Data Limited Stormwater Management Modelling

Miguel A. Medina, Jr., Professional Hydrologist,
Fellow, ASCE, Professor Emeritus
Department of Civil and Environmental Engineering,
Duke University, Durham, N.C.
miguel.medina@duke.edu
Former President, American Institute of Hydrology

South Florida Water Management District
UNESCO-IHE Lecture
West Palm Beach, Florida
May 27, 2016

The EPA Storm Water Management Model (SWMM) is a dynamic, distributed-routing, rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. The runoff component of SWMM operates on a collection of subcatchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each subcatchment, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period (a few hours to several years) comprised of multiple time steps.

(Rossman, EPA/600/R-05/040, Revised July 2010)

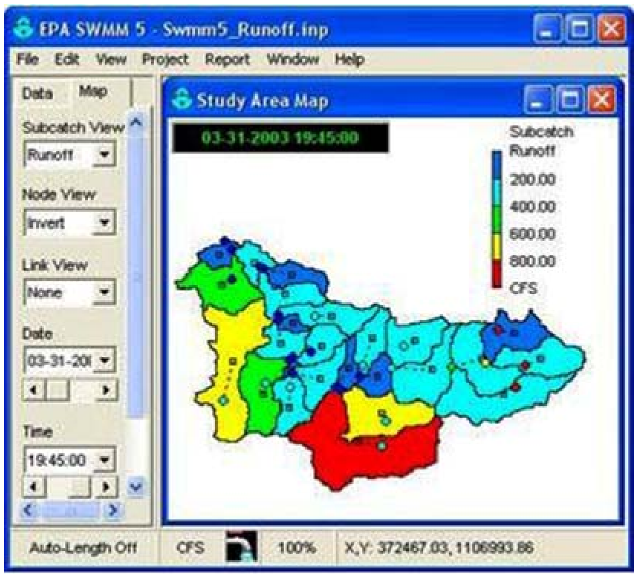
Accommodates most levels of available data – can obtain meaningful results with very rough to very refined inputs

The Storm Water Management Model Climate Adjustment Tool (SWMM-CAT) is an Add-In Tool for SWMM (December 2014). It is a simple software utility that allows future climate change projections to be incorporated into the Storm Water Management Model. SWMM was updated to accept monthly adjustment factors for the time series that could represent the potential impact of future changes in climatic conditions. SWMM-CAT provides a set of location-specific adjustments derived from global climate change models, run as part of the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3) archive.

Rossman, Lewis, "SWMM-CAT User's Guide," EPA 600-R-14-428, Cincinnati, Ohio, 2014.

Development History of SWMM

Storm Water Management Model Reference Manual – Revised (Rossman and Huber, 2016)



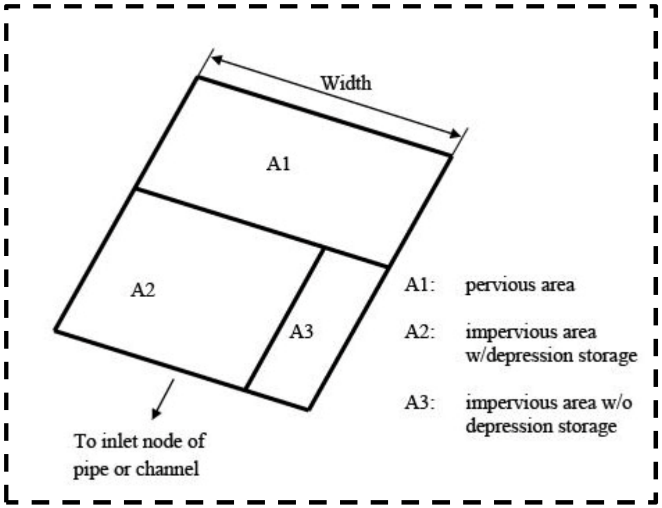
SWMM-CAT (2014)

Current Version: SWMM 5.1.010 August 5, 2015

Version	Year	Contributors	Comments
SWMM I	1971	Metcalf & Eddy, Inc. Water Resources Engineers University of Florida	First version of SWMM; focus was CSO modeling; few of its methods are still used today.
SWMM II	1975	University of Florida	First widely distributed version of SWMM.
SWMM 3	1981	University of Florida Camp Dresser & McKee	Full dynamic wave flow routine, Green-Ampt infiltration, snow melt, and continuous simulation added.
SWMM 3.3	1983	US EPA	First PC version of SWMM.
SWMM 4	1988	Oregon State University Camp Dresser & McKee	Groundwater, RDII, irregular channel cross-sections and other refinements added over a series of updates throughout the 1990's.
SWMM 5	2005	US EPA CDM-Smith	Complete re-write of the SWMM engine in C; graphical user interface added; improved algorithms and new features (e.g., LID modeling) added.

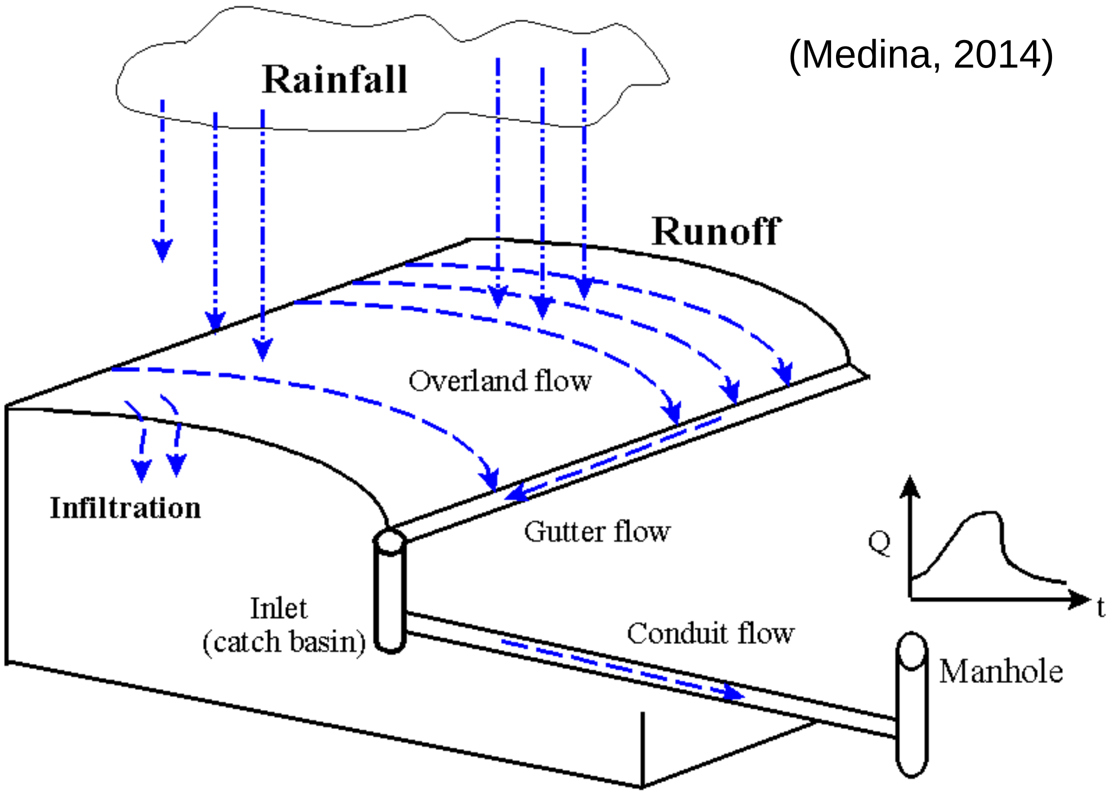
Download Web Site → https://www.epa.gov/water-research/storm-water-management-model-swmm

EPA Storm Water Management Model SWMM5

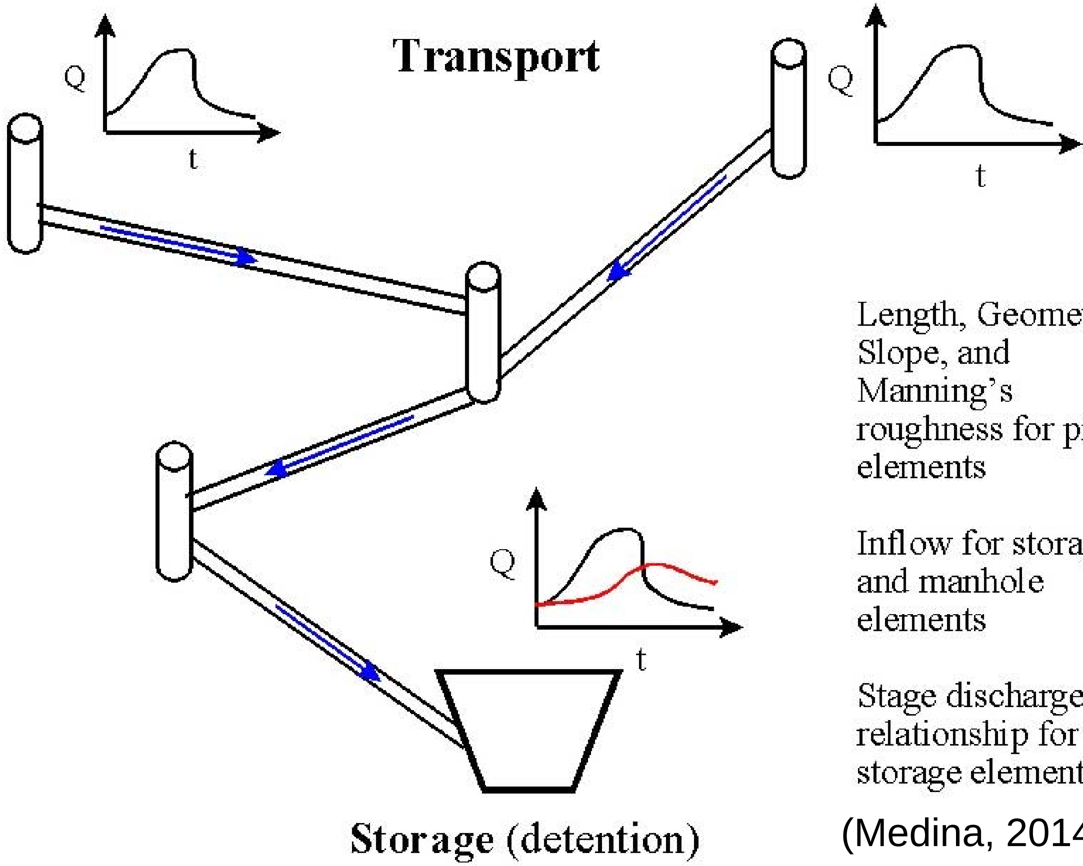


Subcatchment data: Width, Area, Percent Imperviousness, Ground Slope, Manning's n for impervious and pervious areas, Infiltration rate parameters

(Medina, 2014)



EPA Storm Water Management Model SWMM5



Length, Geometry, Slope, and Manning's roughness for pipe elements

Inflow for storage and manhole elements

Stage discharge relationship for storage elements

(Medina, 2014)

Overland and Channel Flow:

Kinematic Wave Routing

$$\left.\begin{aligned}&\frac{\partial y}{\partial t}+\frac{\partial q}{\partial x}=i-f\\&q=\alpha\, y^{m}\end{aligned}\right\}\Rightarrow\frac{\partial y}{\partial t}+\alpha\frac{\partial\left(y^{m}\right)}{\partial x}=i-f$$

Diffusion Wave Routing

$$\frac{\partial y}{\partial t}+c\frac{\partial y}{\partial x}=K_1\frac{\partial^2 y}{\partial x^2}+\left(i-f\right)$$

$$K_1=\frac{Vy}{2S_o}=\text{hydraulic diffusivity}=\frac{\text{velocity}\bullet\text{depth}}{2\,(\text{bed slope})}$$

Channel Flow:

Dynamic Wave Routing

Continuity:

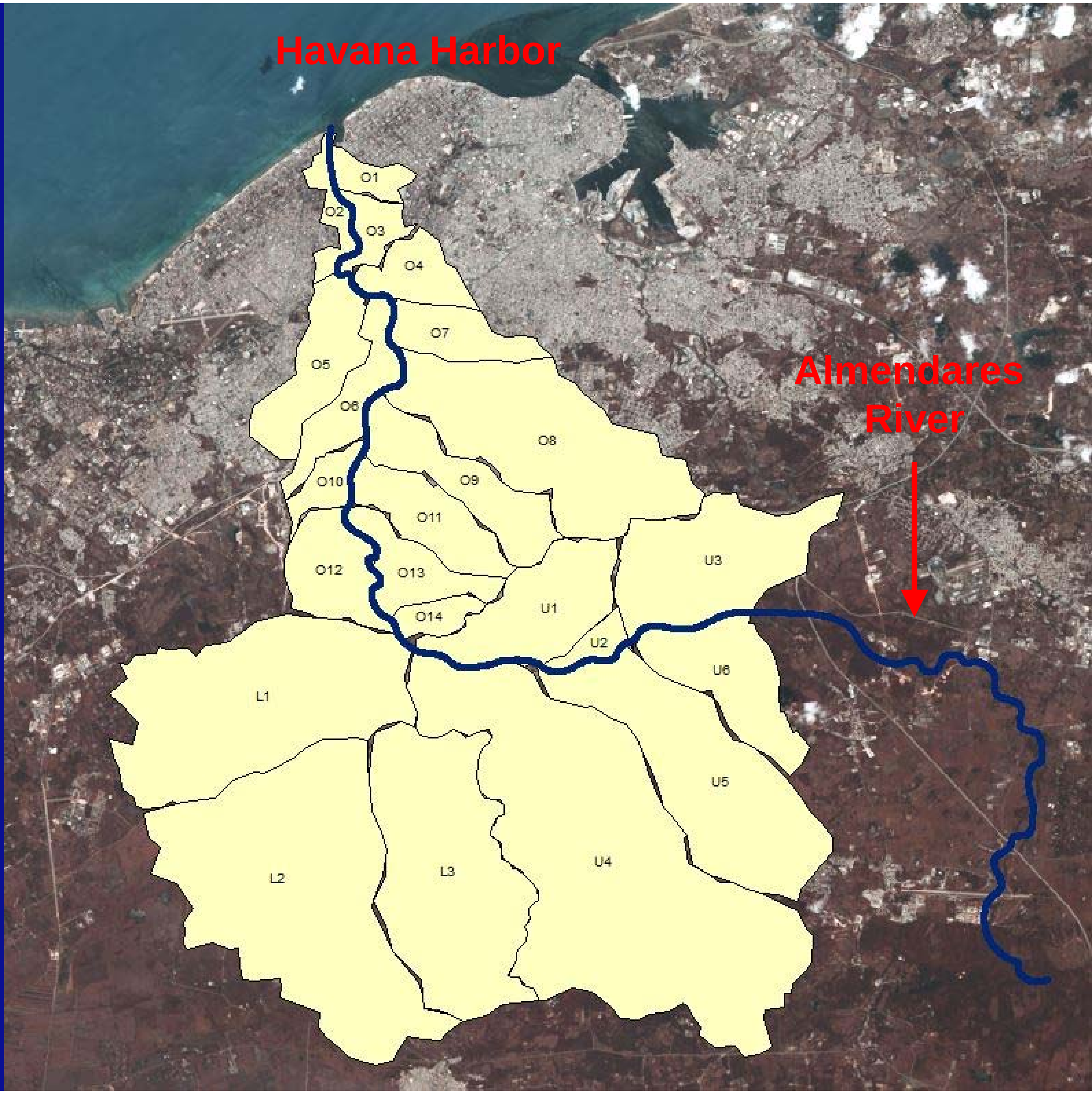
$$\frac{\partial y}{\partial t}+V\frac{\partial y}{\partial x}+y\frac{\partial V}{\partial x}=i-f$$

