ADAPTING SWM FOR CLIMATE CHANGE:
- SWM FACILITY CAPACITY <u>AND</u> INFLOW DESIGN
- ENGINEERED STORMWATER TREATMENT WETLANDS

VILLANOVA URBAN STORMWATER PARTNERSHIP (VUSP) OCTOBER 13, 2022

Mark Derham Bowen, PE, CFM, CCR - Senior Project Manager at NTM Engineering.

Since 2006, I have been working on bringing good science to stormwater management implementation.

For the past several years I have been working on the writing of the Pennsylvania Post Construction Stormwater Management Manual for the Pennsylvania Department of Environmental Protection and Villanova University. One significant change the new manual will include is adaptation for climate change. Much of this presentation explains how the new PCSM Manual will address adaptation for climate change.

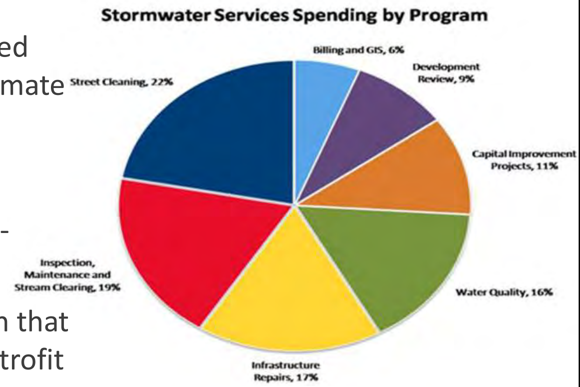
AGENDA

- Predictions for future rainfall
- Engineering approaches to addressing changing rainfall patterns
- Adapting stormwater control measure (SCM) design for increased rainfall
- Inflow component capacity is a major limiting factor (now and in the future)
  - Dual drainage paths for inflow
- Engineered Stormwater Treatment Wetlands self-adjust to changing hydrology

(Read slide.)

CLIMATE CHANGE GOALS – DRAFT PCSM MANUAL

- Protect the waters of the Commonwealth.
- Incorporate the findings of the Pennsylvania Climate Impacts Assessment 2021 into the guidance for stormwater management design.
- Provide adaptation techniques for the observed trends in precipitation and modeled future climate change.
- Provide resilient stormwater management.
- With climate change considered, provide cost-effective solutions for stormwater design.
- Provide guidance on inflow component design that can be cost-effectively applied, even to the retrofit of existing stormwater facilities.



(Read Slides)

There are limited funds to spend on stormwater. Changes to stormwater design for climate change is vital, but it needs to be accomplished in a cost-effective way. As we will show, we have identified a reasonable adaptation technique that identifies strengths in current Pennsylvania guidance and incorporates an understanding of the true long-term cost of stormwater facility construction, operation, and maintenance. A stormwater facility has a lower life cycle cost if the design is resilient. To be resilient, the facilities constructed under future guidance must include the consideration of climate change.

CHANGING RAINFALL PATTERNS

“Each 1 degree C we warm the planet adds an additional 7% increase in moisture into the atmosphere.”

Sierra Club 2021, Emily Williams, PhD

(Read slide)

How we can address this with stormwater management guidance is the subject of this presentation. This statement is largely accepted in the scientific community. There is not a one-to-one relationship between moisture in the atmosphere and rainfall in a particular location, but for Pennsylvania it is a reasonable assumption that the increase in atmospheric moisture will result in increased rainfall.

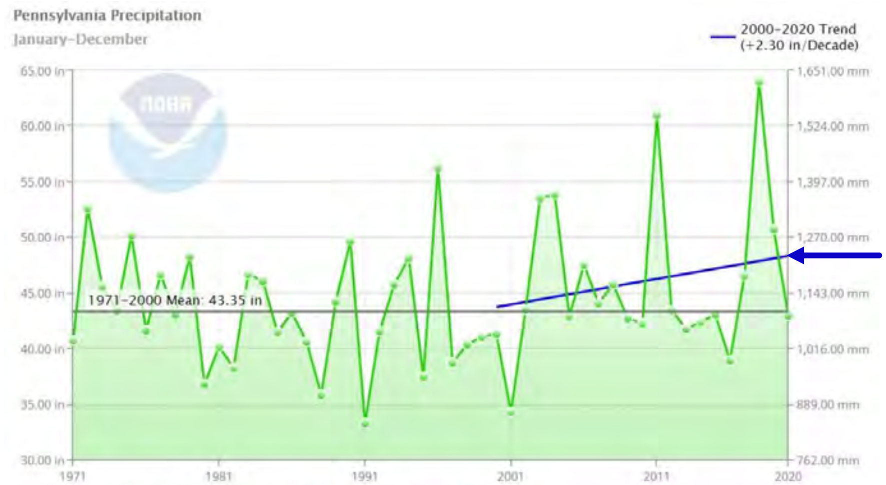
APPLYING CLIMATE DATA TO STORMWATER MANAGEMENT

"The 2021 mid-century projections are essentially the same as that from the 2015 assessment."

The State of Pennsylvania publishes several documents on the likely effects of climate change. We will focus on the Department of Environmental Protection's Pennsylvania Climate Impacts Assessment 2021.

ICF International Inc. developed the predictions in this publication from both climate modeling available and trend analysis. While these are just projections, they have remained consistent for over 6-years now.

INCREASE IN ANNUAL PRECIPITATION



Increasing Trend in Mean Annual Precipitation

Figure 13. Annual precipitation in Pennsylvania 1971–2020

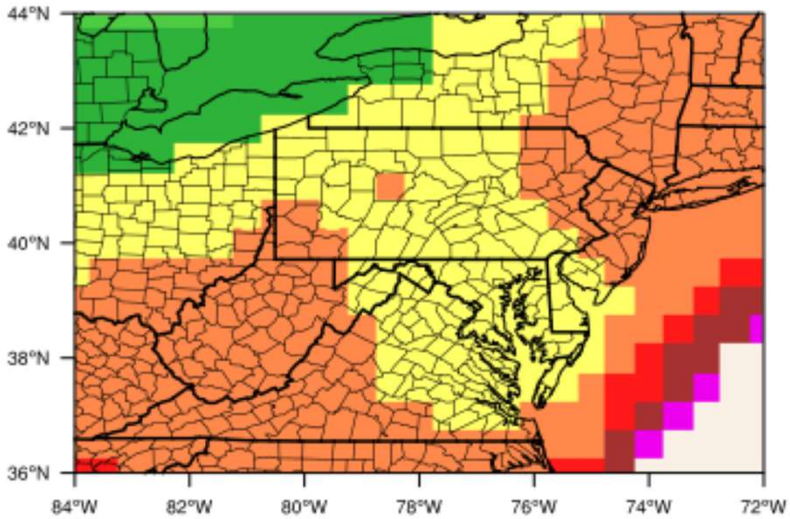
Source: National Centers for Environmental Information. Climate at a Glance- Statewide Time Series.

Pennsylvania Climate Impacts Assessment 2021

This tracking of historic precipitation shows clearly that annual totals of rainfall have been increasing for two decades.

Of note is that the rainfall records we use for SCM design does not include the increase.

GLOBAL CLIMATE MODELS – CMIP5



Scale is too large to use!

Rainfall Projections

51-57 inches

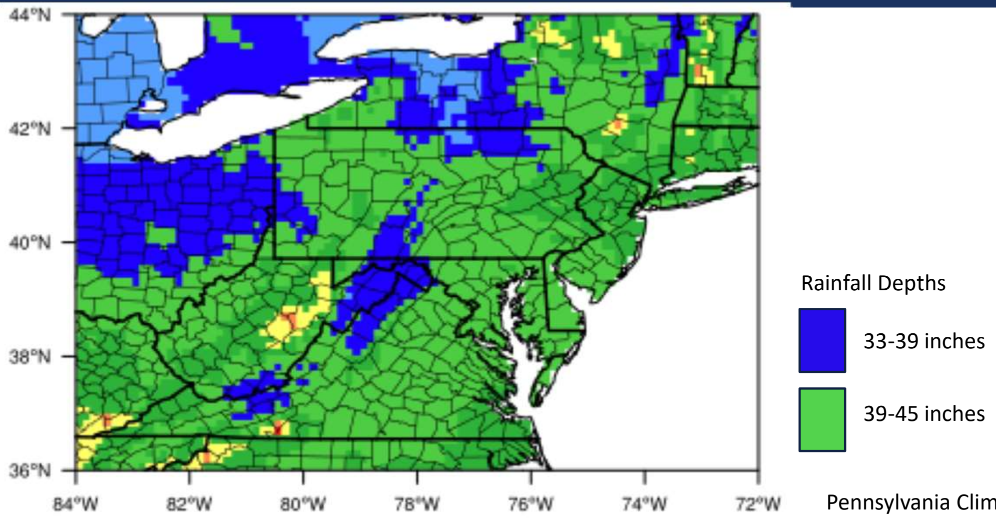
57-63 inches

Philadelphia 54 inches

Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012)

All of the models we will discuss are based on global projections. Un-scaled, the global CMIP5 models predict a lot of precipitation across the entire state. It is not global un-scaled models that were used to develop predictions for the state. Downscaled models like the ones that follow were used.

