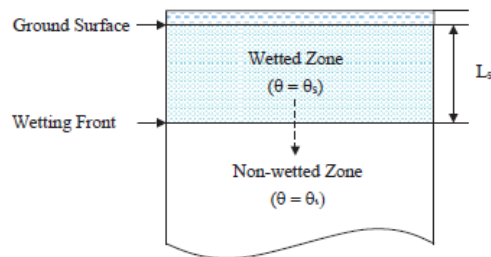


Figure 4-5 Two-zone representation of the Green-Ampt infiltration model (after Nicklow et al., 2006).

The water velocity within the wetted zone is given by Darcy's Law as a function of the saturated hydraulic conductivity  $K_s$ , the capillary suction head along the wetting front  $\psi_s$ , the depth of ponded water at the surface  $d$ , and the depth of the saturated layer below the surface  $L_s$ :

$$f_p = K_s \left[ \frac{d + L_s + \psi_s}{L_s} \right] \quad (4-26)$$

The depth of the saturated layer  $L_s$  can be expressed in terms of the cumulative infiltration,  $F$ , and the initial moisture deficit to be filled below the wetting front,  $\theta_d = \theta_s - \theta_i$  as  $L_s = F / \theta_d$ . Substituting this into Equation 4-26 and assuming that  $d$  is small compared to the other depths gives the Green-Ampt equation for saturated conditions:

$$f_p = K_s \left[ 1 + \frac{\psi_s \theta_d}{F} \right] \quad (4-27)$$

Equation 4-27 applies only after a saturated layer develops at the ground surface. Prior to this point in time the infiltration capacity will equal the rainfall intensity:

$$f_p = i \quad (4-28)$$

As time increases, one can test whether saturation has been reached by solving 4-27 for  $F$  (which will be denoted as  $F_s$ ) with  $f_p$  set equal to  $i$  and check if this value equals or exceeds the actual cumulative infiltration  $F$ :

$$F_s = \frac{K_s \psi_s \theta_d}{i - K_s} \quad (4-29)$$

Note that there is no calculation of  $F_s$  when  $i \leq K_s$ , although  $F$  still gets updated during such periods. Finally, in this scheme the actual infiltration  $f$  is the same as the potential value  $f_p$ :

$$f = f_p \quad (4-30)$$

The two equations are illustrated in Figure 4-6 for the situation  $K_s = 0.25$  in/hr,  $\psi_s = 6.5$  in, and  $\theta_d = 0.20$ . The initial, flat portion of the curve corresponds to  $f = i$ , up to the point where  $F = F_s$  (Equation 4-29). The remainder of the curve corresponds to the potential rate computed with Equation 4-27. Note that the infiltration rate approaches  $K_s$  (0.25 in/hr) asymptotically.

## Documentation

Date	Title
09/30/2015	<a href="#">SWMM 5.1 User's Manual</a>
09/01/2014	<a href="#">SWMM-CAT User's Guide</a>
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# Use the SWMM Tutorial's

## CHAPTER 2 – QUICK START TUTORIAL

*This chapter provides a tutorial on how to use EPA SWMM. If you are not familiar with the elements that comprise a drainage system, and how these are represented in a SWMM model, you might want to review the material in Chapter 3 first.*

### 2.1 Example Study Area

In this tutorial we will model the drainage system serving a 12-acre residential area. The system layout is shown in Figure 2-1 and consists of subcatchment areas<sup>3</sup> S1 through S3, storm sewer conduits C1 through C4, and conduit junctions J1 through J4. The system discharges to a creek at the point labeled *Out1*. We will first go through the steps of creating the objects shown in this diagram on SWMM's study area map and setting the various properties of these objects. Then we will simulate the water quantity and quality response to a 3-inch, 6-hour rainfall event, as well as a continuous, multi-year rainfall record.

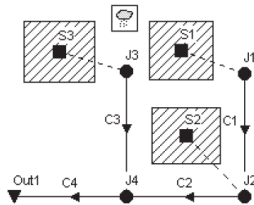


Figure 2-1 Example study area

### 2.2 Project Setup

Our first task is to create a new SWMM project and make sure that certain default options are selected. Using these defaults will simplify the data entry tasks later on.

1. Launch EPA SWMM if it is not already running and select **File >> New** from the Main Menu bar to create a new project.
2. Select **Project >> Defaults** to open the Project Defaults dialog.