Momentum:

$$\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}+g\frac{\partial y}{\partial x}=g\left(S_o-S_f\right)+\left[\left(i-f\right)\frac{V}{y}\right]$$

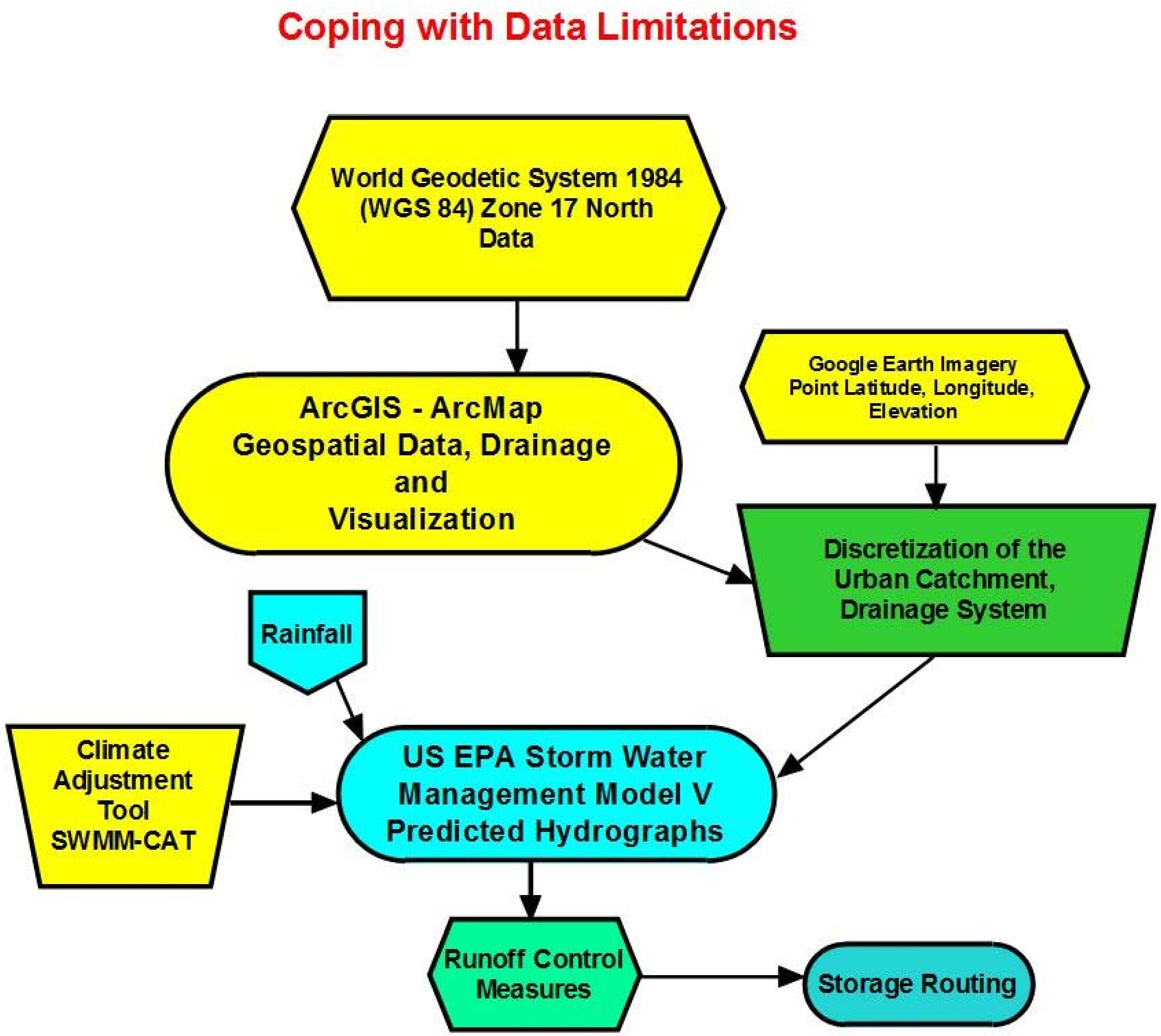
Data Limited Case Study:
Modelling the Runoff from
Urban and Nonurban Subcatchments
draining into the Upper Almendares
River, west of Havana, Cuba

[Mentorship of a Cuba Infrastructure
Scholarship Competition sponsored
by the Cuban American Association of
Civil Engineers, Miami, Florida]



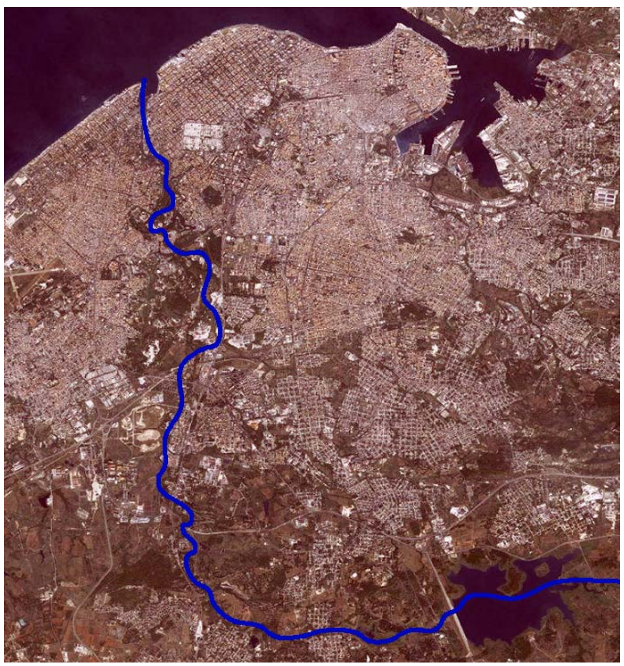
The Havana area is referenced in the WGS1984 Zone 17 North data set. A standard spatial reference frame was then created for the Earth's surface, allowing area measurements to be calculated within ArcGIS.

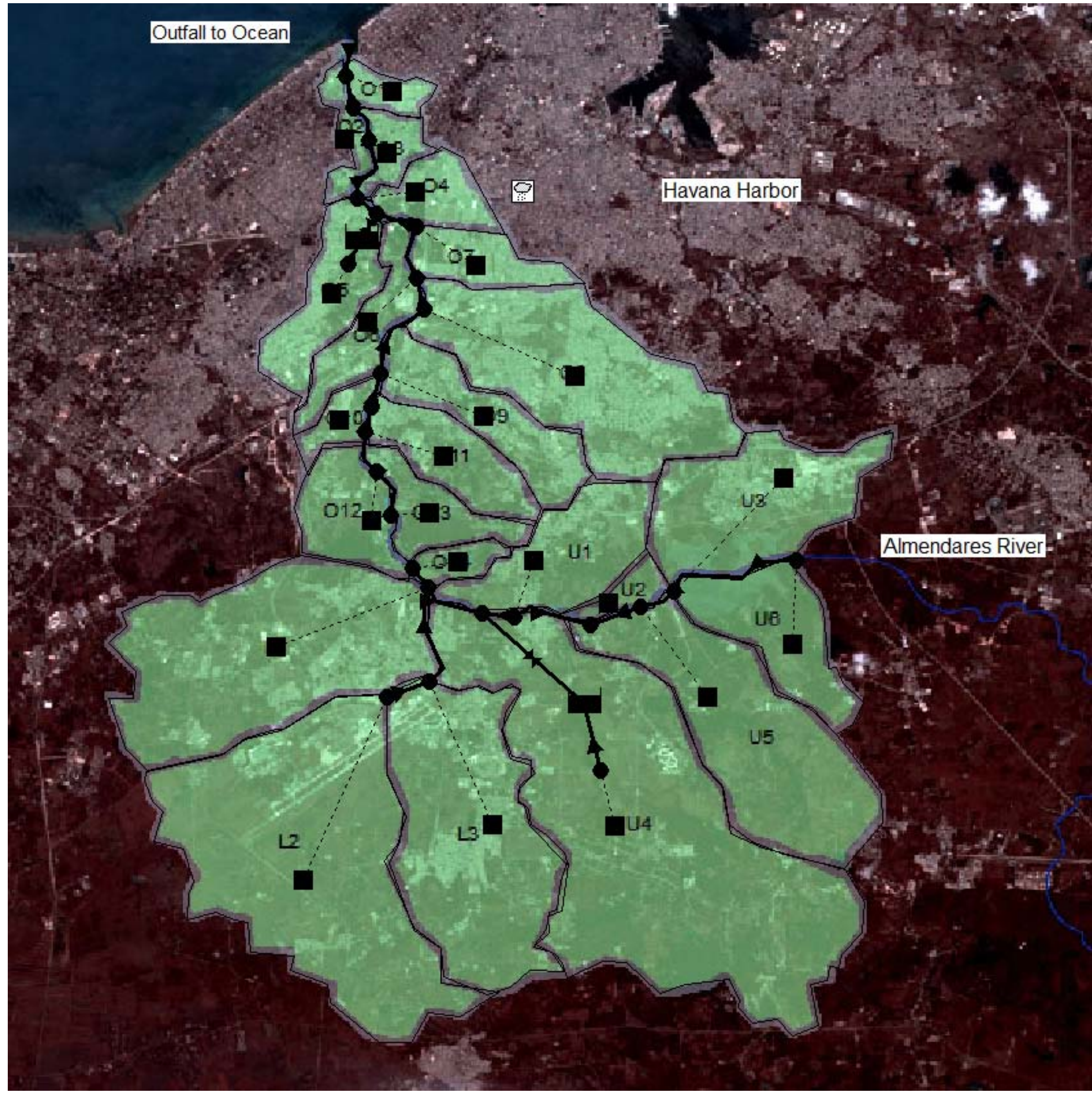
Iudicello, Jeffrey J., et al., "Identification and Remediation of Water-Quality Hotspots in Havana, Cuba: Accounting for Limited Data and High Uncertainty," *The West Indian Journal of Engineering,* (35) 2, (2013), pp.72-82, ISSN 0511-5728.



Actual Application of SWMM5 to the Almendares River

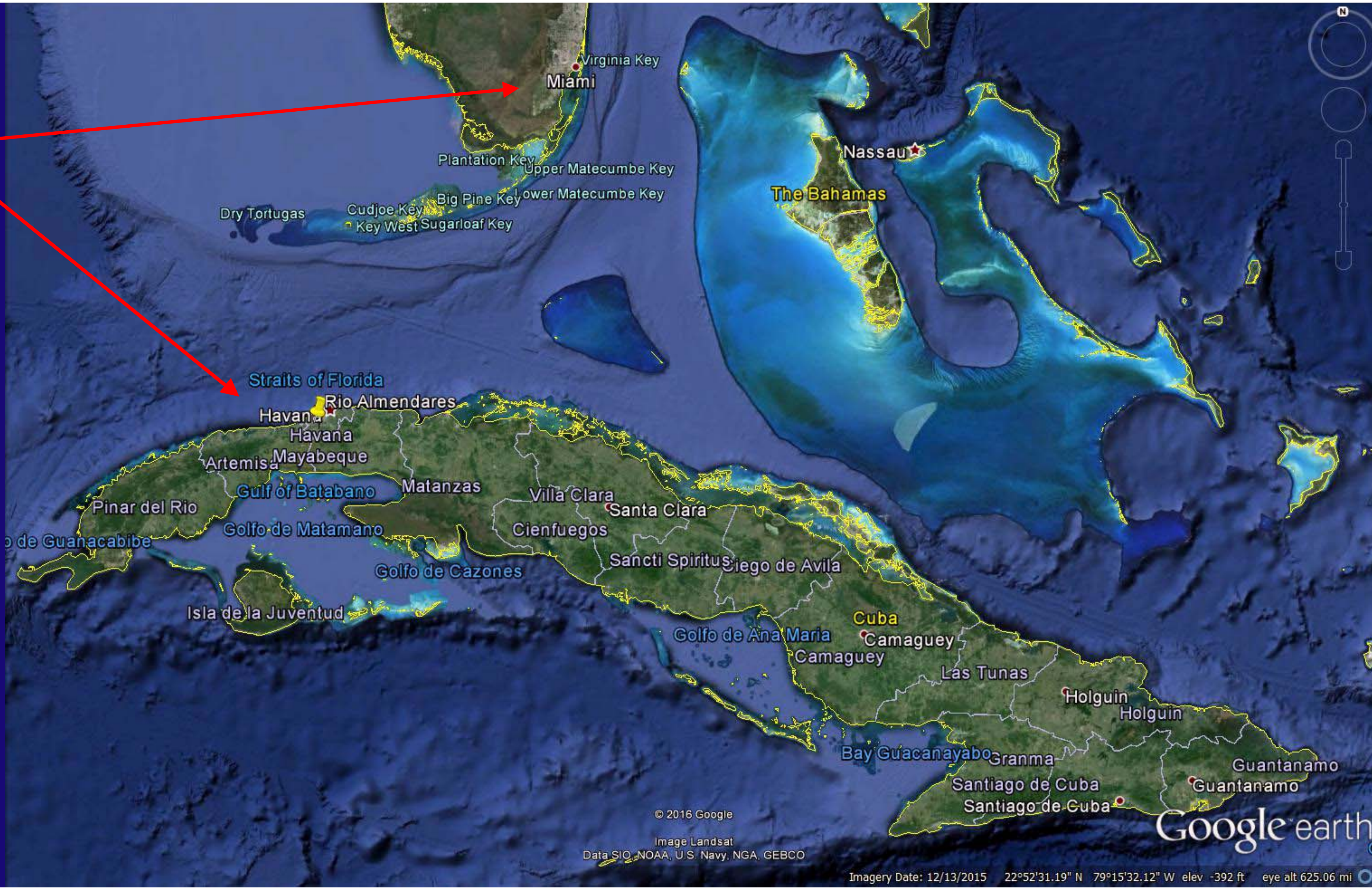
ArcMap-ArcGIS map was imported into SWMM5 as a background image: the watershed boundaries were drawn-in using SWMM5 tools, the river network was defined such that the surrounding urban and semi-urban areas contributed runoff to the junctions along the trapezoidal open channel representing the river geometry. The SWMM5 network also shows proposed detention ponds in subcatchments O5 and U4.