ANNUAL HISTORIC RAINFALL – STATISTICALLY DOWNSCALED

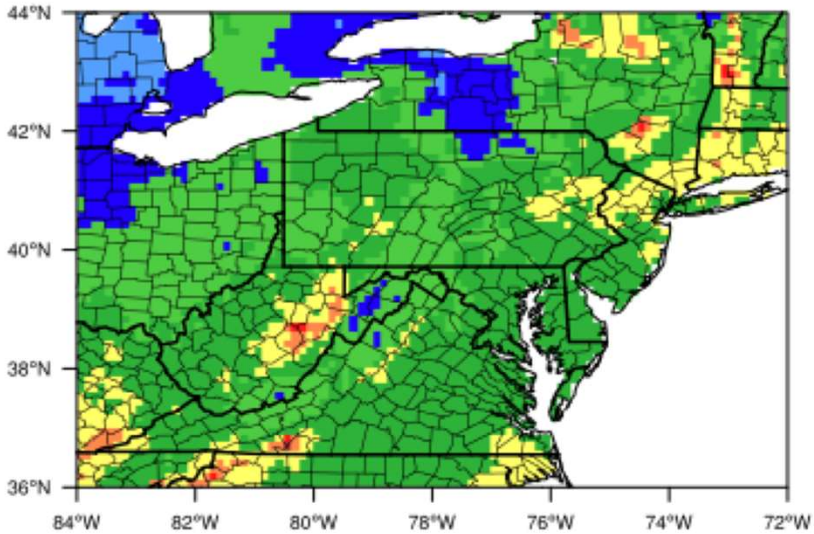


Pennsylvania Climate Impacts Assessment Update
May 2015

Philadelphia 43 inches

Downscaled climate models begin with modeling the baseline (as shown here) to develop a foundation for future projections. The two downscaled models we will discuss are based on a historical period of 1971-2000 and a future period of 2041-2070. This is a screenshot of a statistically downscaled model that mathematically focuses global predictions on our region. The downscaled models recreate the known climate fairly well.

ANNUAL RAINFALL PROJECTED – DYNAMICALLY DOWNSCALED



Philadelphia 48 inches

Based on Global Climate Model (CMIP5) Coupled Model Intercomparison Project

Underestimates Temperature

Rainfall Projections

45-51 inches

51-57 inches

Pennsylvania Climate Impacts Assessment Update
May 2015

The CMIP5 models use large grids. To produce a workable model for the state of Pennsylvania, CMIPS5 was dynamically interpolated to a 0.5-degree grid, which is a finer resolution than most of the GCMs.

One of the advantages of dynamic downscaling is an improved treatment of topography, but it has been found to slightly underestimate temperature increases.

MID-CENTURY RAINFALL PROJECTIONS

- Global Climate Change 2022 to 2050
  - 8% Increased Annual Rainfall in Pennsylvania
    - 14% increase in winter precipitation
  - Pennsylvania will be about 3.3 degrees Centigrade warmer
  - More Extreme Storm Events (storms larger than 1.2-inches of rainfall in one day)
    - Climate change is expected to increase the intensity and frequency of cloudburst events.
    - The number of days with more than 3 inches of rainfall is projected to increase by 52% by mid-century and 93% by end-of-century.

Pennsylvania Climate Impacts Assessment 2021

Some of the key projections of climate change include.

(Read slide.)

The recommendations included in the new PCSM Manual (2022) recognize the changes in rainfall patterns by including design guidance that includes modeling for increased rainfall.

LONGER PROJECTIONS – ANNUAL RAINFALL

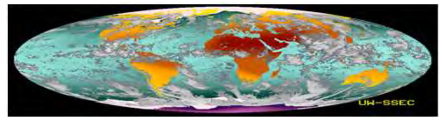
"Pennsylvania will likely experience … a (12%) increase by end-of-century compared to the observed historical baseline (1971–2000)."

Pennsylvania Climate Impacts Assessment 2021

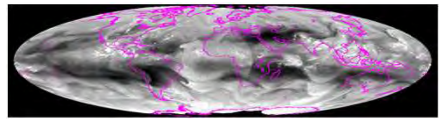
Although the new PCSM Manual will likely be replaced again by the Mid-Century, the facilities (BMPs & SCMs) constructed under its guidance need to last past the mid-century. Adjusting the design parameters to mid-century projections is a conservative first step.

INDIVIDUAL RAIN EVENT PROJECTIONS

- 12% and 18% increase “very heavy rainfall” - historical baseline 0.7-inch/day
  - Rises to 0.78-inch/day by mid-century
  - 0.83-inch/day by end-of-century.



- 13% and 20% increase “extremely heavy rainfall” - historical baseline 1.2-inch/day
  - Rises to 1.3-inch/day by mid-century
  - 1.4-inch/day by the end-of-century.



- 24% more days of “very heavy” by mid-century
- 42% more days of “extremely heavy” by mid-century

Pennsylvania Climate Impacts Assessment 2021

Much of the increase in annual rainfall will occur in rain events of a size the stormwater facilities we are designing are already intended to manage. The problem is that these events are anticipated to be more frequent and include intense cloud bursts that may not get the SCMs we are building.

Keep in mind that we are not trying to solving climate change, we are discussing adapting stormwater management facility design to create resiliency in the face of changing rainfall patterns.

WHAT IS EXPECTED TO IMPACT STORMWATER MANAGEMENT DESIGN

- More days with precipitation.
- Increases in the number of storms under 1.5 inches.
- Increased periods of intense rainfall.
- More erosive events that need WQ/Volume management.
- Warmer temperatures will increase evapotranspiration.

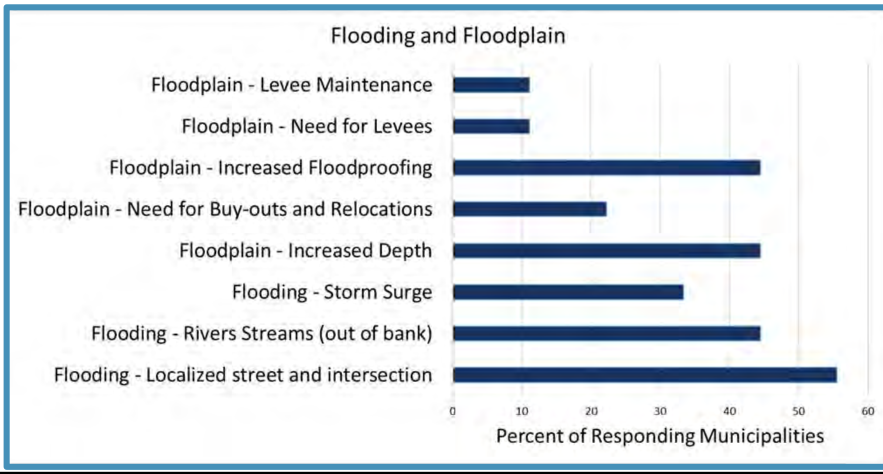
"The literature does not expect that climate change will impact the frequency of tropical cyclones or major winter cyclones." Pennsylvania Climate Impacts Assessment 2021

(Read Slide)

EFFECT OF CLIMATE CHANGE ON EACH SCM COMPONENTS IS DIFFERENT

- Inflow Components
  - Storm Drain
  - Overland flow path
- SCM - (a.k.a. BMPs)
  - Natural SCMs
  - Water Quality/Volume Management SCMs
  - Rate Control SCMs
- Outfall Components
- Receiving waters

Inventory of Municipal Preparedness
DELAWARE BASIN REGIONAL WATER RESOURCE COMMITTEE
2022 STATE WATER PLAN Source: NTM 2022



Inflow – The storms need to get into the storm drain and reach the SCM. Local road flooding reported by many municipalities is a clear indication it is not. We have identified that inflow components are an important limiting factor even in current designs, and it is our opinion that it will become even more limiting with increases in intense rainfalls anticipated for mid-century.