<sup>3</sup> A subcatchment is an area of land containing a mix of pervious and impervious surfaces whose runoff drains to a common outlet point, which could be either a node of the drainage network or another subcatchment.

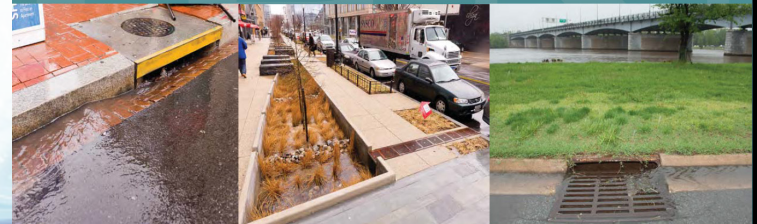
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01/29/2016	<a href="#">SWMM Reference Manual Volume I—Hydrology</a>
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<https://swmm5.org/2017/08/14/epa-swmm5-tutorial-with-images-for-swmm-5-1-012/>

**Storm Water Management Model  
User's Manual Version 5.1**





# LID Modeling in SWMM



# Types of LIDs Modeled



Disconnection



Infiltration Basin



Rain Garden



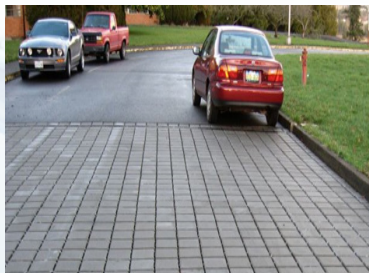
Cistern



Infiltration Trench



Green Roof



Porous Pavement



Vegetative Swale



Street Planter



# Testing of SWMM Model's LID Modules

Michelle Platz, Michelle Simon, and Michael Tryby

United States Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory

## Introduction

- Municipalities rely heavily on software such as the EPA's Storm Water Management Model (SWMM) to design storm water and wastewater infrastructure, a multi-billion dollar, multi-decade effort.
- Study Main Objective:** quantify SWMM v5.1.10 accuracy in simulating hydrologic activity of previously monitored low impact development storm water control measures.
- This study's results and parameter sensitivity analysis led to several SWMM LID module improvements.

## Methodology

- Model performance was evaluated by mathematically comparing multi-event storm empirical data to modeled results.
- The calibration methodology utilized PEST software to determine the valuation of unmeasured hydrologic parameters.

## Results

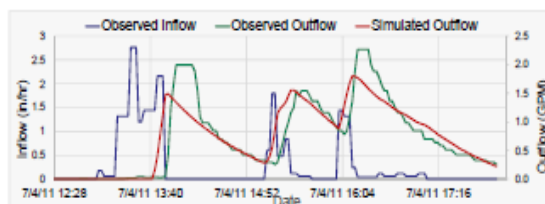


Figure: Boone Porous Pavement hydrograph depicting early outflow start-time

Table 1: Sensitivity analysis summary

LID Name	First Most Sensitive Parameter		Second Most Sensitive Parameter		Third Most Sensitive Parameter	
	Layer	Parameter	Layer	Parameter	Layer	Parameter
Graham Bio-Retention	Drainage	Flow Coefficient	Soil	Wilting Point	Soil	Field Capacity
Villanova BTI Rain Garden	Surface	Surface Roughness	Surface	Vegetation Volume	LID Usage	Surface Width
Villanova Infiltration Trench	Drainage	Flow Coefficient	Drainage	Flow Emission	Storage	Void Ratio
UND BioSwale	Roadway	Roughness	Surface	Side Slope	Surface	Roughness
Washington DOT BioSwale	Surface	Surface Roughness	Surface	Vegetation Volume	Infiltration	Surface Section Head
Hamilton EcoRoof	Soil	Wilting Point	Soil	Porosity	Soil	Thickness
EOC Green Roof	Soil	Wilting Point	Soil	Field Capacity	Drainage Mat	Void Ratio
PS10 Green Roof	Soil	Field Capacity	Soil	Wilting Point	Drainage Mat	Void Ratio
Boone Porous Pavement	Storage	Conductivity	Storage	Void Ratio	Drainage	Drain Coefficient