360
km

(224 mi.)



Virginia Key
Miami
Plantation Key
Upper Matecumbe Key
Lower Matecumbe Key
Big Pine Key
Cudjoe Key
Key West
Sugarloaf Key
Dry Tortugas
Nassau
The Bahamas
Straits of Florida
Rio Almendares
Havana
Havana
Artemisa
Mayabeque
Gulf of Batabano
Matanzas
Pinar del Rio
Golfo de Matamano
Villa Clara
Santa Clara
Cienfuegos
Golfo de Cazones
Sancti Spiritus
Ciego de Avila
Isla de la Juventud
Cuba
Golfo de Ana Maria
Camaguey
Camaguey
Las Tunas
Holguin
Holguin
Bay Guacanayabo
Granma
Santiago de Cuba
Santiago de Cuba
Guantanamo
Guantanamo
© 2016 Google
Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth
Imagery Date: 12/13/2015 22°52'31.19" N 79°15'32.12" W elev -392 ft eye alt 625.06 mi

Iudicello, Jeffrey J., et al., "Identification and Remediation of Water-Quality Hotspots in Havana, Cuba: Accounting for Limited Data and High Uncertainty," *The West Indian Journal of Engineering,* (35) 2, (2013), pp.72-82, ISSN 0511-5728.

Flooding in Havana ...

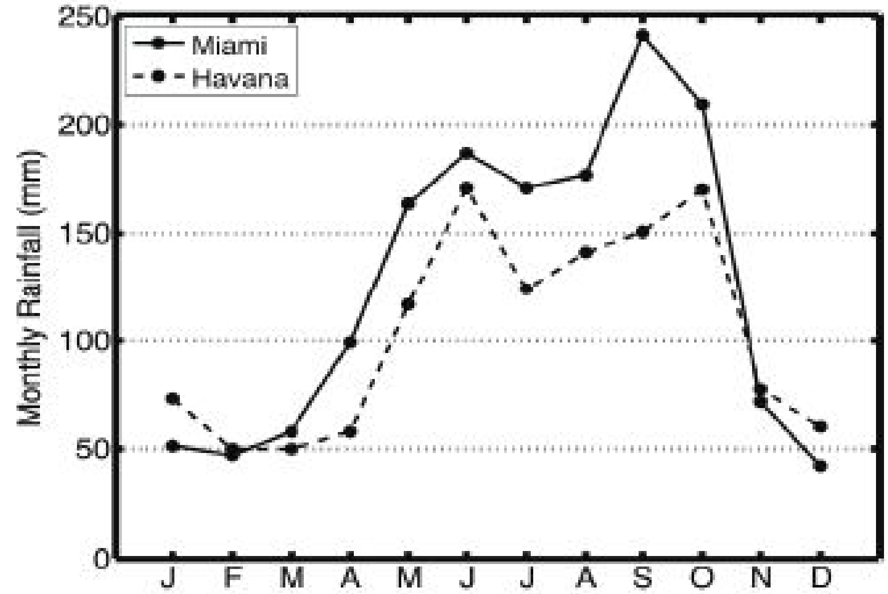


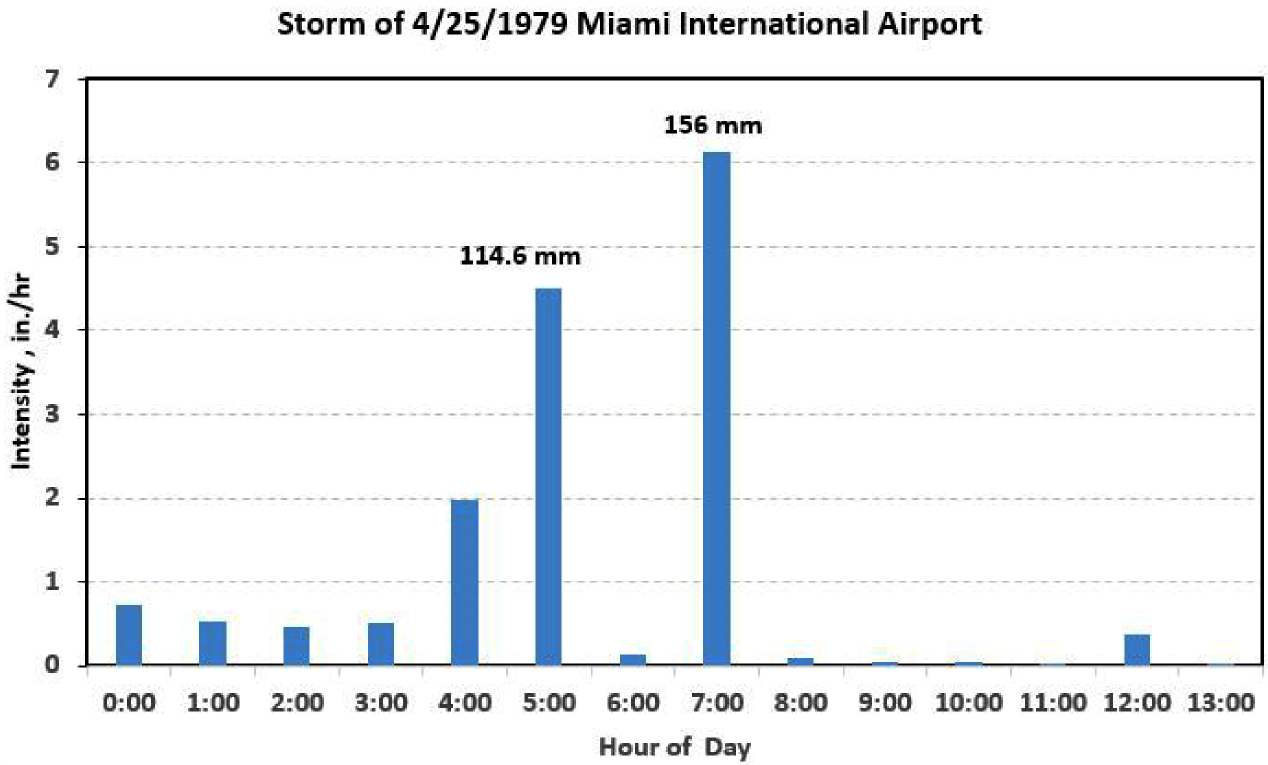
Figure 3. Comparison of monthly rainfall characteristics between Havana and Miami

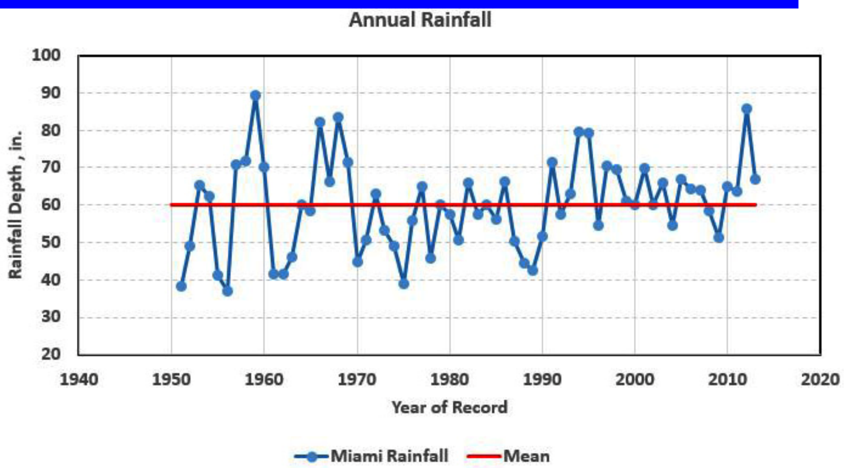
Table 2. Climate comparison between Havana and Miami

	Avg. Temp (°C)	Wet Days (> 0.1 mm)	Avg. Relative Humidity (%)	Avg. Windspeed (km/hr)
Miami	24	132	60.6	12-19
Havana	25	121	74.3	10-15

Miami International Airport
Hourly Precipitation Record
Analyzed: 1950-2013

Wettest year: 1959 (89.3 in.; 2269 mm)
Driest year: 1956 (37 in.; 940 mm)
Avg. annual depth: 60 in. (1524 mm)

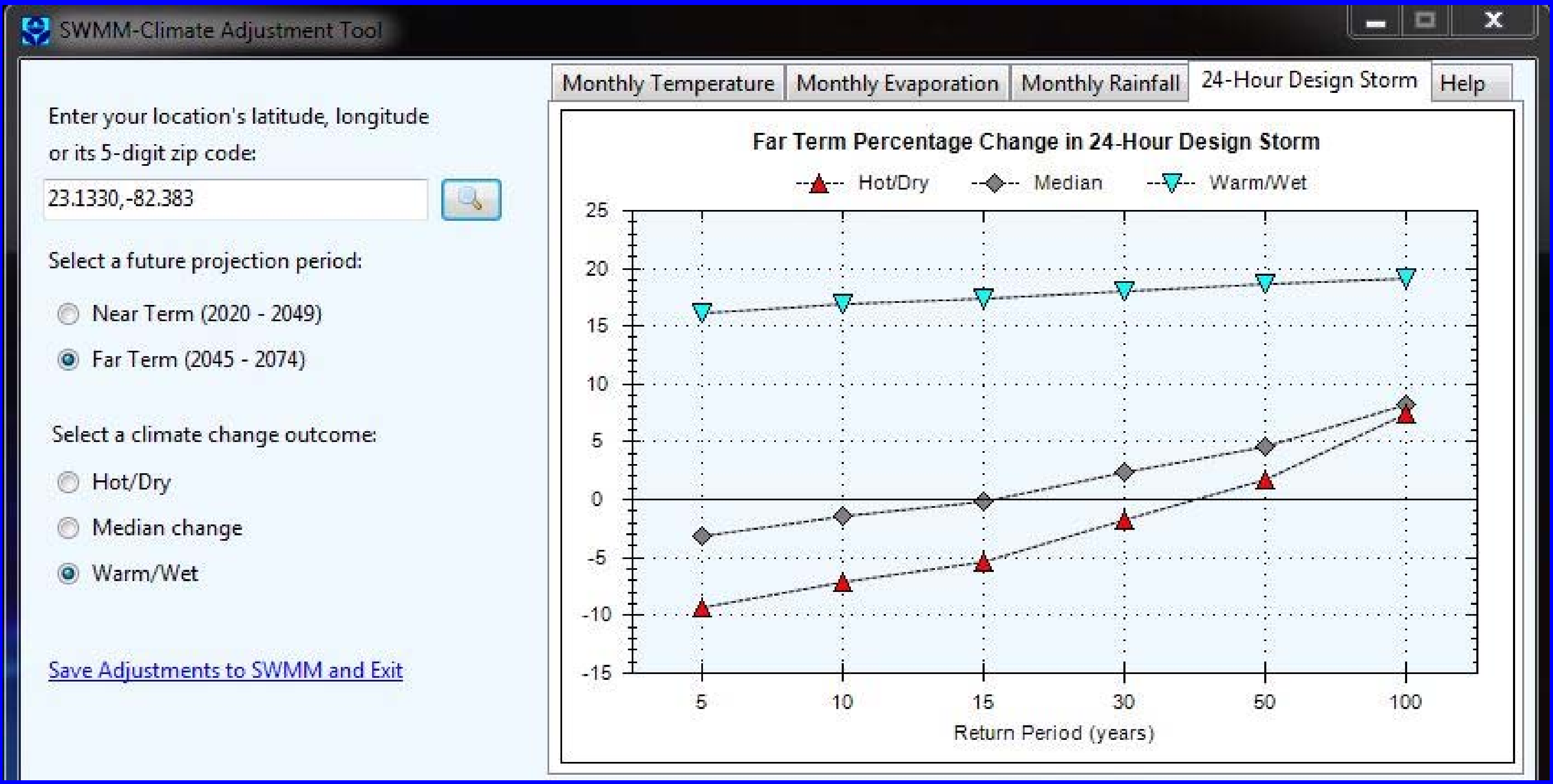




Record Storm for 1-hr, 6-hr and 24-hr Intensities

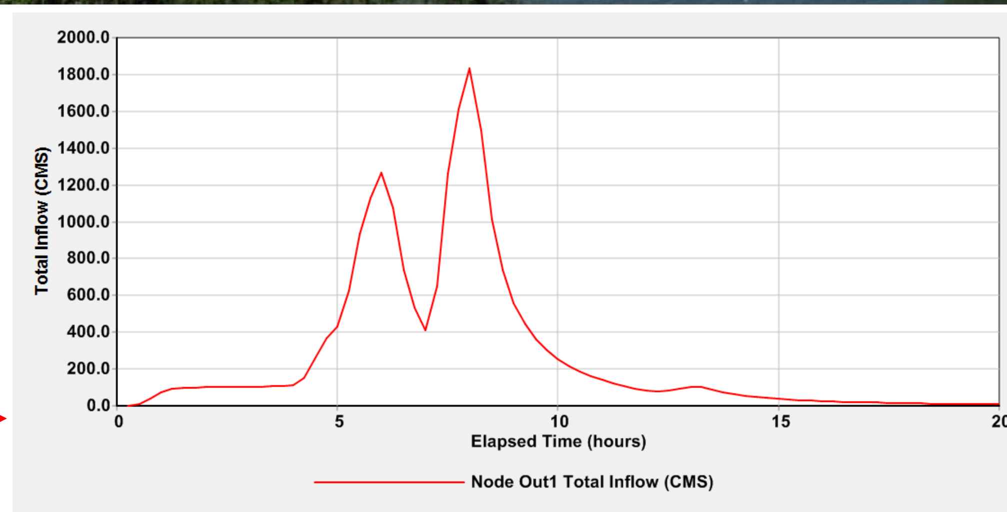
Total depth: 16.24 in. (412.5 mm)