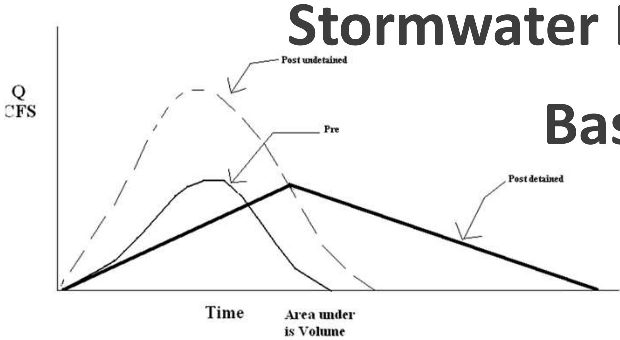
The sizing of the SCM and protection of WQ/Volume SCMs during larger storm events is, surprisingly, a bit easier to adapt for a changing climate, in part because we already design them for the 2-year storm. As we will explore, it is the increases in storms of around the 2-year/24-hour depth that are likely to be most impactful to stormwater management facilities designed for small sites.

Outflow components are generally already designed for larger storms and flood management.

Ultimately, we need to protect the waters of the Commonwealth by designing for the anticipated increase in rainfall intensity due to climate change.

PART II

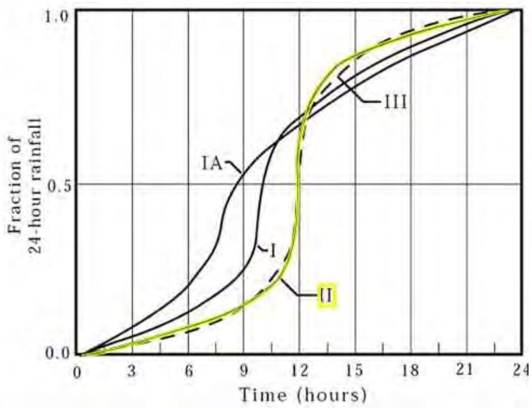
Modeling of Rainfall for Stormwater Management Basins

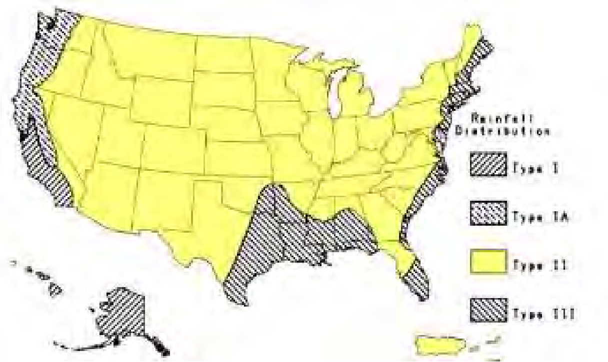


We will now examine how stormwater management basins are currently sized and how the proposed PCSM Manual includes design guidance for the anticipated increased rainfall.

SCS (NRCS) RAINFALL DISTRIBUTIONS DEVELOPED FROM NWS DATA

- Regions I, IA, II, and III
- One region for PA - Region II (Type II storm)





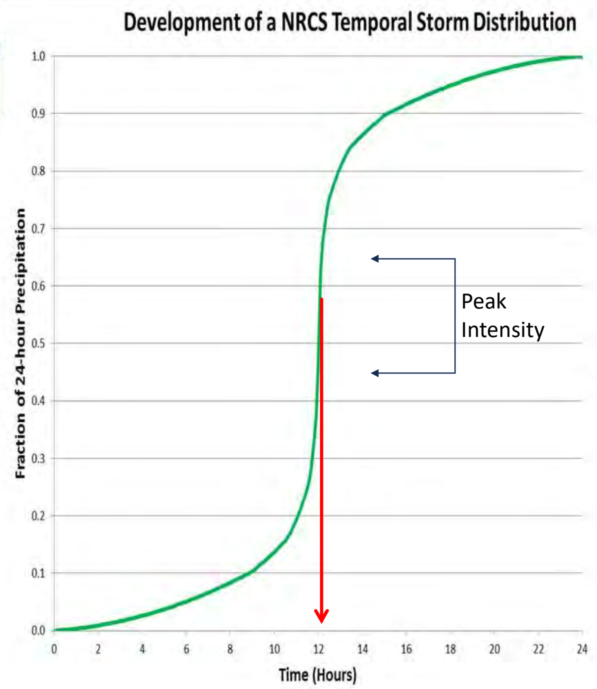
Historically, we have sized SCMs based on regional temporal distribution curves (S curve) that estimate the intensity of rainfall and are based on the type of storm that creates major flooding in an area developed by the Natural Resource Conservation Service (NRCS). We are in a region that experiences Type 2 distribution, a large thunderstorm. These curves are based on data from the last century. An update is needed.

To these S curves we apply rainfall depths provided by the National Oceanographic and Atmospheric Administration (NOAA) in Atlas 14, also based on data from the last century. This data is being updated and we have taken that into account while developing our recommendations.

There has always been a question about how well this approach applies to the design of stormwater management facilities for site development. Based on my almost 30-years of being out in the rain observing many, many, definitional storms (storms with depth that matches a 2-year, 5-year, 100-year, etc.), it is my opinion that the NRCS Design Storm overestimates stormwater runoff for larger storms on your average development site.

NRCS TEMPORAL DISTRIBUTIONS

- Intended to be conservative for design purposes.
- Not intended to duplicate actual storm distributions.

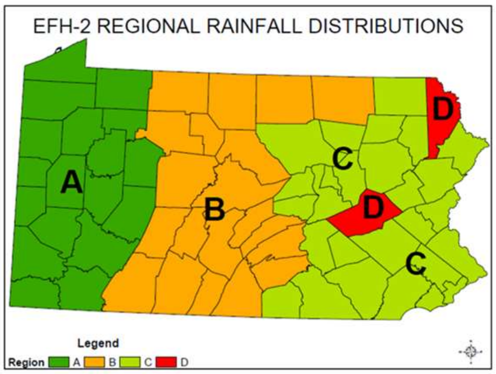


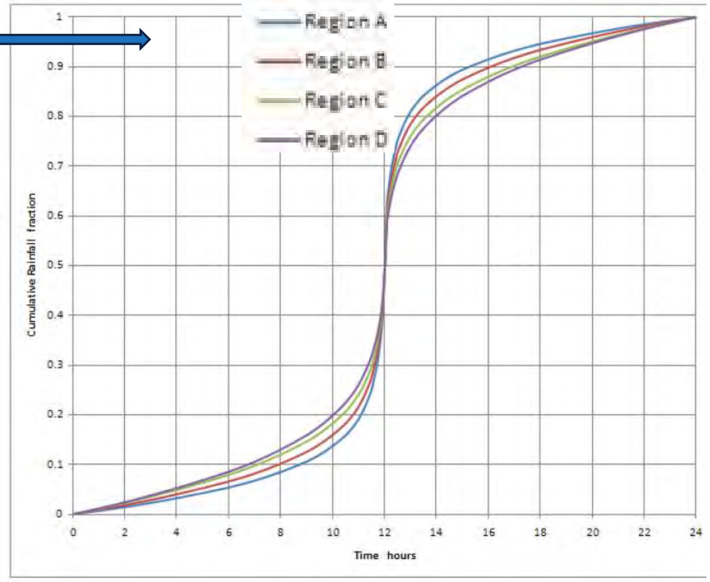
The “S Curve” shows how much rain falls as a storm progresses. The intensity of the rainfall increases as the slope of the graph increases. With climate change more intense cloud bursts are anticipated to occur. Intensity increases will be one of the design criteria we will discuss, mostly with respect to inflow component design. With respect to SCM design, these curves remain conservative.

(Read Slide)

NEW RAINFALL DISTRIBUTION – S CURVE

- NRCS Type II A, B, C, D Distributions:
- A is most intense (steepest curve), D is the least intense.
- Implications: A should produce higher peaks than Type II, D lower peaks.



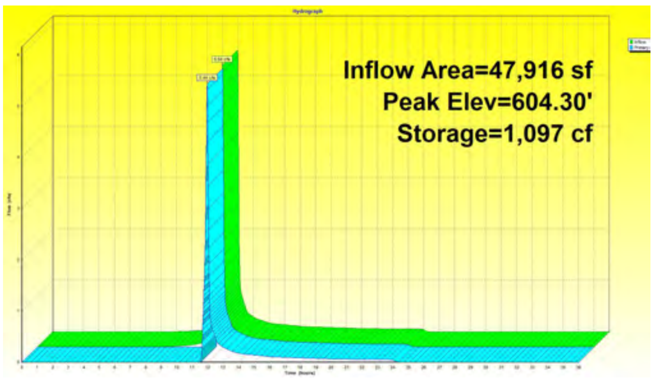


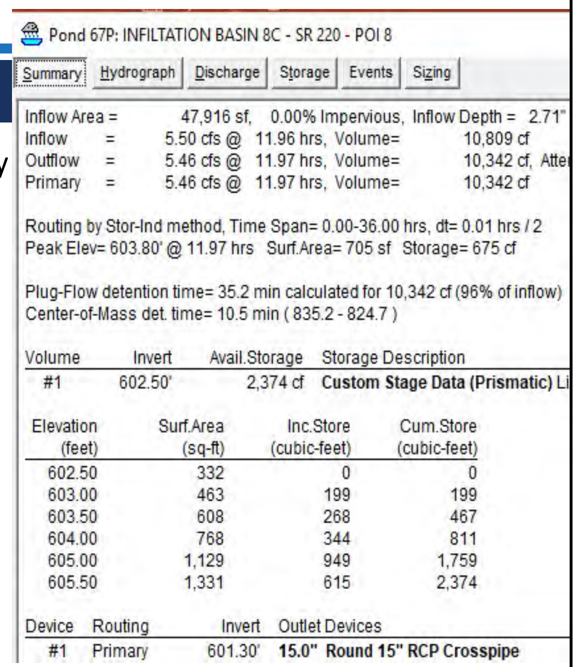
Recently, the NRCS distributions have been slightly modified based on recent analysis of more storms. These curves are what designers should already be using, but the effects of using these curves is small and not intended to account for climate change.