Table 2: N-S Efficiency Value and R<sup>2</sup> Value results summary

LID Name	Average N-S Efficiency Value	Average R <sup>2</sup> Value
Graham Bio-Retention	0.67	0.91
Villanova BTI Rain Garden	0.86	0.96
Villanova Infiltration Trench	0.65	0.67
UND 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
PS10 Green Roof	0.93	0.84
Boone Porous Pavement	0.74	0.89

## Discussion and Conclusions

- The most significant discovery made in this analysis was that given proper instrumentation, site specific parameter measurement, and calibration, SWMM can accurately reproduce hydrologic response of enhanced infiltration-based LID storm water controls.
- SWMM does not model lateral exfiltration, severely limiting its accuracy in predicting hydrologic performance for narrow low impact development controls LIDs such as infiltration trenches.

## Acknowledgements

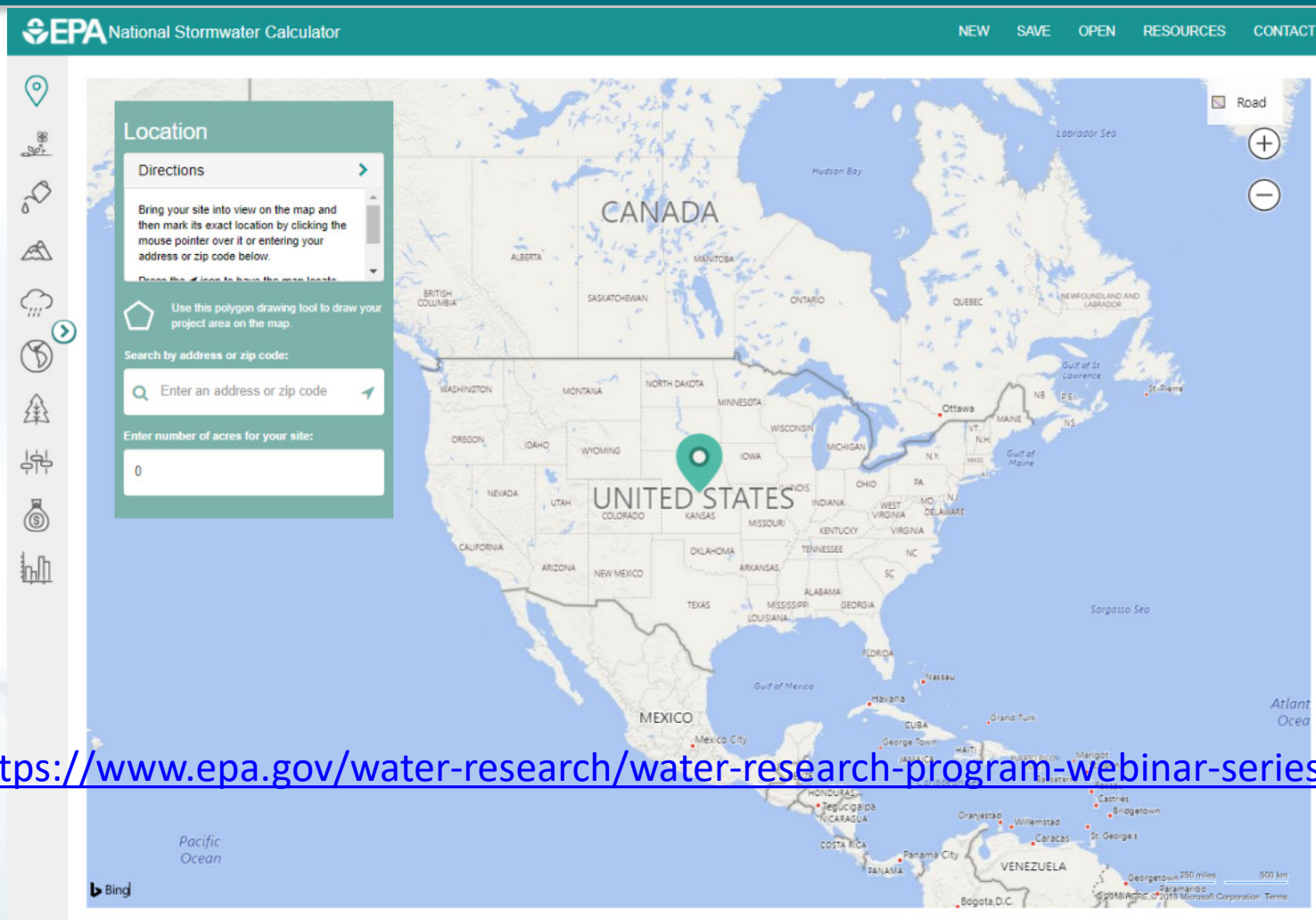
The authors heavily relied upon the information supplied by The Cadmus Group, Inc., in collaboration with Michael Baker Corporation, Inc. via Contract No. EP-C-11-03 who performed a thorough study of the literature, identifying the Low Impact Development data sets, wrote the project descriptions, and formatting the SWMM input files for that we used for this work. Any opinions expressed in this paper are those of the author(s) and do not necessarily reflect the views of the Agency; therefore, no official endorsement should be inferred. Any mention of trade names or commercial products does not constitute endorsement or recommendation for use.