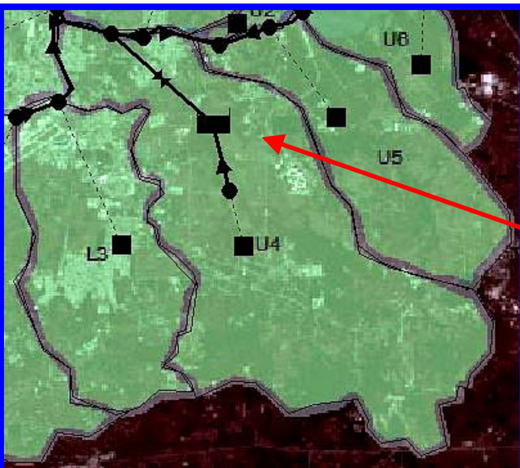
SWMM-CAT Climate Adjustment Tool: 20% increase for Far Term 2045-2074 Warm/Wet Climate Change Outcome for Havana Latitude and Longitude



Almendares River looking North towards the Mouth (ArcGIS and Google Earth)

Predicted Hydrograph at the mouth

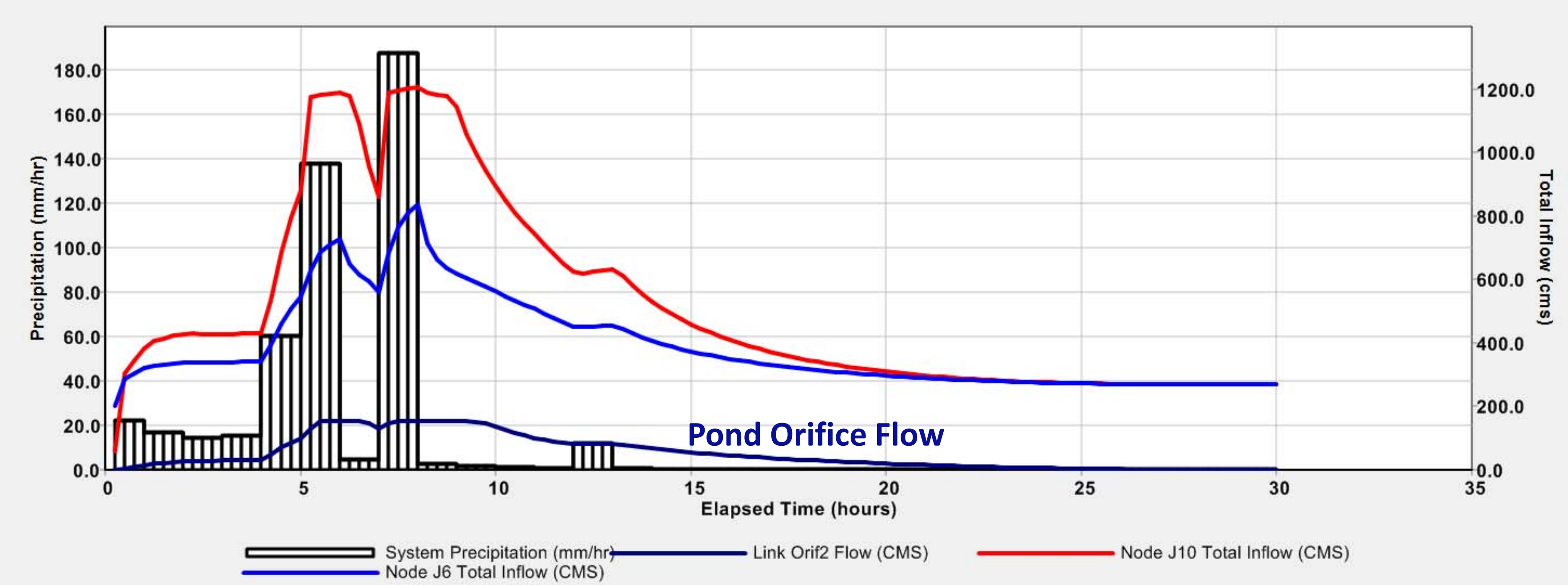




Proposed Detention Pond

Almendares River
23° 6′ N 82° 24′ W
(Google Earth)

Computed Link and Node Hydrographs

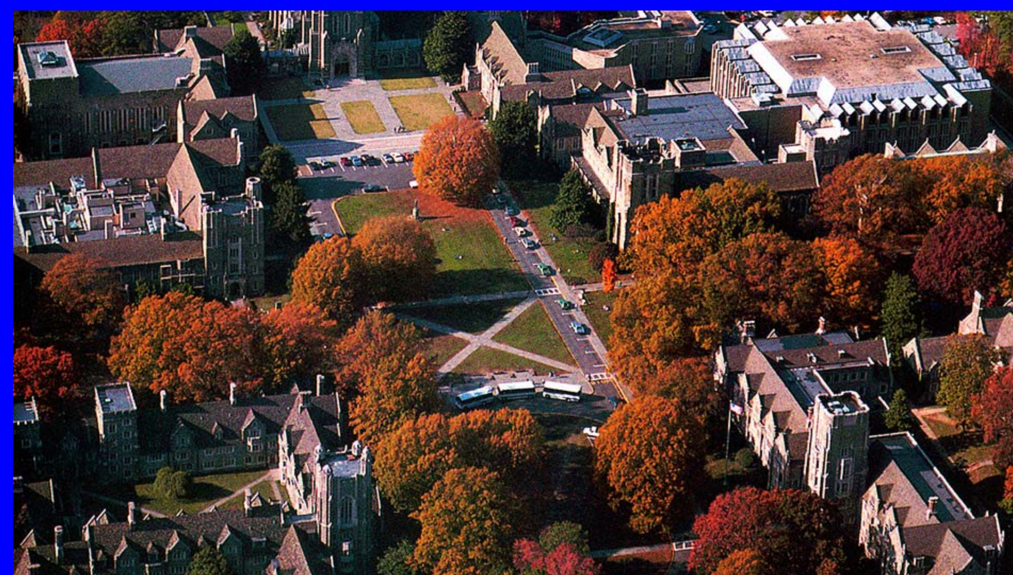


Data-Rich Stormwater Management Modelling

West Campus
Duke University

Both wooded areas
and a highly urbanized
Medical Complex

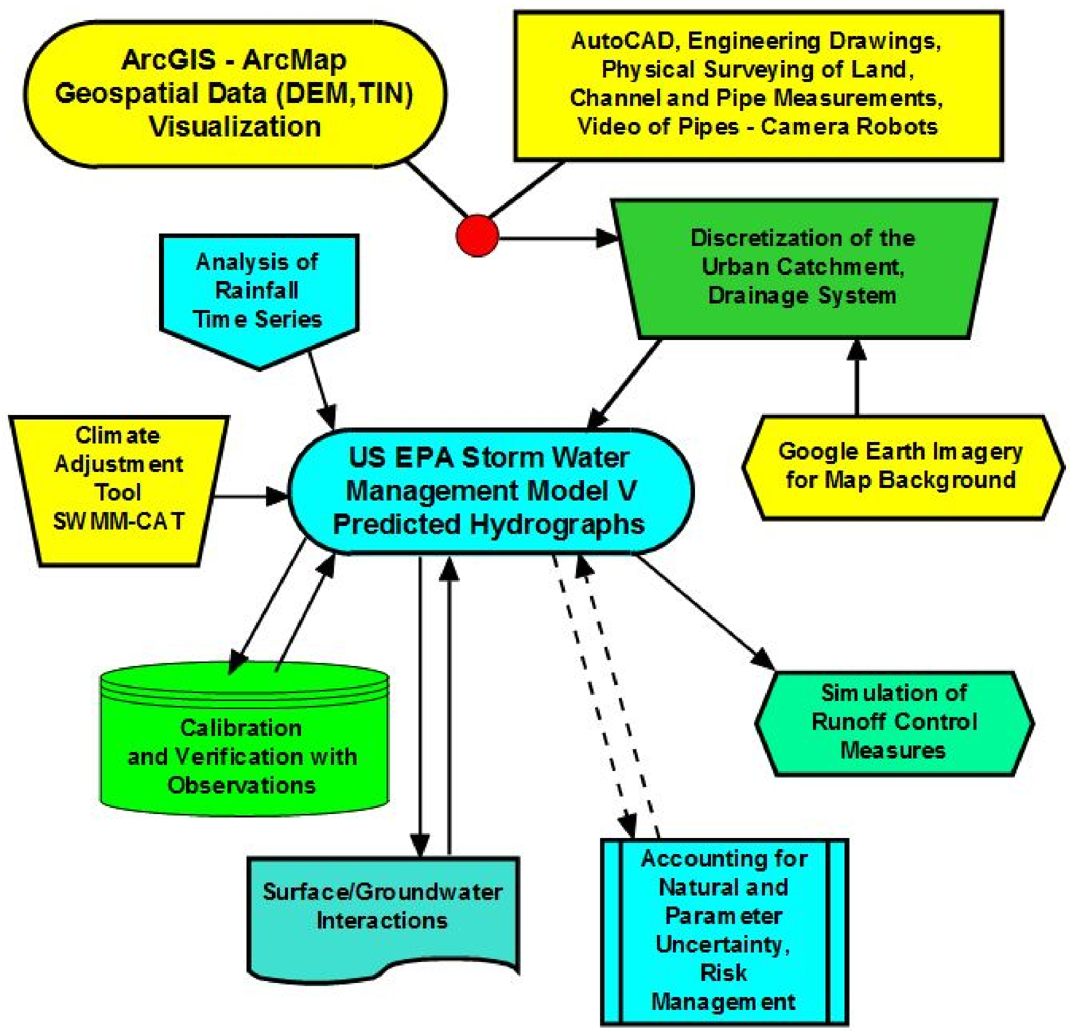
Chapel and Quadrangle



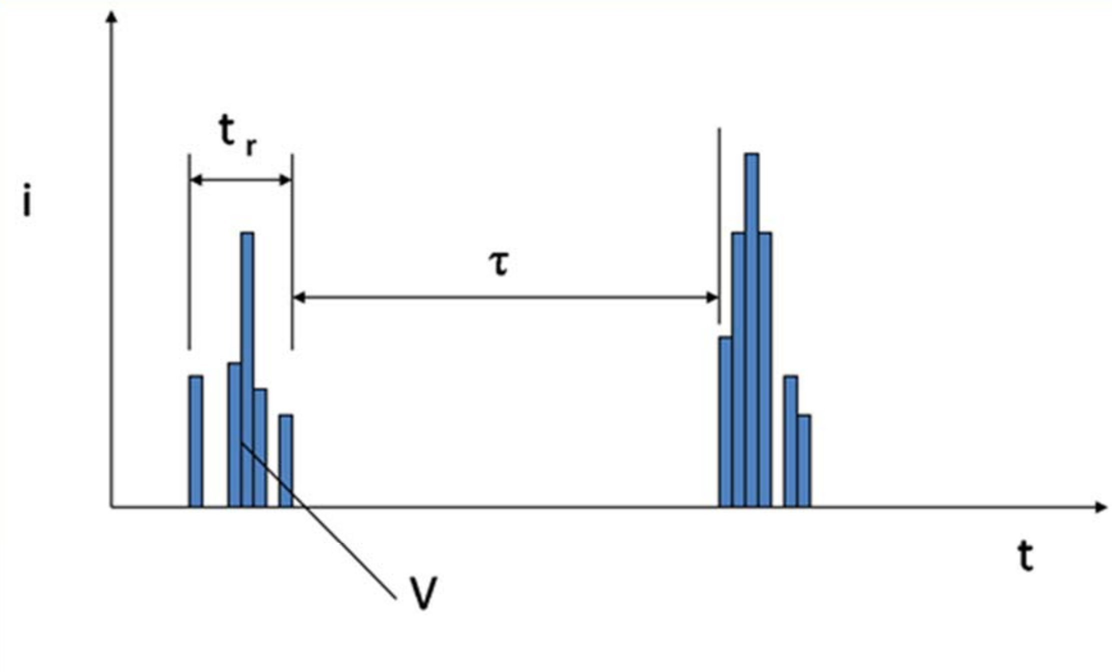
Articles Published On Campus Applications:

Kazezyilmaz-Alhan and Medina, *Applied Mathematical Modelling* (2015)
Medina M.A., Jr., *Handbook of Engineering Hydrology* (2014)
Medina and Kazezyilmaz-Alhan, *Overland Flow and Surface Runoff* (2011)
Kazezyilmaz-Alhan and Medina*, Journal of Hydraulic Engineering* (2007)
Kazezyilmaz-Alhan, Medina and Richardson, *Water Resources Research* (2007)

With Wealth of Data Available



Definition of Storm Event Variables



i = intensity, in./hr V = volume (total depth), in.

t_r = duration, hr τ = time between independent events, hr

Statistics of Storm Event Variables[1]

NOAA Rainfall Station Description and Statistics of Storm Events, RDU, N.C. (1948-2013)