In the new PCSM Manual (due out later this year) these curves are fully endorsed.

DETENTION BASIN ANALYSIS - HYDROCAD

- In our analysis Type II produced the same or slightly higher peaks than Type A.
- Types B, C, & D were all lower than Type II.
  - tc' s were short (< 18 minutes). Longer tc would change this.





Pond 67P: INFILTATION BASIN 8C - SR 220 - POI 8

Summary | Hydrograph | Discharge | Storage | Events | Sizing

Inflow Area = 47,916 sf, 0.00% Impervious, Inflow Depth = 2.71"
Inflow = 5.50 cfs @ 11.96 hrs, Volume= 10,809 cf
Outflow = 5.46 cfs @ 11.97 hrs, Volume= 10,342 cf, Atte
Primary = 5.46 cfs @ 11.97 hrs, Volume= 10,342 cf

Routing by Stor-Ind method, Time Span= 0.00-36.00 hrs, dt= 0.01 hrs / 2
Peak Elev= 603.80' @ 11.97 hrs Surf.Area= 705 sf Storage= 675 cf

Plug-Flow detention time= 35.2 min calculated for 10,342 cf (96% of inflow)
Center-of-Mass det. time= 10.5 min (835.2 - 824.7)

Volume	Invert	Avail.Storage	Storage Description
#1	602.50'	2,374 cf	**Custom Stage Data (Prismatic) Li**

Elevation (feet)	Surf.Area (sq-ft)	Inc.Store (cubic-feet)	Cum.Store (cubic-feet)
602.50	332	0	0
603.00	463	199	199
603.50	608	268	467
604.00	768	344	811
605.00	1,129	949	1,759
605.50	1,331	615	2,374

Device	Routing	Invert	Outlet Devices
#1	Primary	601.30'	**15.0" Round 15" RCP Crosspipe**

NTM 2019

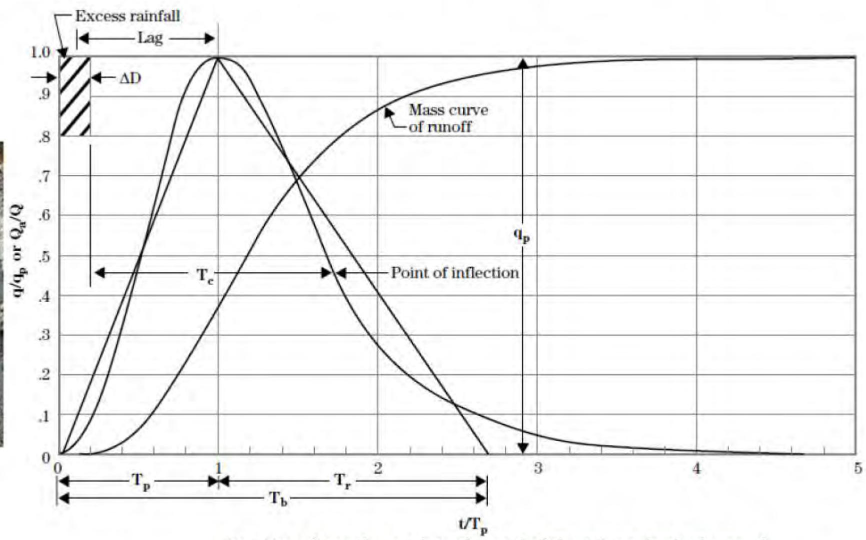
(Read Slide)

But, as you can see, the difference they produce is small.

UNIT HYDROGRAPH

Runoff Concentrating

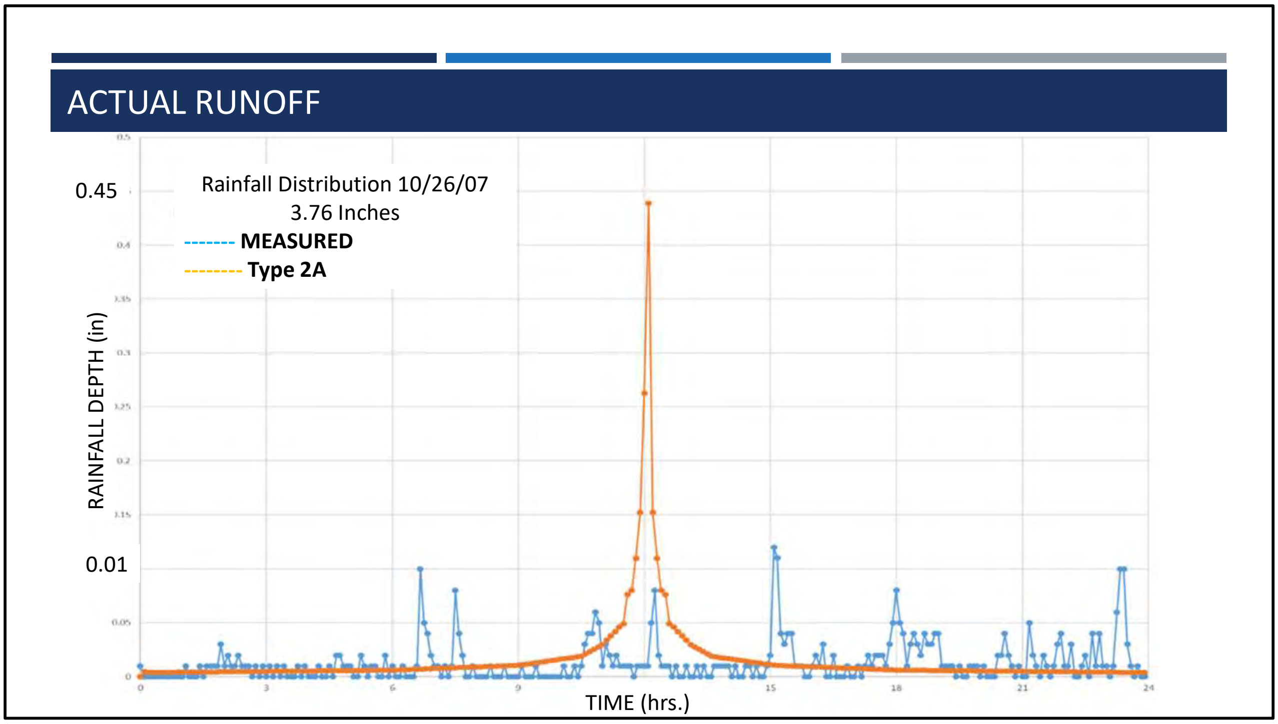
Figure 16A–1 Dimensionless curvilinear unit hydrograph and equivalent triangular hydrograph



Tr = time from the peak to the end of the triangular hydrograph
Tp = time from the beginning of the triangular hydrograph to its peak
Tc = time of concentration
qp = peak discharge