## References

- Roosman, L. A. and W. C. Huber (2016b). Storm Water Management Model Reference Manual Volume III - Water Quality. EPA/600/R-16/093.
- Deberry, J. (2005). "PEST Model-Independent Parameter Estimation User Manual: 5th Edition." 333.

# National Stormwater Calculator

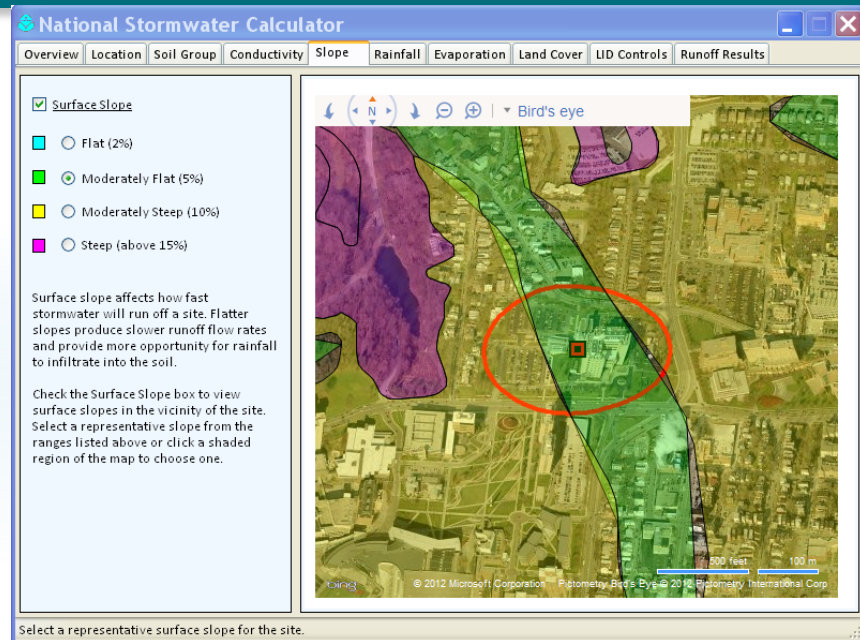
<https://www.epa.gov/water-research/national-stormwater-calculator>