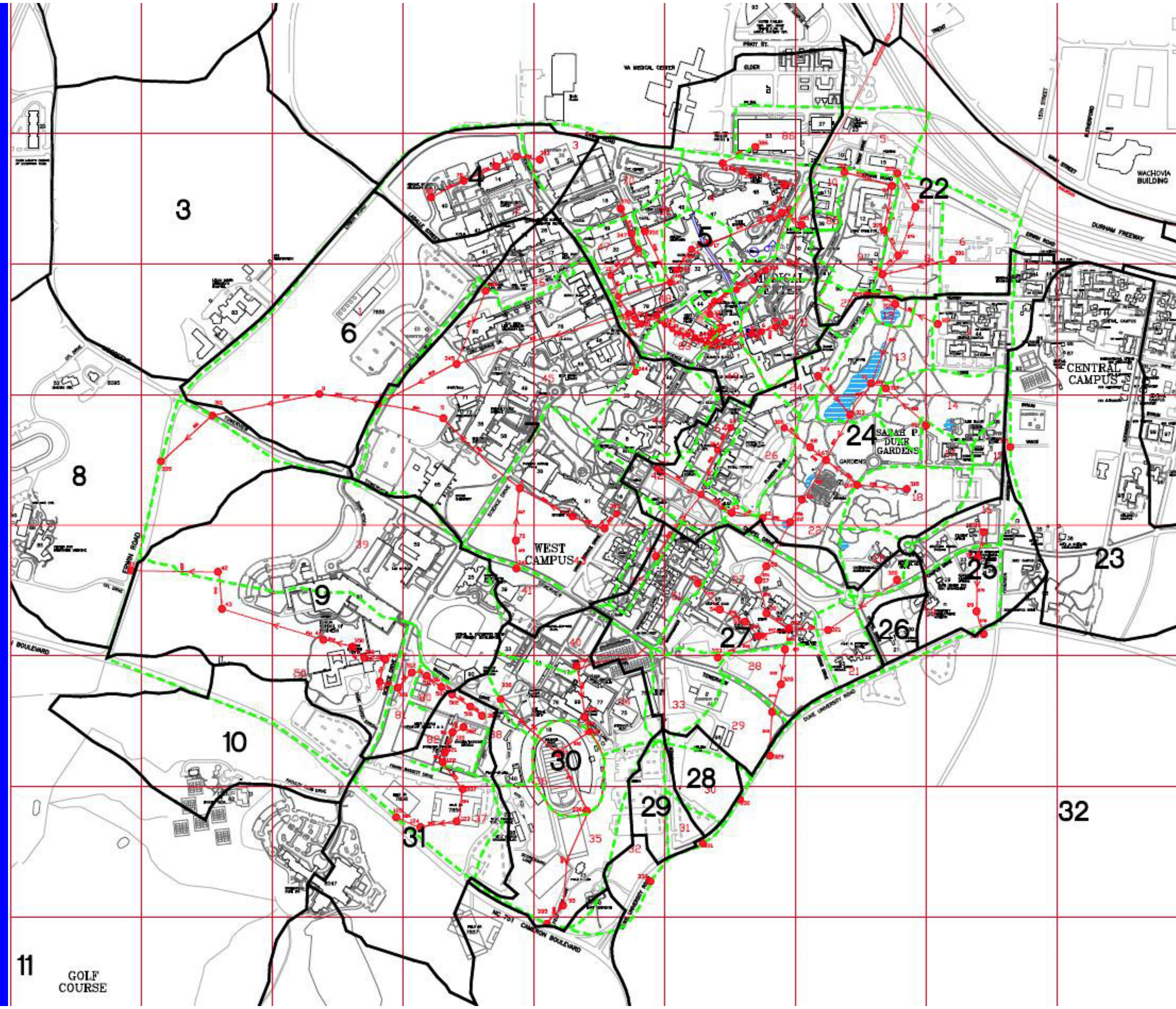
Raleigh Durham Airport 317069; Hourly rainfall	Lat: N 35:52:00 Long: W 78:47:00 Elevation: 416 ft	Record Length: 65 years

Storm Event Variable	**Mean**	**COV**
No. of Storms per year	99.523	0.11
Depth, inches	0.421	1.391
Intensity, in./hr	0.079	1.253
Duration, hours	6.867	1.097
Time Between Events, hrs	87.502	1.005
Total No. of Storms	6361	

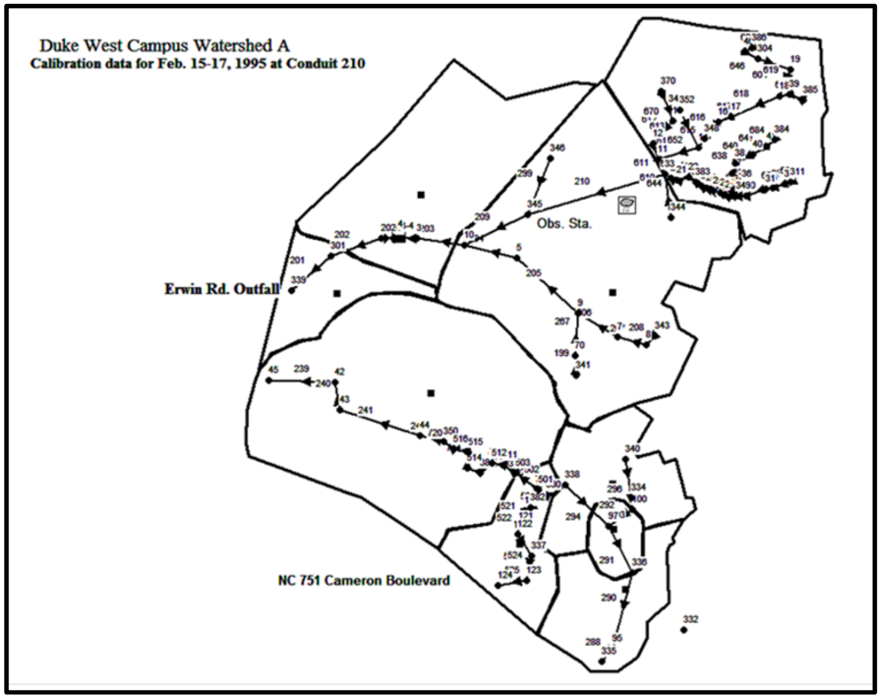
[1] Note: independent events based on a minimum of 6-9 consecutive hours of no rainfall (when exponential distribution fitted to time between events yields COV = $\sigma/\mu \cong$ 1.0). In table above, actual calculated value = 1.005 (close enough).

SWMM5 Network (in red): of Subcatchments (black borders), Circular Pipes, Natural Channels (as Trapezoidal Channels), Manholes, Detention Ponds – all superimposed over West Campus map.

(1174 acres, 475 hectares)

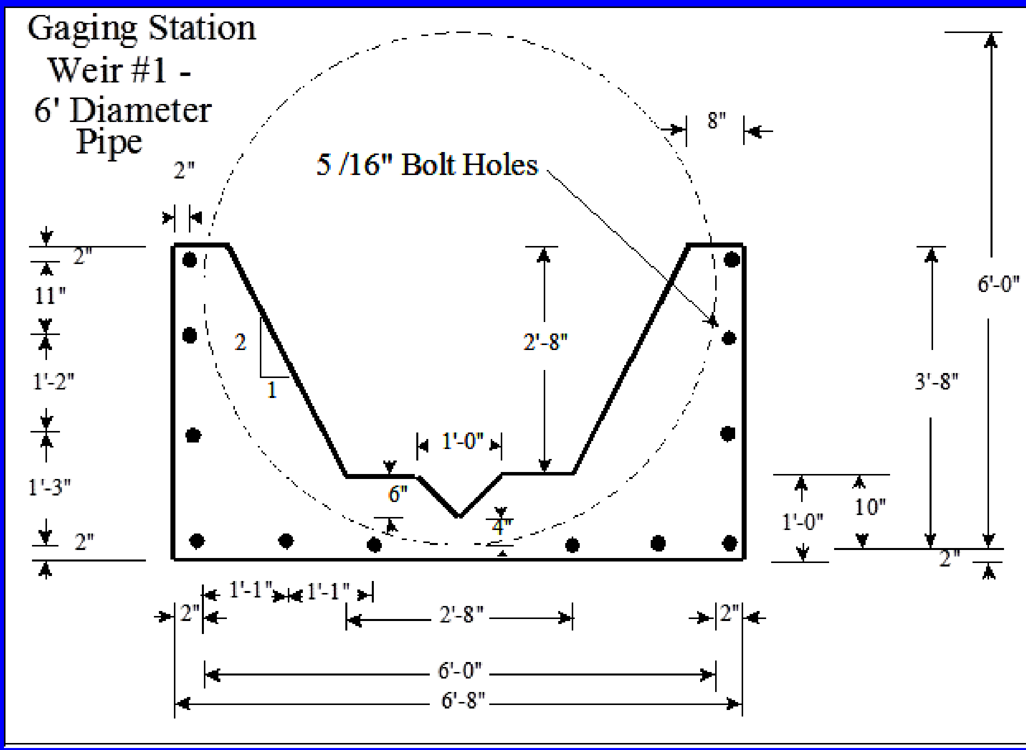


Duke University West Campus
SWMM5 Watershed A Network



Google Earth Image as Background

Flow Measurement at Conduit 210, West Campus Watershed A



Combination Trapezoidal and 90º V-notch Weir

$$Q = 4.28\,H^{5/2} \quad , \quad 0 < H \le 0.5\text{ ft.}$$

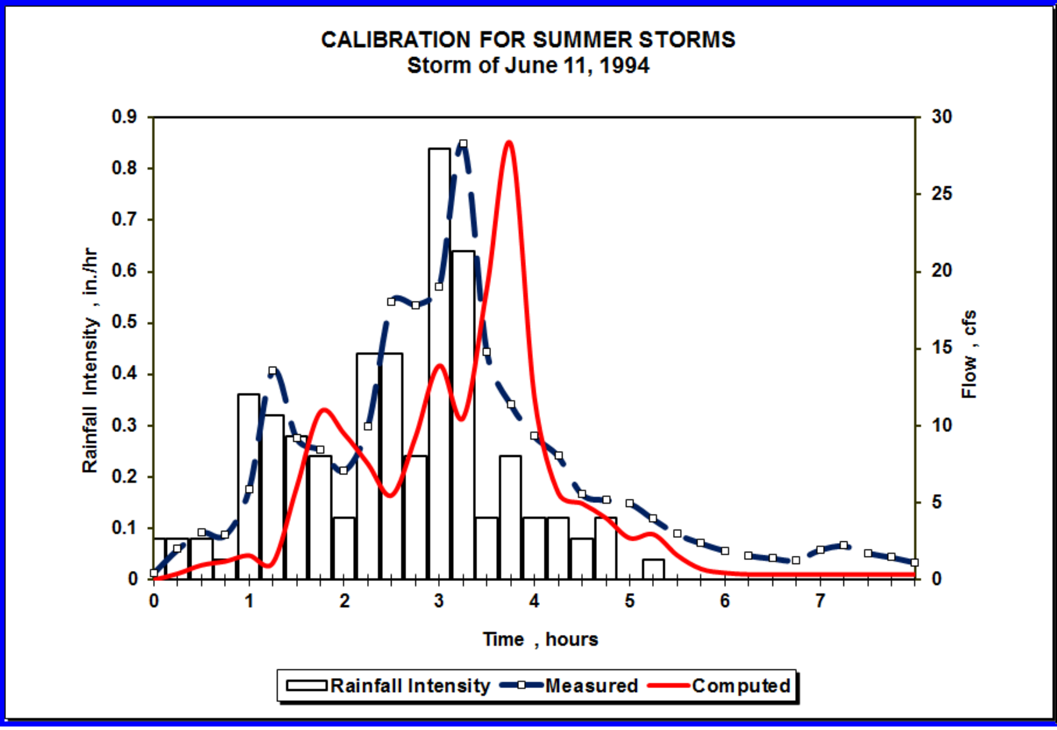
$$Q = 2.14\,(H - 0.5)^{5/2} + 14.27\,(H - 0.5)^{3/2} + 0.757 \quad , \quad 0.5 < H \le 3.16667\text{ ft.}$$

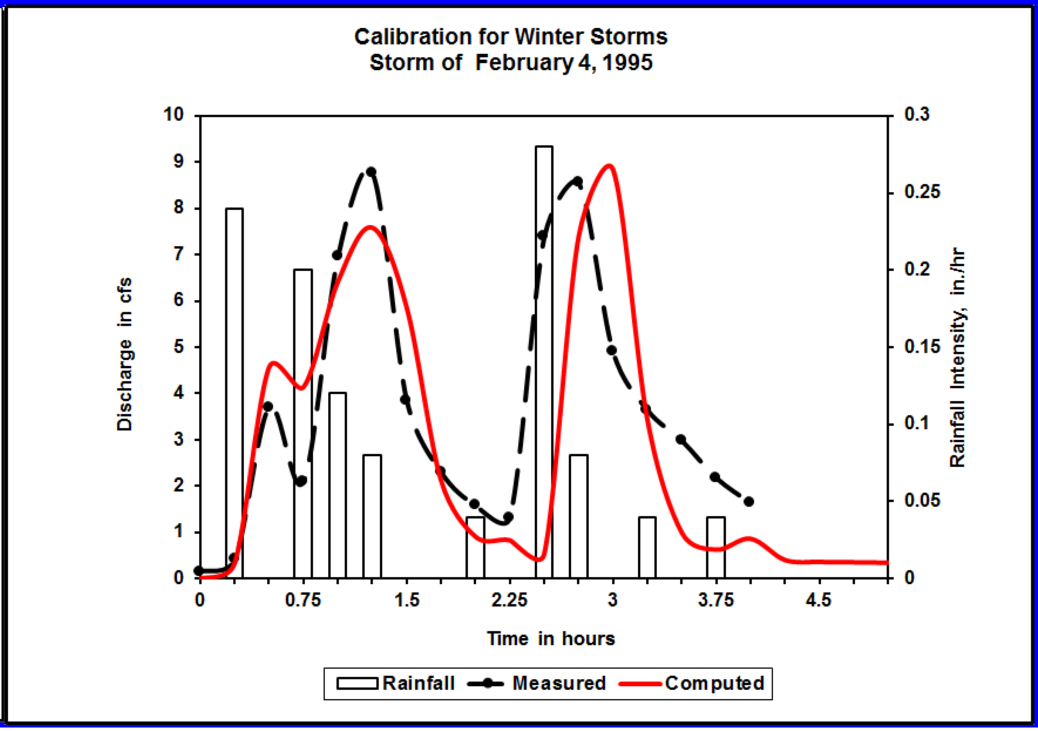
$$\text{where } H = d - 0.33333$$

Calibration parameters and several different storm-size events:
subcatchment imperviousness, width of subcatchment (length of overland flow), impervious depression storage, channel Manning’s roughness, infiltration parameters