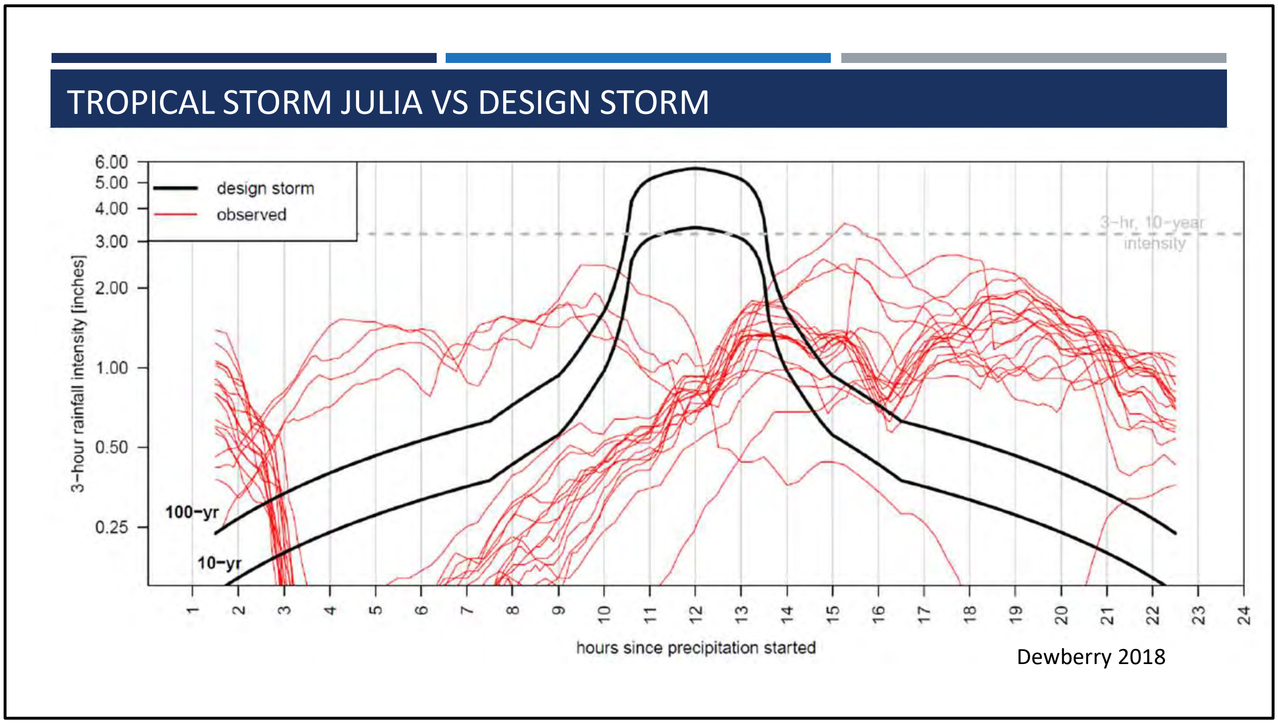
To model the rainfall runoff process we use the "S Curve" intensities to create a hydrograph that mathematically represents a rainstorm over time. It is uniform and tied to the time it takes the entire watershed to contribute flow to a point.

It is the assumption of uniformity that contributes to the method being conservative.



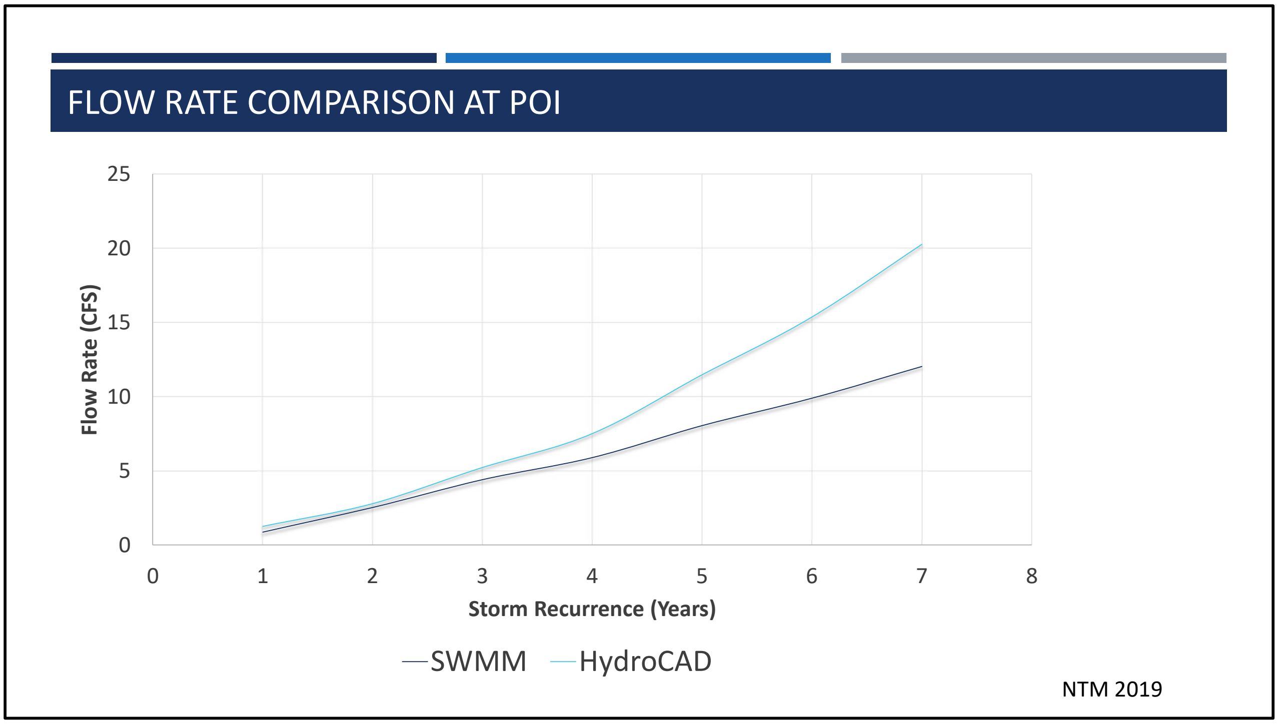
Actual rainfall looks more like the blue line. The orange line is a Type IIA distribution. Notice that none of the real storm peaks get close to the Type IIA distribution peak.

The net result is that sizing an SCM based on Type IIA rainfall is conservative. Flows come in and leave over the course of the storm, leaving excess volume, especially in rate management facilities.



Even in hurricanes the peak intensities are lower and longer than the NRCS storm distribution models.

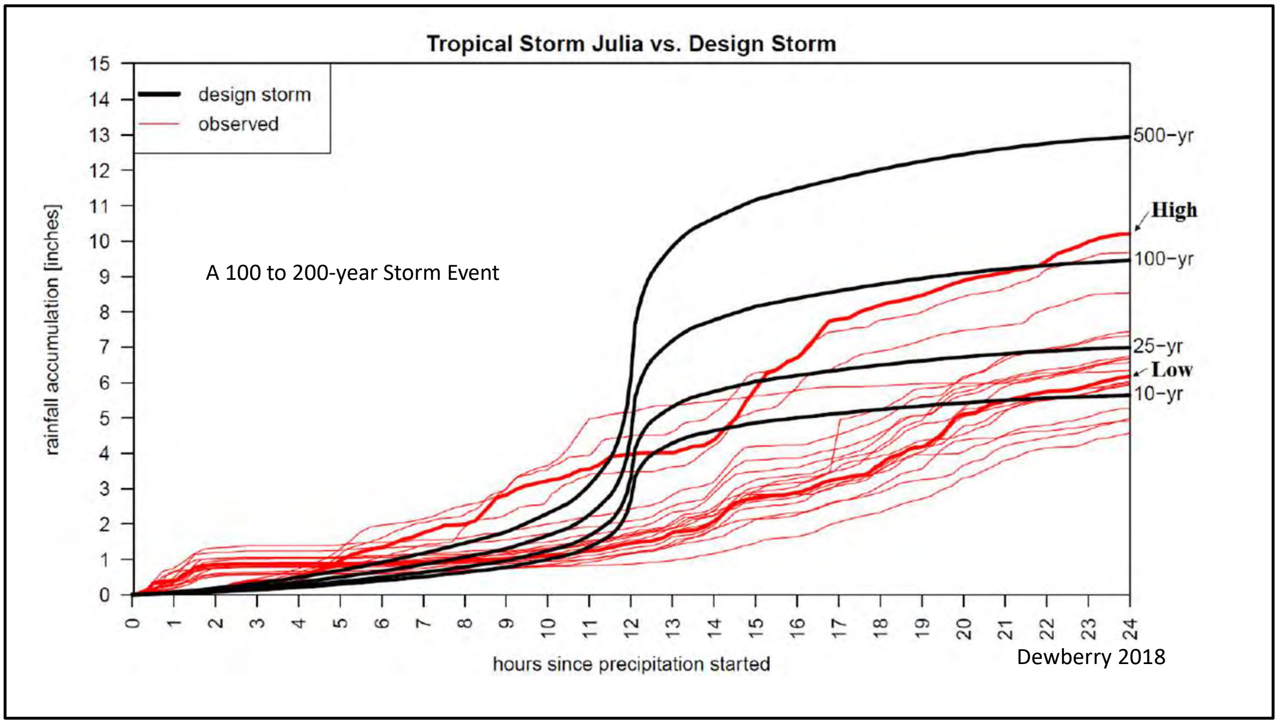
This is a 9-inch storm – larger than a 100-year storm event – with a 10-year storm intensity at the peak.