: <https://www.epa.gov/water-research/water-research-program-webinar-series>

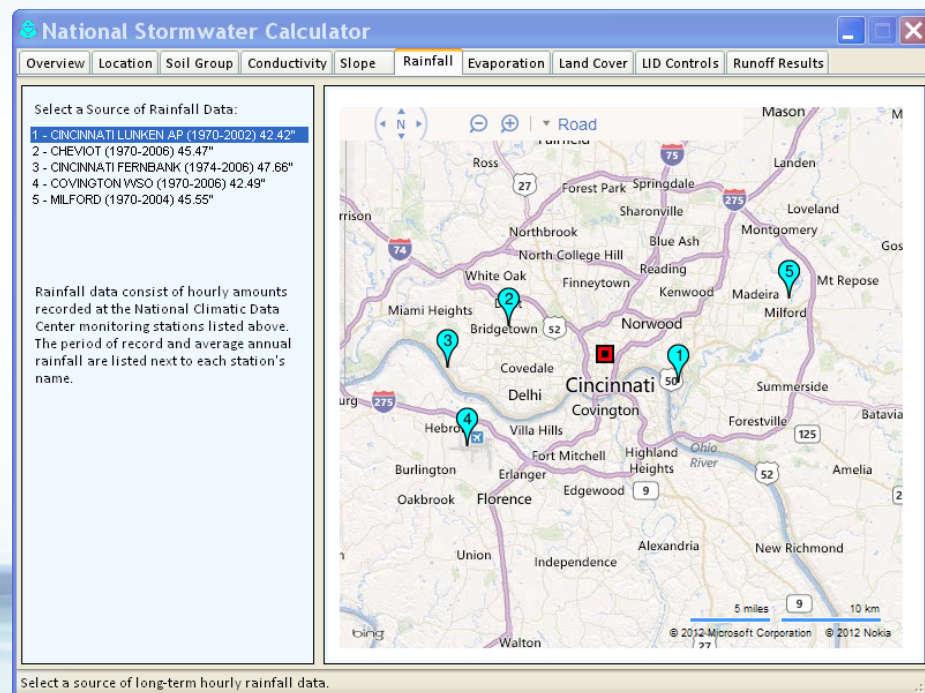


# National Stormwater Calculator



Displays soil properties obtained from querying the NRCS SSURGO database

Uses a source of long term hourly rainfall data from over 7000 NWS measurement stations



# National Stormwater Calculator

The user specifies the site's land cover and selects a set of LID controls.

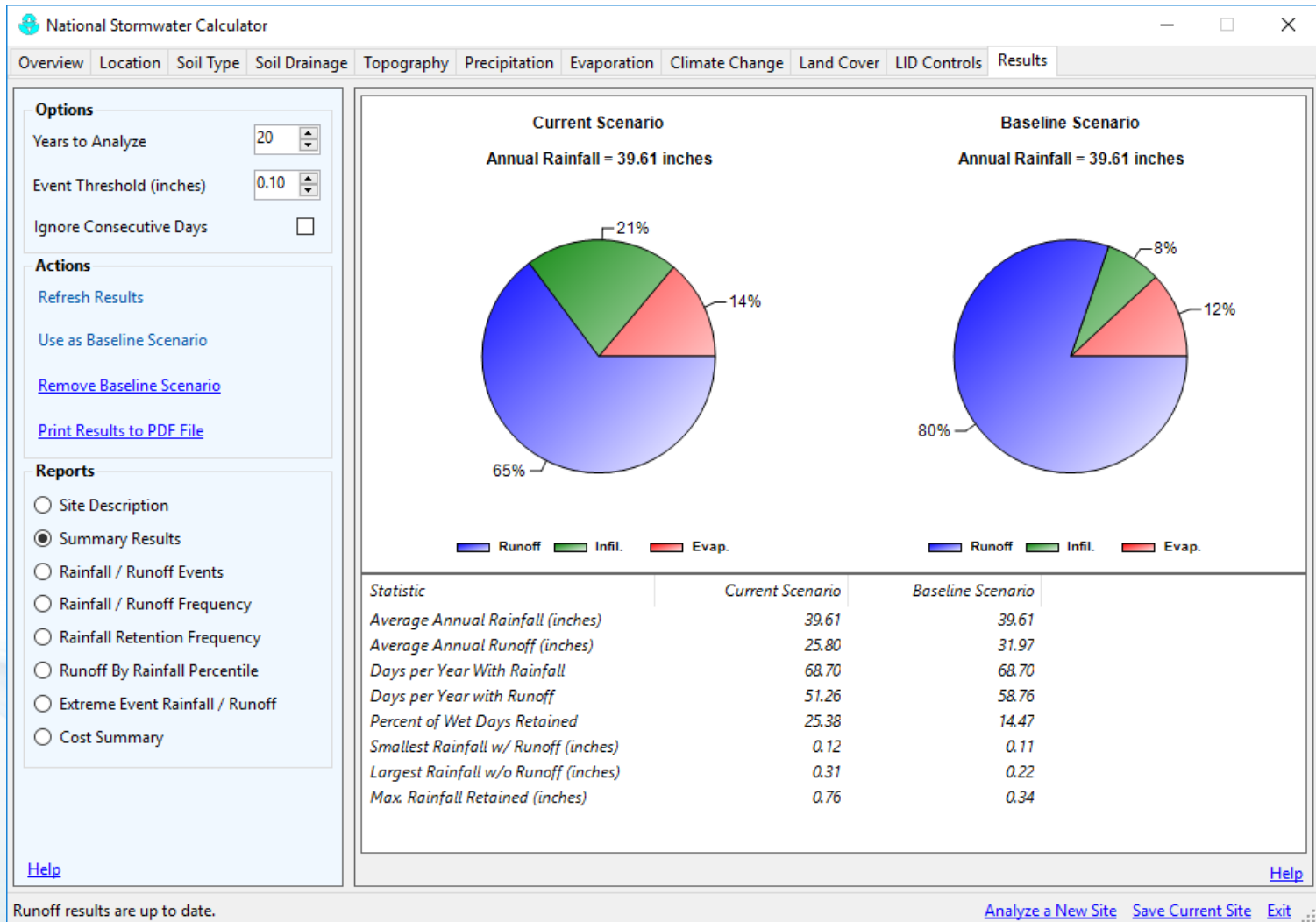
The screenshot displays the National Stormwater Calculator software interface. The main window has a tabbed menu at the top: Overview, Location, Soil Group, Conductivity, Slope, Rainfall, Evaporation, Land Cover, LID Controls (selected), and Runoff Results. On the left, under '% of Impervious Area Treated By:', several LID practices are listed with corresponding percentage values: Disconnection (0), Rain Harvesting (20), Rain Gardens (10), Green Roofs (0), Street Planters (0), Infiltration Basins (0), and Porous Pavement (70). Below this list, a text box explains that LID controls are landscaping practices designed to retain stormwater on site, and provides instructions on how to enter the percent of the site's impervious area treated by a listed LID practice and how to click a practice to learn more about it or to change its design parameters. A 'Design Storm Depth (in) (for Auto-Sizing)' is set to 1.59. At the bottom of the main window, it says 'Assign LID practices to capture runoff from impervious areas.'