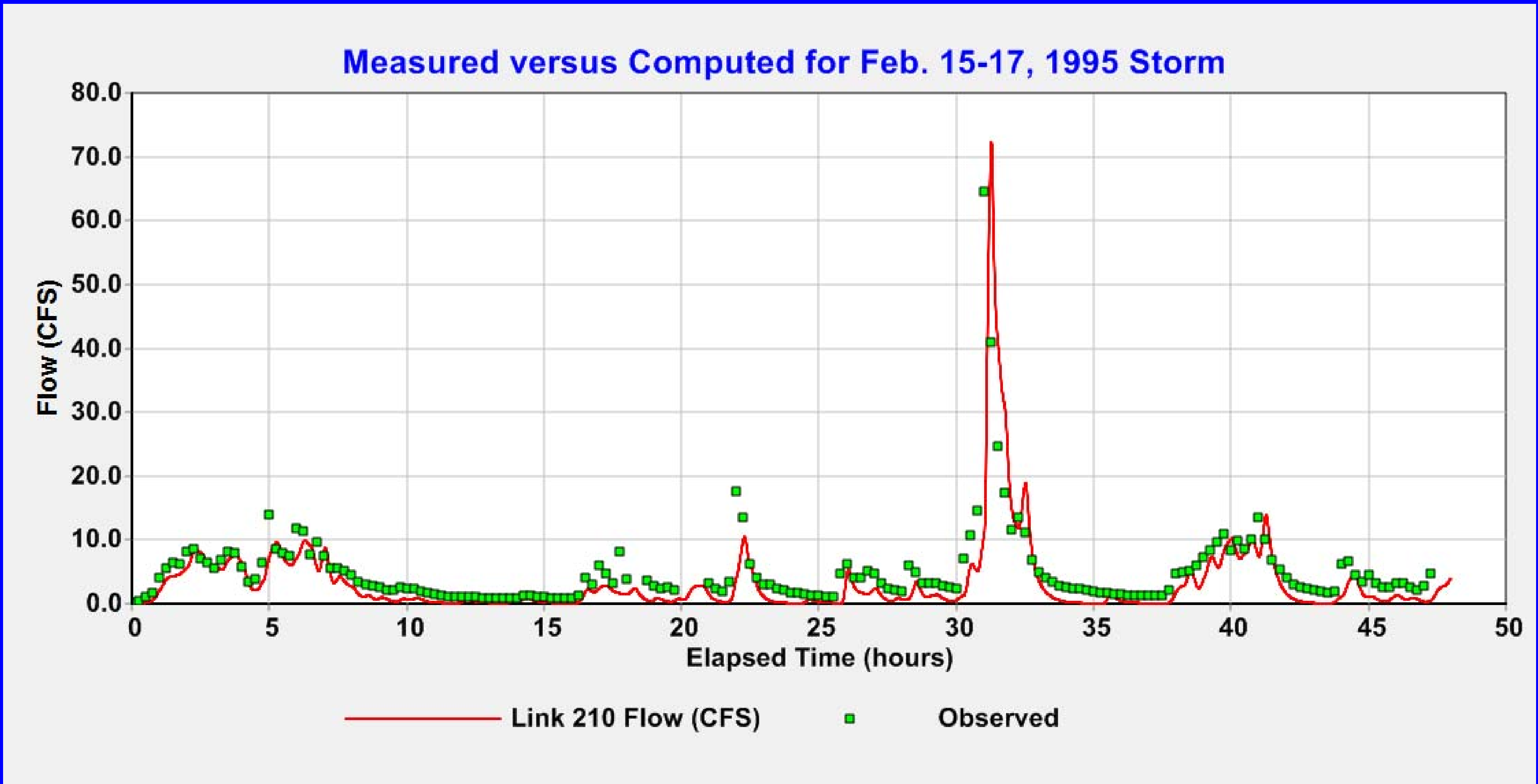
Duration = 7 hours Maximum flow = 0.80 cms