This graph shows a 2019 comparison of a NRCS Design Storm model done in a program called HydroCAD with a model that includes actual rainfall using the EPA's Stormwater Management Model (SWMM). This is for a real site that includes several SCMs. The flow rate out of the SCMs is shown as lower using actual rainfall with SWMM; therefore, the basin storage is oversized for larger storms developed using the NRCS design storm method, which matches our field observation at this site.

Note that for larger storms the degree of oversizing is greater. These Basins could have been approximately 15% smaller. This has contributed to a recommendation that rate management design procedures be only slightly modified to accommodate mid-century global warming.

Our conclusion is that the NRCS Design Storm method is conservative enough on a development site scale to manage larger storms in the face of near-term climate change if the management of storms up to about the 2-year/24-hour storm is enhanced. AND if the inflow components are designed for increased intensities. We will discuss both of these prerequisites separately in the coming slides.



Notice that the total storm depth for this very large storm is reasonably well predicted by the NRCS method when applying NOAA Atlas 14 depths. The intensities are not extreme, but more of the volume comes early in the storm.

The guidance in the new PCSM manual is to increase management of the 2-year storm using modeling procedures that account for the observed and anticipated changes in rainfall patterns.

PREDICTED CHANGE IN DESIGN STORM DEPTH

Mid-Level Estimate of Global Warming

Return Period, yr	Modeled Historical Value (in).	Mid-term [2045] Value, in.	Mid-term [2045] % change	Long-term [2075] Value, in.	Long-term [2075] % change
1	1.4	1.6	**+14%**	1.7	**+21%**
2	3.2	3.7	**+16%**	3.7	**+16%**
5	4.4	4.9	+11%	4.9	+11%
10	5.4	5.8	+7%	5.8	+7%
20	6.5	6.7	+3%	6.7	+3%
50	8.0	7.9	-1%	8.0	0%
100	9.4	8.9	-5%	9.2	-2%

Dewberry 2018

Conclusion: Increase the size of WQ/Volume Management SCMs.

Although hurricane-sized storms remain a concern, it is the events with rainfall of under 4-inches that are predicted to deliver the bulk of the increased rainfall that will likely occur as a result of climate change. [Note: There are likely not enough data points to accurately state that the 50-year and 100-year storms will decrease.]

(Rain of 1.2-inches is considered "Heavy " and over that depth is considered "Extreme." Storms smaller than these are the most common.)

Fortunately for PA we already design "WQ/Volume Management" for the 2-year event (Approximately 3 inches), so adaptation for climate change will not be as difficult as it could have been.

As I said, the new PCSM Manual recommends that management of larger storms continue to be based on generally accepted NRCS design storm modeling with only minor modifications. For larger sites, the new guidance includes providing a separate rate control facility to protect the WQ/Volume Management facility and provide system resilience.

The size for WQ/Volume Management SCMs is recommended to be slightly increased, and the design of inflow components becomes the major constraint that needs to be addressed with respect to climate change. In fact, inflow components are routinely undersized even for historical rainfall.

Recommendations

for

SCM

Sizing in the

Current Draft of PCSM Manual

The probability that we will experience increases in frequency and intensity of "Heavy" and "Extreme" rainfall has been included in the guidance in the new PCSM manual.

We will first focus on the design of SCMs, then discuss the design of inflow components.

KEY TAKE-AWAYS FOR SCM SIZING IN A CHANGING CLIMATE

- Rainfall for storms up-to the 2-year/24-hour storm will need to be adjusted to account for climate change.
- Storms above the 2-year/24-hour storm managed as follows:
  - In a separate basin when feasible.
  - Using the current NRCS design storm
    - Those guidelines are conservative!
  - Using the NOAA Median Value of Rain Depth

(read Slide)

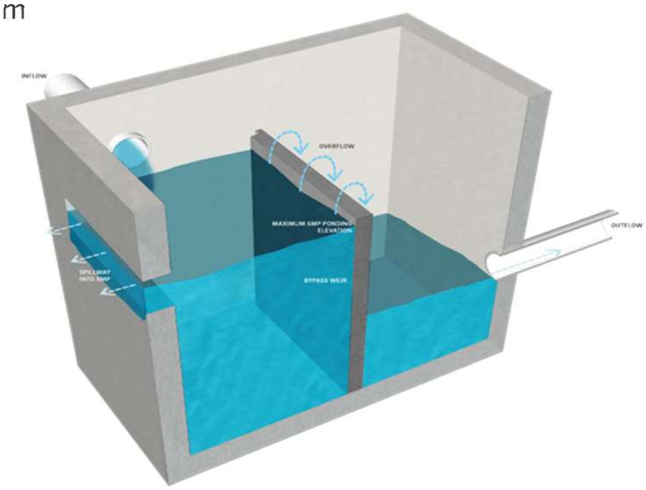
KEY CONSIDERATIONS WITH REGARDS TO CLIMATE CHANGE AND PCSM

- Storms smaller than 4-inches of rain will increase in frequency and depth.
- The intensity of storms appears to be increasing.
- Larger storm events may be accompanied by intense downpours.

(Read Slide)

THE PROBLEM DISSECTED

- Protecting the volume/WQ SCM from larger storms
  - Separate WQ/Volume SCM from rate control SCM
- Getting “Heavy” and “Extreme” storms to the SCM. (See Part IV)
  - Inflow capacity
  - Storm drain & inlet capacity
  - Duel overland flow path
- Reducing runoff by encouraging natural landscape preservation and SCMs
  - Increase riparian buffers and open space



Flow Splitter can be used to protect WQ /Volume SCM

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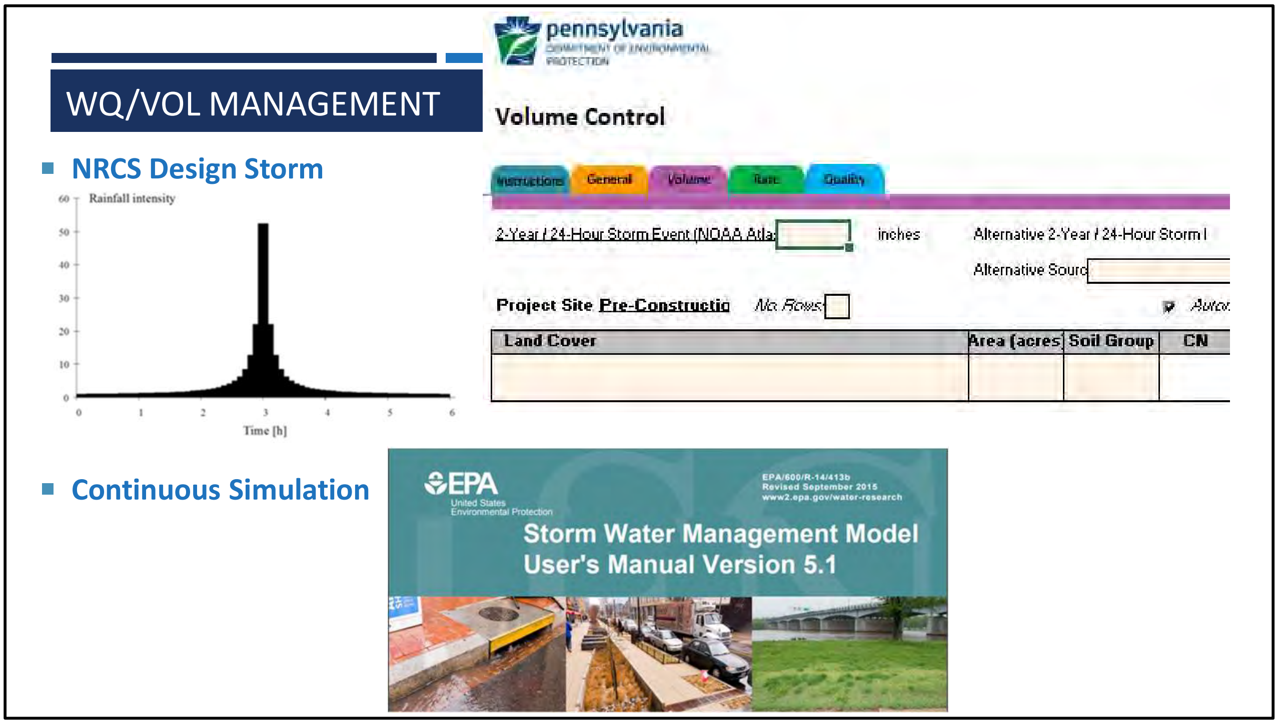
Although we are not going to spend a lot of time in this presentation on the subject, diverting larger storms on larger sites around WQ/Volume Management SCMs is a major change in the guidance that will protect water quality in the face of increased storm intensity and frequency.

A flow splitter is placed upstream of the WQ/Volume Management SCM to limit the amount of stormwater that enters. Excess flows are directed to a rate control SCM.

We will not focus here on natural landscape preservation and SCMs, but the new manual emphasizes these and provides increased incentives.