The central part of the interface shows an aerial map of a residential area with a red circle highlighting a specific site. A small red square on the map indicates the selected location. The map includes navigation controls (compass, zoom in/out, pan) and a 'Bird's eye' view selector.

An 'LID Design' window is open, showing details for 'Porous Pavement'. It includes a cross-section diagram of the pavement system with labels: 'RIVERLAKES OPEN INTO RECHARGE BED', 'POROUS ASPHALT PAVEMENT', 'UNCOMPACTED SURGRADE IS CRITICAL FOR PROPER INFILTRATION', 'UNIFORMLY GRADED STONE AGGREGATE WITH 40% VOID SPACE FOR STORMWATER STORAGE AND RECHARGE', and 'FILTER FABRIC LINES THE SUBSURFACE BED'. Below the diagram, the 'Gravel Layer Thickness (inches)' is set to 18, and the '% Capture Ratio' is set to 26. To the right of the diagram, text explains that Continuous Porous Pavement systems are excavated areas filled with gravel and paved over with a porous concrete or asphalt mix. Normally all rainfall will immediately pass through the pavement into the gravel storage layer below it where it can infiltrate at natural rates into the site's native soil. It also states that the gravel storage layers below the pavement are typically 6 to 18 inches high. Below this text is a photograph of a paved area with a red car parked on it. A 'Learn more...' link is at the bottom right of the LID Design window. At the bottom of the LID Design window are buttons for 'Auto-Size', 'Restore Defaults', 'Accept', and 'Cancel'.

# National Stormwater Calculator

The Calculator runs SWMM to generate daily rainfall/runoff statistics.