Duration = 4.25 hours Maximum flow = 0.25 cms

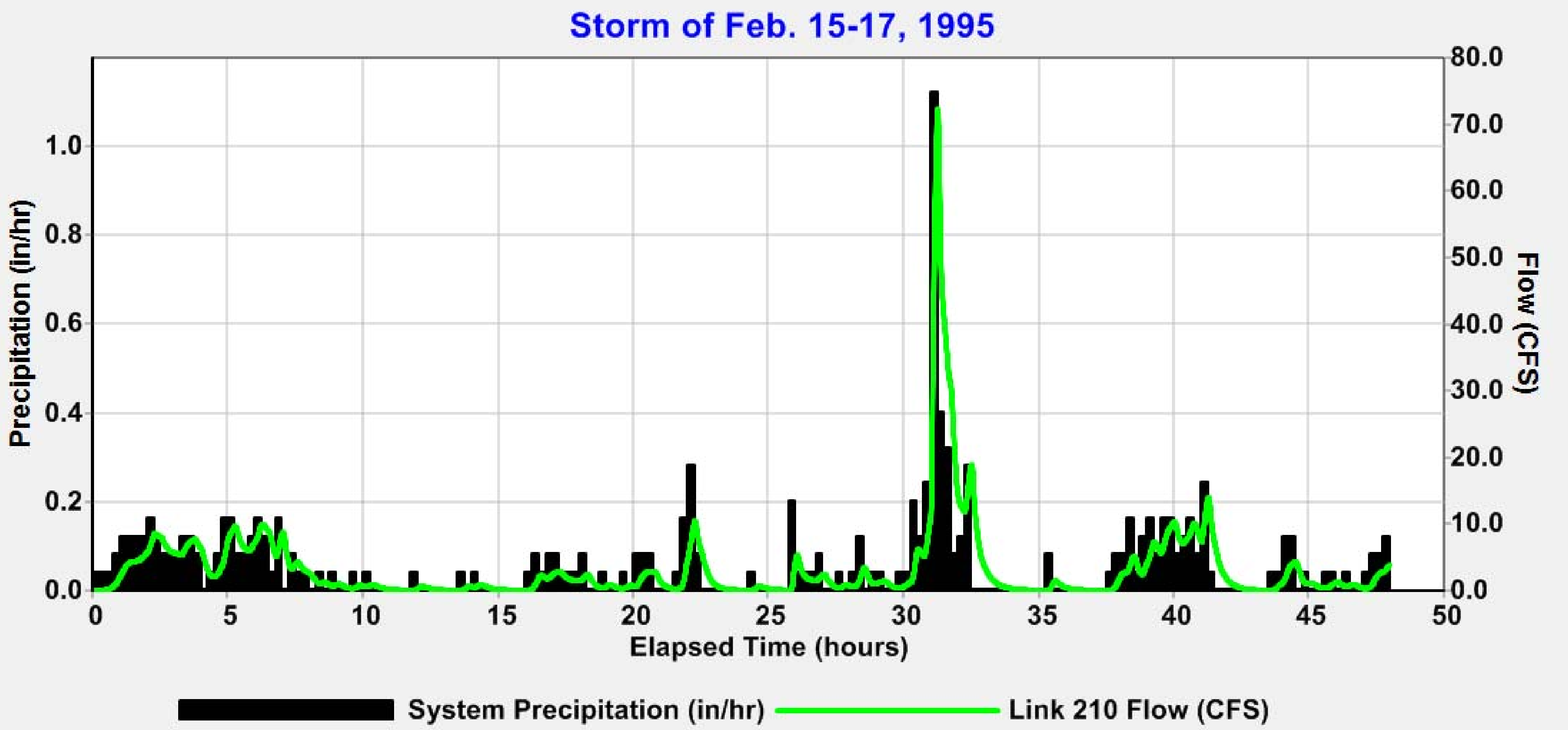




Results of Using Calibration for Winter Storms

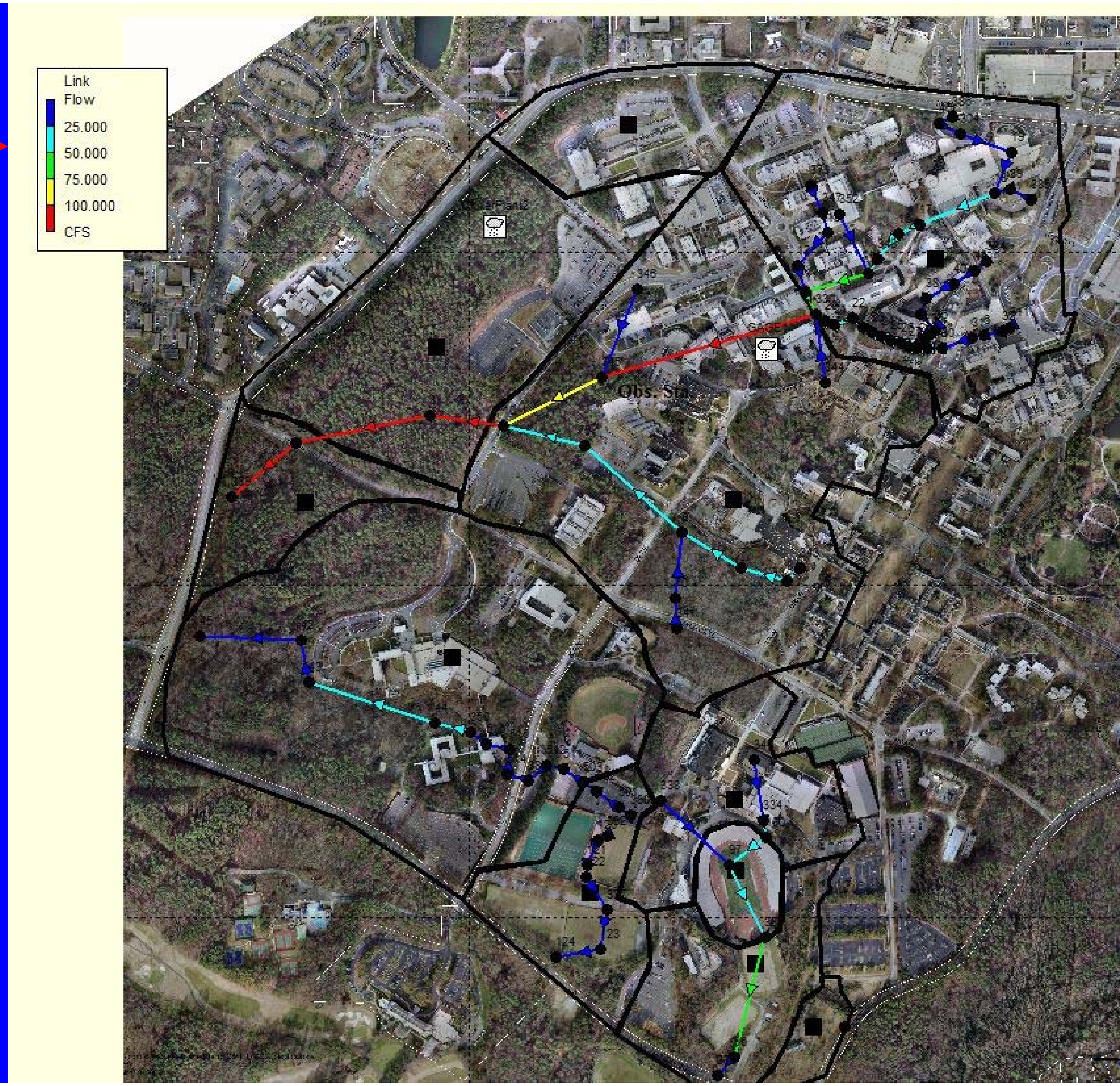


Predicted Hydrograph versus Subcatchment Precipitation

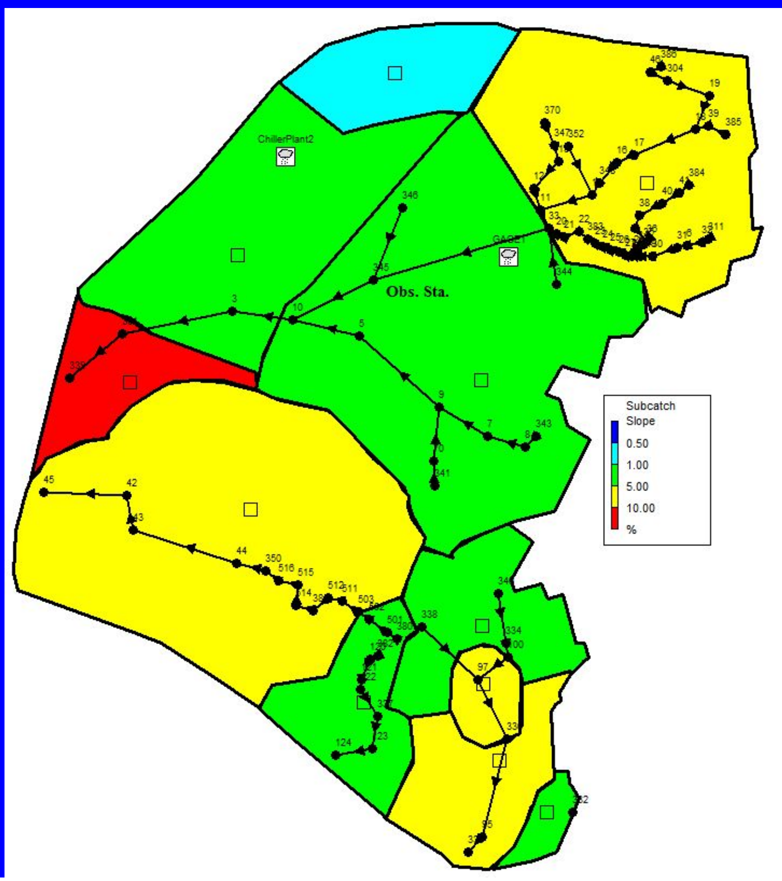


Animation Features

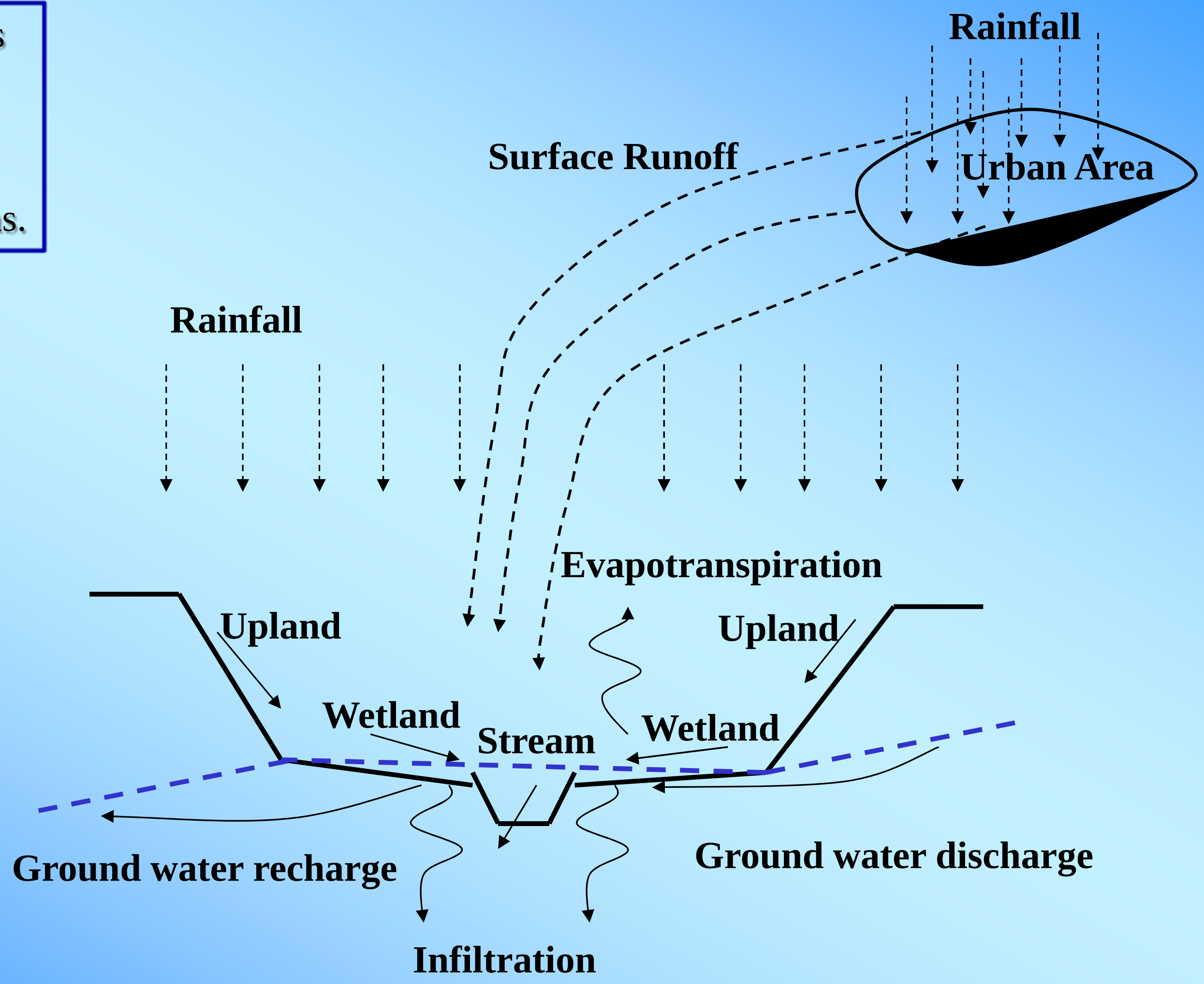
Flow through Transport Network



Subcatchment Variable: Slope



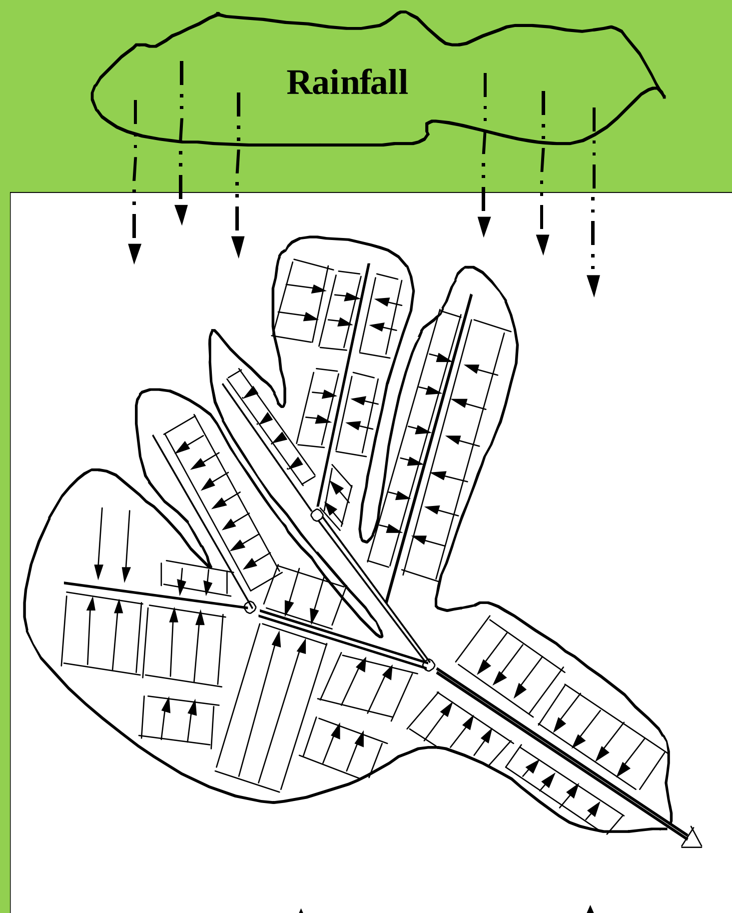
Urban stormwater inputs (SWMM5) to a constructed wetland; stream/ground water flow/transport interactions.

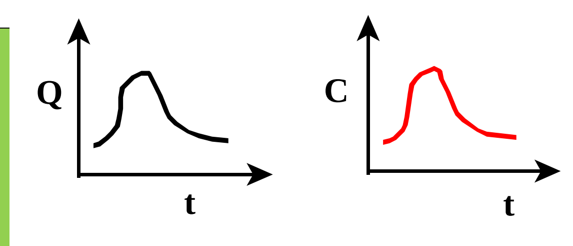


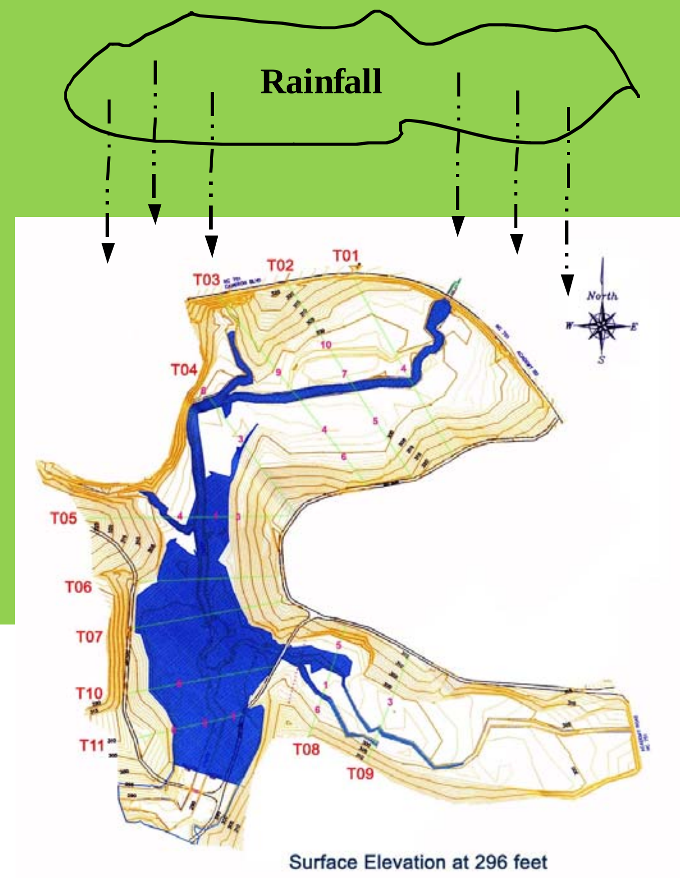
Kazezyilmaz-Alhan, Medina, and Richardson (2007)

Linkage of Urban Catchment – Wetland Flow and Mass Transport Models

Kazezyılmaz-Alhan and Medina (2015)







Governing equations and numerical solutions are presented in referenced article.

Natural and Parameter Uncertainty, Urban Stormwater Modelling under Hydrologic Change Uncertainty

Hydrologic Change is the combined effect of climate change (e.g., extreme rainfall) and land change (e.g., changes in land-use, land-cover patterns) in a nonstationary world.

"In many urbanizing watersheds, annual flood peaks are increasing due to continuous land-use changes. In such situations project designs will need to consider nonstationarity in the probability distribution of flood peaks."
Salas and Obeysekera, "Revisiting the Concepts of Return Period and Risk for Nonstationary Hydrologic Extreme Events," *Journal of Hydrologic Engineering* (2014)

Calibration and SWMM5 Parameter Sensitivity

Subcatchment imperviousness, width of subcatchment (length of overland flow), impervious depression storage, channel Manning's roughness, soil and infiltration parameters, etc.

- Manual calibration is laborious, but the analyst gains considerable intuition about model parameters and their sensitivity
- Calibrate the parameters sequentially that are most sensitive to the objective (e.g., peak flow, volume-total flow, hydrograph match)
- Measured values should always be used as a starting point for calibration
- Reduce uncertainty in the data: analyze data for consistency
- Different parameters are sensitive for different sizes of storms: use a variety of events in your calibration efforts
- Imperviousness of directly connected areas can be calibrated by using small storms (less pervious area runoff generated)
- Soil and infiltration parameters can be calibrated to match larger measured storms.

Automatic Calibration of SWMM
Chance Constrained Optimization

Major metropolitan areas undergo continuous increases in imperviousness due to urban development: Barco, Wong and Stenstrom (2008) applied automatic calibration methods (constrained optimization) to a SWMM-modeled urban watershed with 1,579 subcatchments (2,500 nodes, total length of all channels and pipes over 283 km). Ten storms were used, and a sensitivity analysis showed that **imperviousness and depression storage** were the most sensitive parameters affecting **total runoff and peak flow**. Their objective function was:

$$F = w_1 \left(\frac{Q^* - Q}{Q^*} \right)^2 + w_2 \left(\frac{P^* - P}{P^*} \right)^2 + w_3 \sum_{i=1}^{n} \left(\frac{f^* - f}{f^*} \right)_i^2$$

Where

Q = total flow volume, P = peak flow rate, f = instantaneous flow rate at the outlet hydrograph,

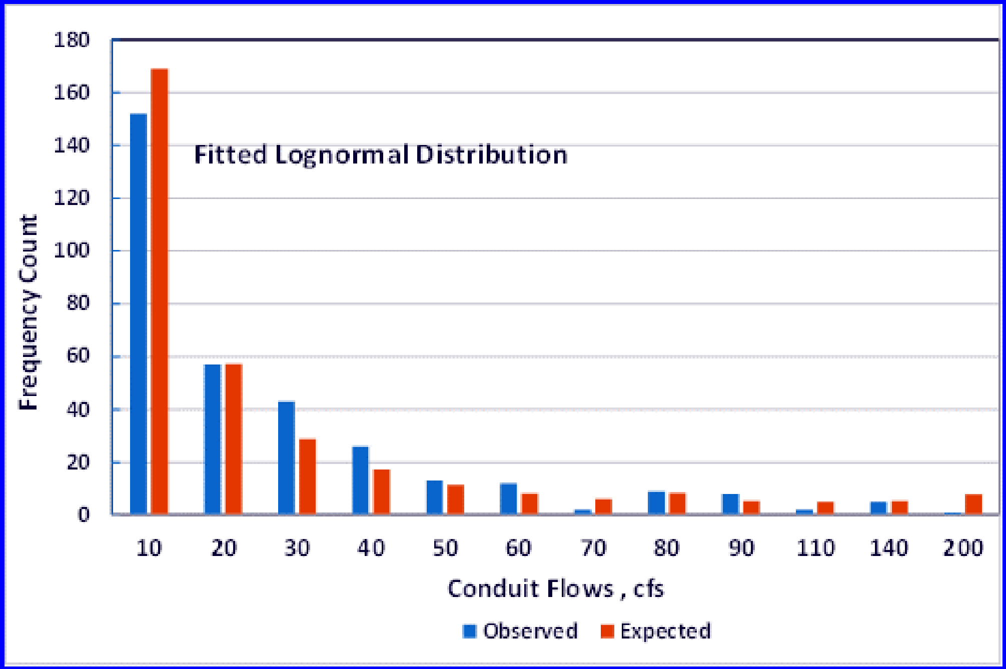
Superscript * = ith predicted value, Subscript i = ith observation of outlet hydrograph,

w_1 , w_2 and w_3 = weights, and n = total number of observed data points in the outlet hydrograph.

Note: four parameters were chosen for calibration – subcatchment imperviousness, width of overland flow, impervious depression storage, and channel Manning's roughness coefficient.

Chance Constrained Optimization with Monte Carlo Sampling

Jacobs, Medina and Ho (1997) developed a mixed integer chance constrained optimization model to determine design and rehabilitation management strategies for stormwater drainage systems conditioned on the likelihood of exceeding the system's conveyance capacity, applied to a small segment of the Duke University West Campus drainage network. The probability that stormwater flows exceed the conveyance capacity of any network segment was expressed as a chance constraint. The model combined kinematic wave routing methods and second-moment analysis to formulate the chance constraint (coded in FORTRAN).