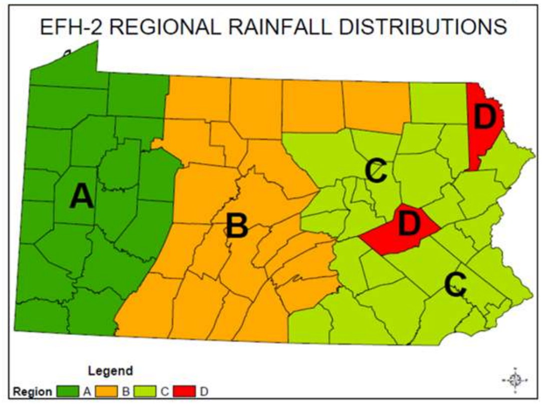
The new PCSM Manual includes guidance on two different ways to calculate the required storage in an SCM for the 2-year storm; NRCS design storm, and continuous simulation. Both of these design methods are presented in the new PCSM Manual with guidance on how to adjust for climate change.

The NRCS design storm method is the traditional approach most engineers use to estimate storage required to manage storms up to the 100-year storm event. In the new PCSM manual an adjustment is added to the 2-year storm to account for climate change, but for larger storms no adjustment is proposed. As I said, the NRCS design storm is inherently conservative at a site scale for larger storms.

Continuous simulation requires multiple years of recent rainfall data. In the new PCSM manual it is recommended that analysis of the 2-year storm (a.k.a. the 50% exceedance event) be performed using a continuous simulation. There is also an adjustment added to a continuous simulation model for global warming.

NEW PCSM MANUAL NRCS DESIGN STORM GUIDANCE – 2-YEAR STORM

- Use NOAA Atlas 14 with NRCS Type II A, B, C, D ***PLUS***
  - Use Upper 90% confidence level NOAA rain depth
- Design inflow components (storm drain, swales, etc.) for storm being managed in SCM
  - Use Upper 90% confidence level NOAA rainfall intensity
- Provide separate rate control SCMs when feasible
  - Use NOAA Atlas 14 with NRCS Type II A, B, C, D ***without adjustment***
- Encourage the preservation of natural landscape SCMs

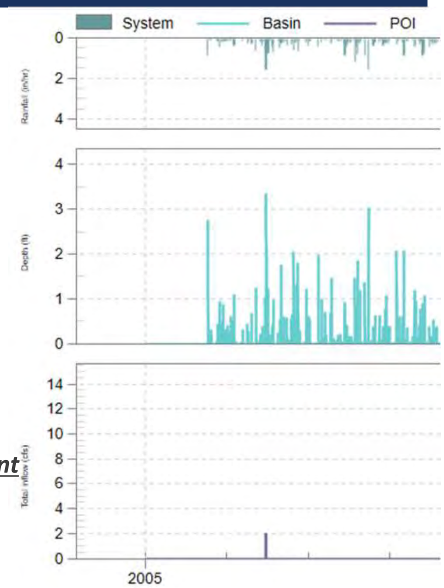


Engineering Field Handbook-2
PA Notice 34 Supplement

(Read Slide)

NEW PCSM MANUAL CONTINUOUS SIMULATION GUIDANCE – 2-YEAR

- Use Continuous Simulation to better match historic storms
  - Use most recent 15-years of rainfall from a local weather station
  - Use SWMM Climate Adjustment Tool (CAT)
  - Statistically determine the 50% exceedance storm event
- Design inflow components (storm drain, swales, etc.) for storm being managed
  - Use Upper 90% confidence level NOAA rainfall intensity
- Provide separate Rate SCMs when feasible
  - Use NOAA Atlas 14 with NRCS Type II A, B, C, D ***without adjustment***
- Encourage the preservation of natural landscape SCMs



(Read Slide)

EXTREME RAINFALL ADJUSTMENT –NRCS DESIGN STORM METHOD

For NRCS Design Storm

- **Use Upper 90% Confidence Level Rainfall Event Depth**

  (From NOAA Atlas 14 Point Precipitation Frequency Estimates)

  - **10% to 20% higher than what is used today**

4.84
(4.45-5.24)

Upper 90% Confidence

PF tabular | PF graphical | Supplementary information | Print page

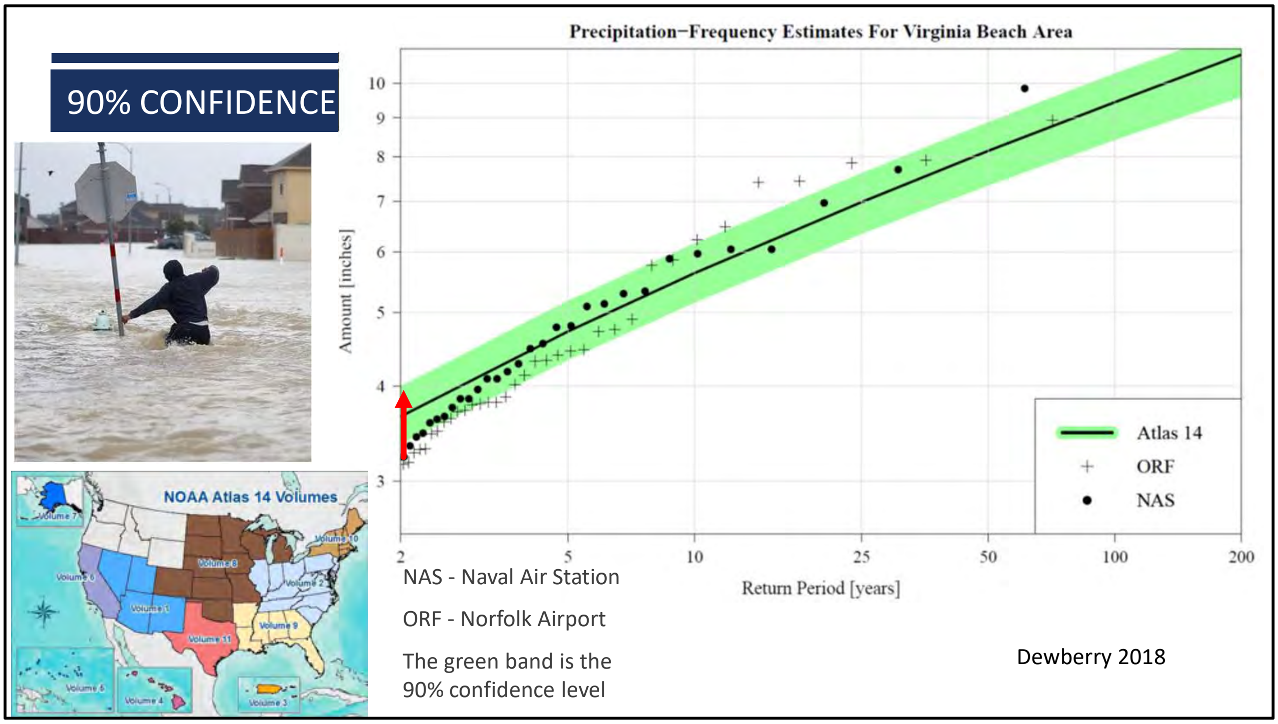
PDS-based precipitation frequency estimates with 90% confidence intervals (in inches)[1]

Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	**0.347** (0.320-0.378)	**0.414** (0.380-0.451)	**0.487** (0.447-0.531)	**0.539** (0.493-0.588)	**0.603** (0.548-0.657)	**0.646** (0.584-0.705)	**0.689** (0.620-0.754)	**0.727** (0.650-0.799)	**0.772** (0.684-0.854)	**0.807** (0.708-0.897)
24-hr	**2.70** (2.50-2.93)	**3.26** (3.01-3.54)	**4.12** (3.80-4.47)	**4.84** (4.45-5.24)	**5.90** (5.40-6.37)	**6.80** (6.18-7.32)	**7.77** (7.03-8.36)	**8.84** (7.93-9.49)	**10.4** (9.22-11.2)	**11.7** (10.3-12.6)

(Read Slide)

The data used for the current NOAA Atlas 14, Volume 2, is older that the year 2000. Atlas 14, Volume 2 was published in 2006.

NOAA is in the process of updating these values, partially funded by PennDOT (no firm delivery date). NOAA propose to produce two different reports; one that includes adjustments for climate change (Non-Stationary) using CMIPS-5 (potentially over-estimates), and one without (Stationary).



As we have discussed, with regards to climate change the expectation is that the storms at the more frequent return periods will increase in depth.

It is predicted that the 3.3-inch depth of the current 2-year return period will increase to 3.8 inches, near the upper 90% confidence level on this graph.