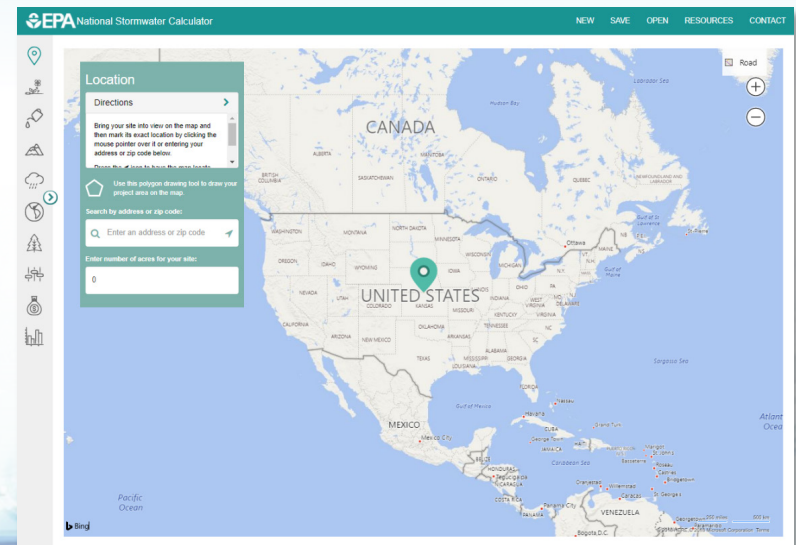




# Data that you need for SWMM

Either you measure it or

- Soil Infiltration from a Soil database (SSURGO or STATSGO)
- Land Use – Land Cover
- (National Land Cover Dataset – NLCD)
- Climatic Data – find closest NOAA station
  - (use Stormwater Calculator)
- Site Configuration
  - Subcatchment area
  - Drainage flow
- Hydraulic Configuration
  - Conduit geometry, length
  - Network schematic





# Where to get information

<https://www.epa.gov/exposure-assessment-models>

<https://www.nrcs.usda.gov>

<https://www.usgs.gov/science/mission-areas/water-resources>

## Gather Data

DEM and NLCD <https://viewer.nationalmap.gov/basic/>

Soils - <https://www.nrcs.usda.gov>

SSURGO

STATGO

Climate - NOAA National Centers for Environmental Information  
([www.ncdc.noaa.gov](http://www.ncdc.noaa.gov))

## Hydrologic Unit Maps (HUC)

NRCS <http://www.usda.gov/wps/portal/nrcs/main/national/water/watersheds>



United States Department of Agriculture

## Geospatial Data Gateway



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You are here: [Home](#) / GDGHome.aspx

### Welcome to GDG

System Status:  
Welcome to GDG 6.0.4.7481. All products and services are running normally.

PLEASE NOTE: As of April 21, 2017 the NAIP datasets are only available through the "NAIP Download" option on the home page and are no longer be available through the Gateway ordering process. Also note, NAIP images are titled by county FIPS codes. FIPS codes may be referenced by clicking on the "county FIPS" link on the Direct Download page.



- ▶ [Natural Resources Conservation Service](#)
- ▶ [Farm Services Agency](#)
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- ▶ [Aerial Photography Field Office \(APFO\)](#)
- ▶ [Web Soil Survey](#)
- ▶ [eFOTG](#)
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The Geospatial Data Gateway (GDG) provides access to a map library of over 100 high resolution vector and raster layers in the Geospatial Data Warehouse. It is the One Stop Source for environmental and natural resources data, at any time, from anywhere, to anyone. It allows you to choose your area of interest, browse and select data, customize the format, then review and download.

This service is made available through a close partnership between the three Service Center Agencies ([SCA](#)); Natural Resources Conservation Service ([NRC](#)), Farm Service Agency ([FSA](#)) and Rural Development ([RD](#)).



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# Technical Support - OPEN SWMM



OPEN SWMM

KNOWLEDGE

CODE

RESEARCH

RESOURCES



PA #SWMM5 Tut x Home - Welcome t x Cincinnati Bell Wel x Introduction to SW x SWMMM 5 User G x R1842ndEd dated x About OPEN SWM x

/www.openswmm.org/Forum/About#swmm-userslistserver



OPEN SWMM

KNOWLEDGE

CODE

RESEARCH

RESOURCES



13531

POSTS

4778

THREADS

1505

CONTRIBUTORS

25

YEARS

## About OPEN SWMM

[Collapse all](#)

### — Mission and Intent

The SWMM Knowledge Base is intended to function as an online learning resource for users of the public domain EPA SWMM program. It consists of digitally curated content from the SWMM-USERS list server, organized in an easily readable format. Fully searchable, the SWMM Knowledge Base provides a high signal-to-noise ratio, and promotes content discoverability through related topic suggestions.

Together with the open access [Journal of Water Management Modeling](#), the annual [International Conference on Water Management Modeling](#), and the SWMM-USERS list server, the SWMM Knowledge Base rounds out a group of high quality resources that supports, promotes and encourages development of SWMM by the EPA and the user community.

The SWMM Knowledge Base continuously solicits feedback from the community in making the presentation and content as accessible and useful as possible. Please send any comments and questions to staff at [info@openswmm.org](mailto:info@openswmm.org). The SWMM Knowledge Base is hosted and moderated by the staff of CHI.