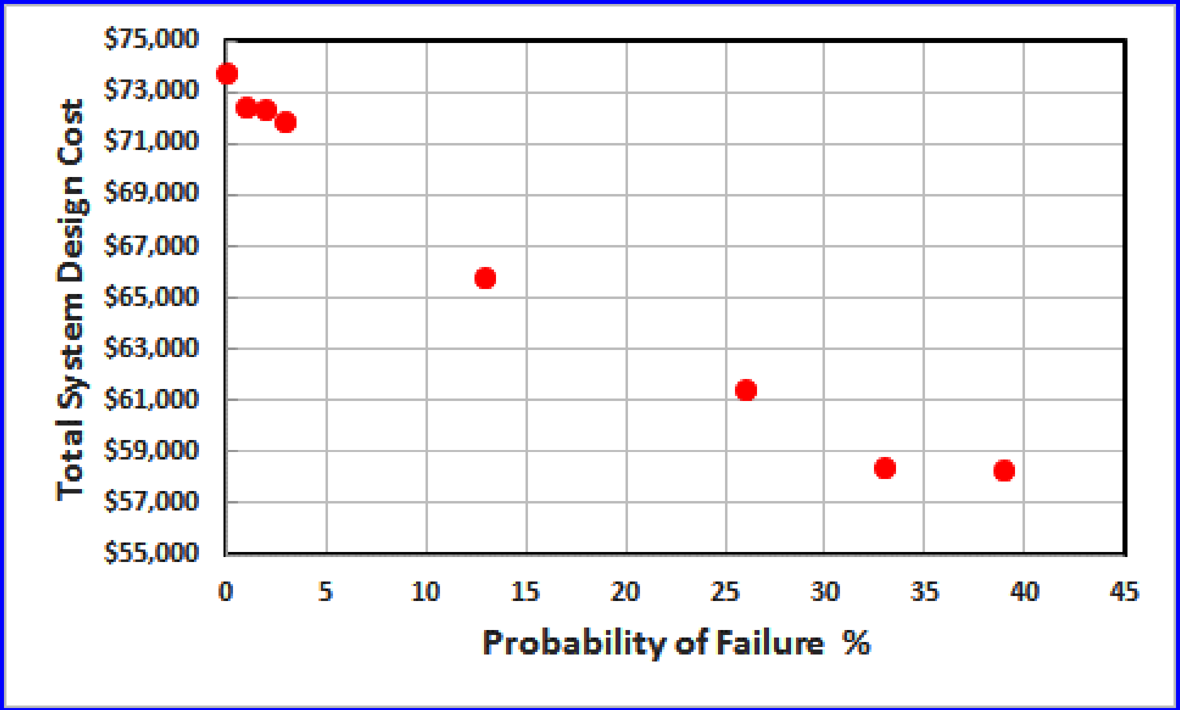
15 network segments, 15 inlet structures

The mean and standard deviation of the maximum segment flows were estimated using 175 Monte Carlo simulations of randomly selected storm events included in the historical record (45 years of hourly precipitation, separated into independent storm events) and 100 time steps for simulating the kinematic wave progression..

Objective: to obtain a tradeoff relationship between cost and reducing the probability of failure (exceeding conduit maximum flows).

For example, the probability of failure can be reduced from 26 % to 13% for an additional $4,000; while further reduction to 3% would cost an additional $6,000.

The figure displays discrete points only, due to the discrete nature of available design options.



Global Climate Models (GCMs)

- Four main components: atmosphere, oceans, land surface and sea ice
- Variables include temperature, pressure, humidity, winds, and water and ice condensate in clouds
- Solve equations of thermodynamics and fluid mechanics for a grid of 0.5° to 4° for the atmosphere component and from 0.2° to 2° for the ocean component

GCMs tend to underestimate the variance and serial persistence in observed climate: engineering design and planning is generally conducted at the regional and local scales, but GCMs perform better at lower spatial resolution and over longer time scales.

Uncertainties in GCM Projections

- Sources (Intergovernmental Panel on Climate Change (IPCC, 2012-2014)
  - Natural variability of climate
  - Uncertainties in model parameters and structure
  - Uncertain projections of future emissions.
- Downscaling
  - Engineering local and regional projects are at smaller scales than GCM grids
  - Statistical downscaling applies historical proportioning
  - Dynamical downscaling can include topographic, land use and vegetation features with Regional Climate Models (RCM)
  - Downscaling techniques used to obtain higher resolution regional and local projections do not reduce the level of uncertainty.

Engineered systems are intended to be functional, durable and safe for their intended service lives (years, century). Functional to a certain level of extreme event, durable to a more severe level, but safe to a still more severe level. (ASCE, 2015)

Simplified schematic of analysis of climate change on discharge (Camici, *et al*., 2014)

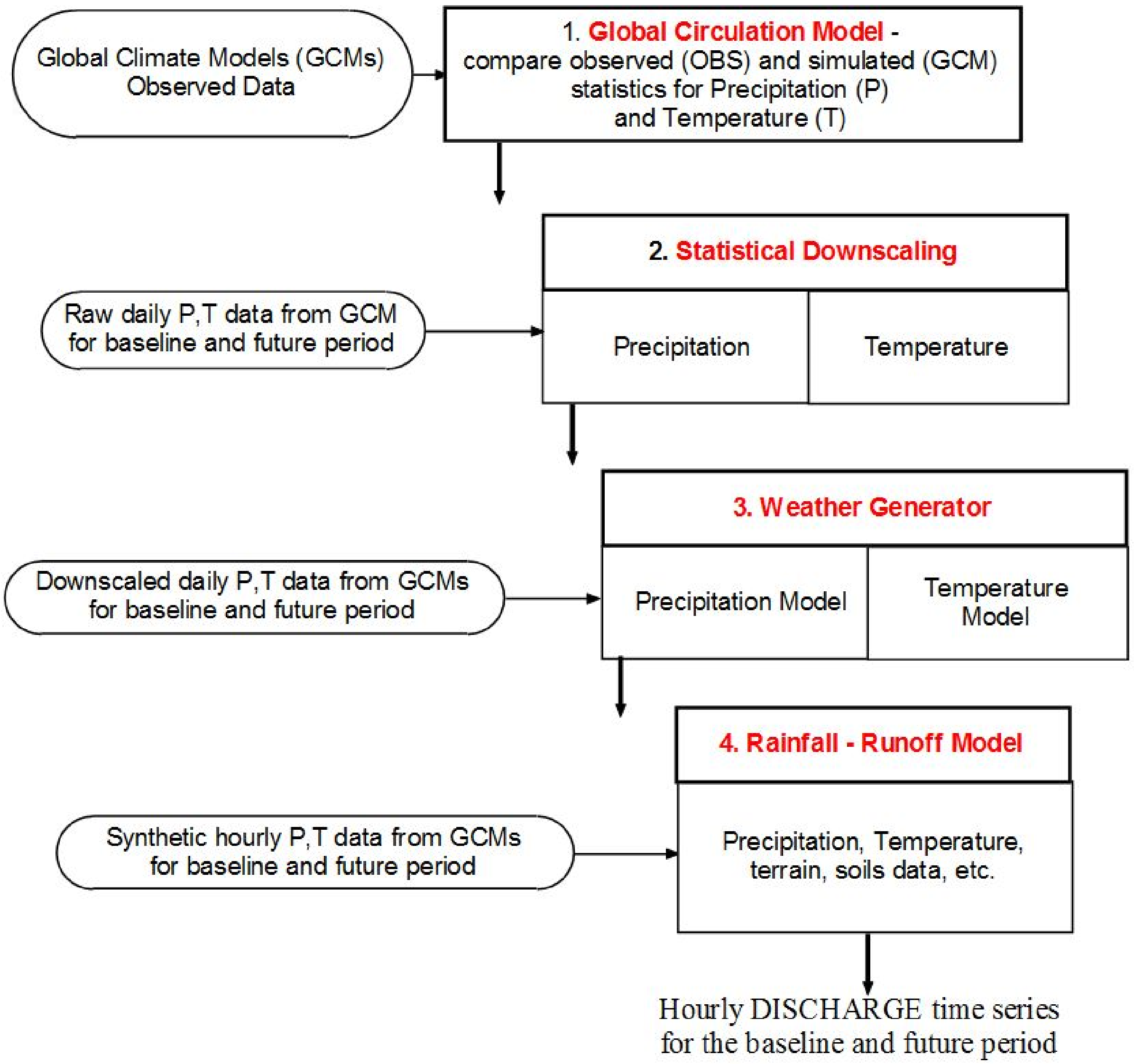
Statistical downscaling applies historical proportioning (Statistical DownScaling Model Decision Centric SDSM-DC 5.2, 2015) Wilby, *et al*. (2014)

"Use of state-of-the-art statistical methods could substantially improve the quantification of uncertainty in assessments of climate change."

Katz, *et al*., *Nature Climate Change* (2013)

SWMM5 is a good tool to predict urban stream hydrologic response to both Climate and Land Cover Change.

Wu, *et al*., *Hydrology and Earth System Sciences* (2013)



Summary and Conclusions

*The SWMM accommodates to most levels of available data – it can produce meaningful results with very rough (**data-limited**) to very refined (**data-rich**) inputs. However, an experienced user is always recommended for data-limited applications. Calibration with measured data and validation with multiple independent events is recommended for data-rich cases. At the regional scale, evidence of **nonstationarity** is closely aligned with the dominant Land Use-Land Cover (LULC) changes associated with urbanization over the last 100 years (Barros, Duan, Brun and Medina (2014). SWMM5 is an invaluable tool to investigate **hydrologic change** when supplied with either single extreme precipitation events, or a long time series of Events.*

*The model add-in tool SWMM-CAT may be used for simple adjustments to climate change. However, it is not a substitute for more rigorous GCM predictions, appropriate downscaling, and thorough application of state-of-the-art statistical techniques (such as historical trends) to adjust these inputs of extreme events, even under **nonstationary** conditions of uncertainty.*

Acknowledgments for Data Limited Presentation

University of Miami (UM) Undergraduate Team: Alec Rodriguez, Jasmine Perez, Miguel Amezcua and Eugenio Victoria won 2nd Place at the Cuba Infrastructure Scholarship Competition on Feb. 27, 2016, sponsored by the Cuban American Association of Civil Engineers (CAACE, Miami, Florida) for their voluntary application of SWMM5 to the Almendares Watershed near Havana, Cuba.

Advisor: Dr. Helena Solo-Gabriele, Professor of Civil, Architectural and Environmental Engineering and Associate Dean for Research, College of Engineering, UM.

Co-Mentor: Dr. Armando Perez, retired Vice-President, CDM-Smith – provided invaluable experience and expertise in water resources engineering, and project management.

References

ASCE, "*Bridging the Gap between Climate Change Science and Civil Engineering Practice,"* Committee on Adaptation to a Changing Climate, Edited by: J. Rolf Olsen; Bilal M. Ayyub, Ana Barros, Wayne Lei, Franklin Lombardo, Miguel Medina, Constantine Samaras, Orson P. Smith, Eugene Z. Stakhiv, Jonathan Tan, Ted S. Vinson, Dan Walker, Richard Wright (Lead Authors), (2015).

Barco, J., K.M. Wong and M.K. Stenstrom, "Automatic Calibration of the U.S. EPA SWMM Model for a Large Urban Catchment," *Journal of Hydraulic Engineering*, 134(4) 466-474, 2008.

Barros, A.P., Y. Duan, J. Brun, and M. A. Medina, Jr., "Flood Nonstationarity in the Southeast and Mid-Atlantic Regions of the United States," *Journal of Hydrologic Engineering*, 19 (10) (2014). http://dx.doi.org/10.1061/(ASCE)HE.1943-5584.0000955. .

Camici, S., L. Brocca, F. Melone, and T. Moramarco,"Impact of Climate Change on Flood Frequency Using Different Climate Models and Downscaling Approaches," *Journal of Hydrologic Engineering*, Vol. 19, 2014.

Jacobs, T.L., M.A. Medina, Jr., and J.T. Ho, "A Chance Constrained Model for Reliability-Based Design and Rehabilitation of Stormwater Systems," *Journal of Water Resources Planning and Management*, 123(3) 163-168 (1997).

Katz, R.W., P.F. Craigmile, P. Guttorp, M. Haran, B. Sansó and M. Stein, "Uncertainty analysis in climate change assessments," *Nature Climate Change*, Vol. 3, 769-771, 2013.

Kazezyılmaz-Alhan, C. M., and M. A. Medina, Jr., "On numerical modeling of the contaminant transport equations of the wetland hydrology and water quality model WETSAND, *Applied Mathematical Modelling* (2015), .

Kazezyilmaz-Alhan, C. M., M. A. Medina, Jr., and C. Richardson, "A Wetland Hydrology and Water Quality Model Incorporating Surface/Ground Water Interactions," *Water Resources Research*, 43 (4), W04434, 1-16 (2007).

Kazezyılmaz-Alhan, C. M., and M. A. Medina, Jr., "Kinematic and Diffusion Waves: Analytical and Numerical Solutions to Overland and Channel Flow," *Journal of Hydraulic Engineering*, 133 (2) 217- 228 (2007).

Medina M.A., Jr., "Urban Hydrology," Chapter 28, *Fundamentals and Applications*, *Handbook of Engineering Hydrology*, Taylor & Francis, CRC Press (2014).

Medina M.A., Jr., and C.M. Kazezyılmaz-Alhan, "Overland Flow, Surface Flow and Surface/Ground Water Interactions," Chapter 8, *Overland Flow and Surface Runoff*, Hydrological Science and Engineering, Nova Publishers, ISBN 978-1-61122-868-7, pp. 159-209, 2011.

Obeysekera, J. and J.D. Salas, "Quantifying the Uncertainty of Design Floods under Nonstationary Conditions," *Journal of Hydrologic Engineering*, Vol. 19, 1438-1446, 2014.

Rossman, Lewis A., and Wayne C. Huber, "Storm Water Management Model Reference Manual Volume I – Hydrology (Revised)," EPA/600/R-15/162A, January 2016, Cincinnati, Ohio.

Rossman, Lewis A., "Storm Water Management Model User's Manual," EPA/600/R-05/040, Revised July 2010, Cincinnati, OH 45268 U.S.A.

Salas, J.D. and J. Obeysekera, "Revisiting the Concepts of Return Period and Risk for Nonstationary Hydrologic Extreme Events," *Journal of Hydrologic Engineering*, (19)3, 554-568, (2014).

Wilby, R.L., C.W. Dawson, C. Murphy, P. O'Connor and E. Hawkins, "The Statistical DownScaling Model – Decision Centric (SDSM-DC): conceptual basis and applications," *Climate Research*, 61 (3): 259-276 (2014) doi: 10.3354/cr01254.

Wu, J.Y., J.R. Thompson, R.K. Kolka, K.J. Franz, and T.W. Stewart, "Using the Storm Water Management Model to predict urban headwater stream hydrological response to climate and land cover change," *Hydrology and Earth System Sciences*, 17, 4743–4758 (2013)/doi:10.5194/hess-17-4743-2013.