### — SWMM-USERS list server

The SWMM-USERS list server is an email-based forum for users of the public-domain US EPA SWMM program to share ideas and ask questions on issues related



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# Key Websites discussed

## **Storm Water Management Model:**

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

## **National Stormwater Calculator Website:**

<https://www.epa.gov/water-research/national-stormwater-calculator>

## **Water Research Program Webinar Series Website:**

<https://www.epa.gov/water-research/water-research-program-webinar-series>

## **USGS's online Seamless Data Warehouse:**

<https://datagateway.nrcs.usda.gov>

## **YouTube Tutorials:**

<https://www.youtube.com>

## **Openswmm:**

<https://www.openswmm.org/>



# 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."

Under Division Review

# Thank You!



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U.S. EPA Office of Research and Development (ORD)

513-569-7469 [Simon.michelle@epa.gov](mailto:Simon.michelle@epa.gov)

# Questions?

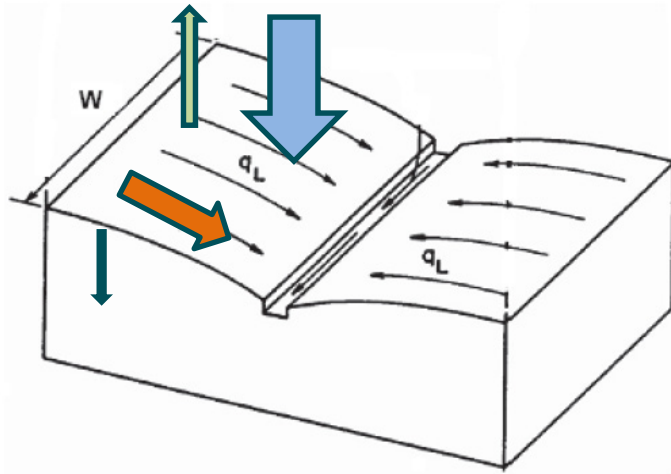





# Extra Slides

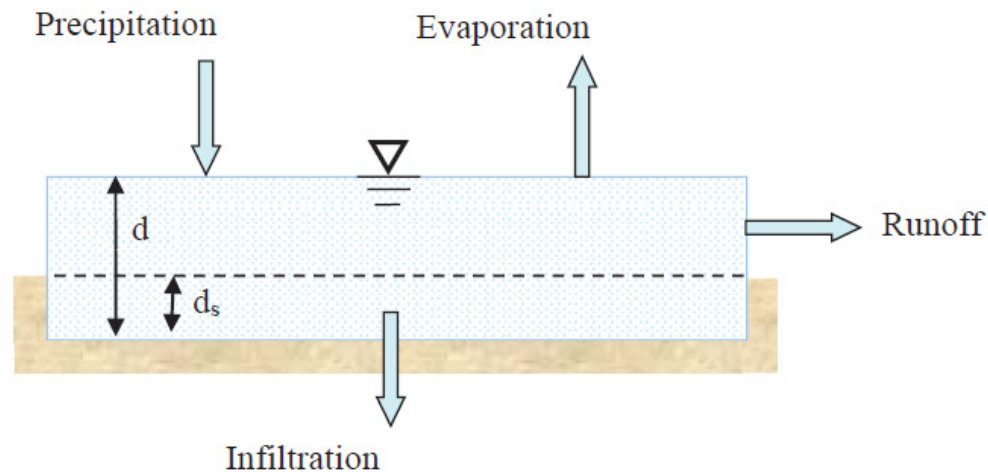




# Idealized Subcatchment



-  Pervious
-  Impervious
-  Impervious w/o Depression Storage



# SWMM - Manning Equation

$$Q = \frac{1.49}{n} A R^{2/3} S^{1/2}$$

Q = flow rate

A = cross sectional area

R = hydraulic radius

S = slope

n = Manning roughness coefficient

# Pipes with Circular Force

## Main Cross sections

### Hazen-Williams

$$Q = 1.318 C A R^{0.63} S^{0.54}$$

Q = flow rate

C = Hazen Williams C-factor

A = cross sectional area

R = hydraulic radius

S = slope

### Darcy-Weisbach

$$Q = \sqrt{\frac{8g}{f}} A R^{1/2} S^{1/2}$$

Q = flow rate

g = gravity acceleration

F = Darcy-Weisbach friction factor

A = cross sectional area

R = hydraulic radius

S = slope