NRCS DESIGN STORM EXAMPLE

2-year Rainfall	2.91	in.
2-year Upper 90% Rainfall	3.21	in.
% Change	9%	
Area	4.567	ac.
SCM Footprint	9754	SF

		2-year Volume to Manage		% Change	Storage Volume Required		% Change
HSG	Infiltration Rate	2-yr WQV	2-yr Upper 90% WQV	-	2-yr WQV	2-yr Upper 90% WQV	-
A	1.43	31,018	34,480	10%	16,800	20,300	17%
B	0.75	28,606	31,003	8%	20,500	22,750	10%
C	0.5	23,518	25,040	6%	17,500	19,000	8%

NTM 2022

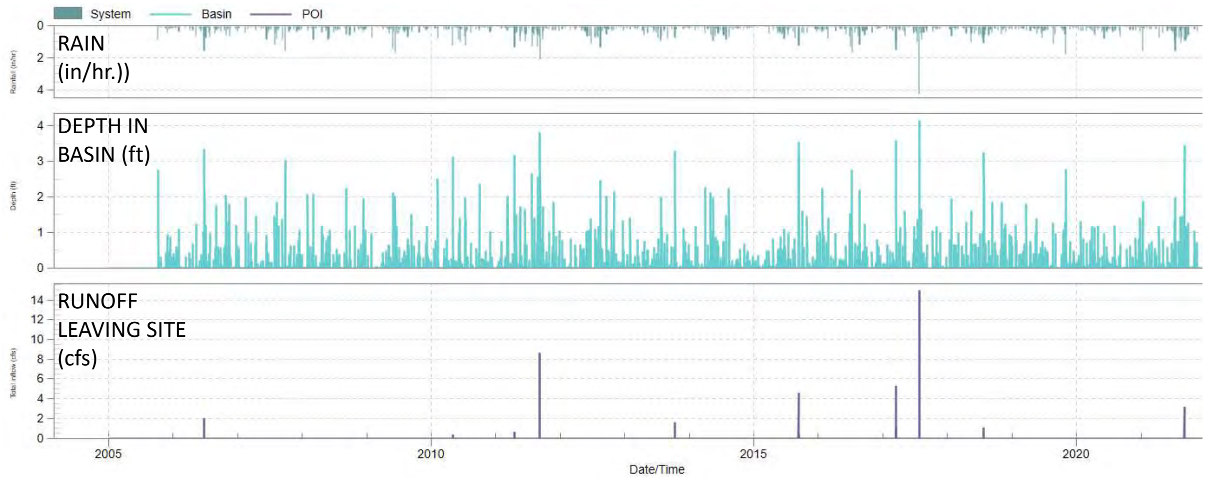
This NRCS design storm example shows that the recommended climate change adjustment produces the expected results. It shows that the size of the basin is increased by the adjustment to manage the WQ/Volume.

We need to get the flows to the basin, however. Addressing climate change in SCM design is highly dependent on inflow and outlet design that we will explore further later in the presentation.

This is a reasonable adjustment of NOAA 14 current data. When NOAA revises their data, the approach will still provide a viable design approach for climate changes.

A key reason to increase WQ/Volume management is to treat the increased erosion that is anticipated to accompany increased storm intensity.

CONTINUOUS SIMULATION MODELING



EPA SWMM with Climate Adjustment Tool (SWMM-CAT)

NTM 2022

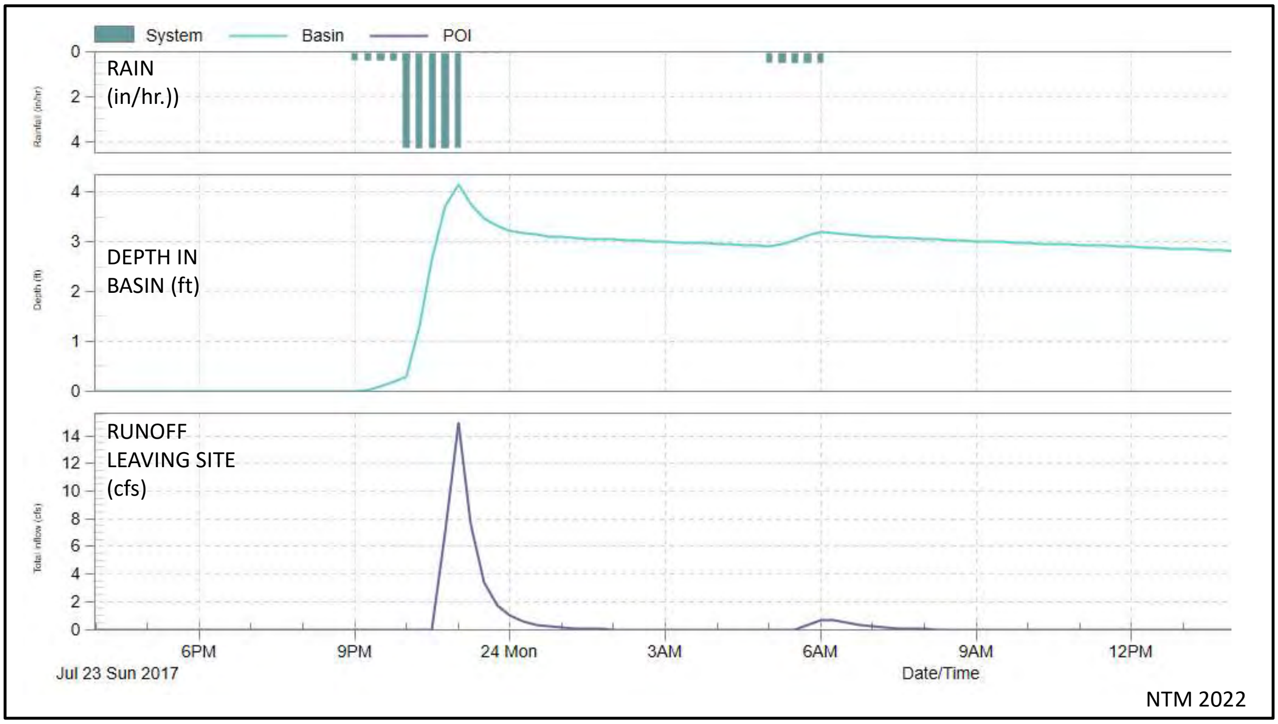
A design method promoted by the new PCSM manual is continuous simulation. The standard model used is EPA's Storm Water Management Model (SWMM).

The modeling results presented here are for the same example site that was modeled using Hydrocad (slide 33).

[Describe the graphs.]

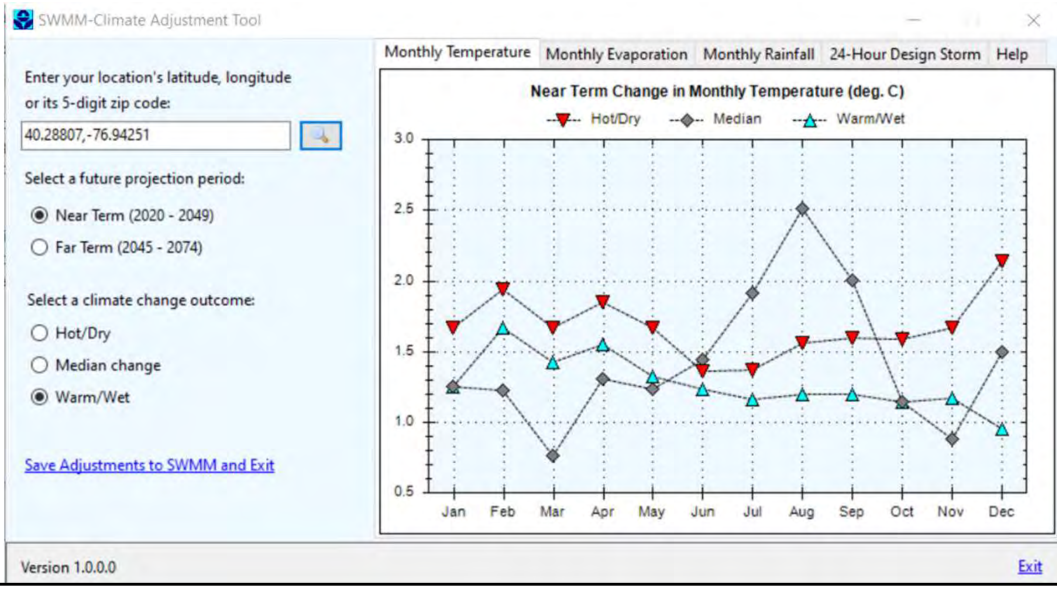
The most recent 15-years of rainfall data is used. This helps account for the change in rainfall patterns we have already experienced.

Note that the rainfall included in this SWMM report is expressed as intensity and that the high intensities of rainfall coincide with runoff events.



Zoom in on one storm and you can see the form of a hydrograph appearing.

SWMM CLIMATE ADJUSTMENT TOOL (CAT)

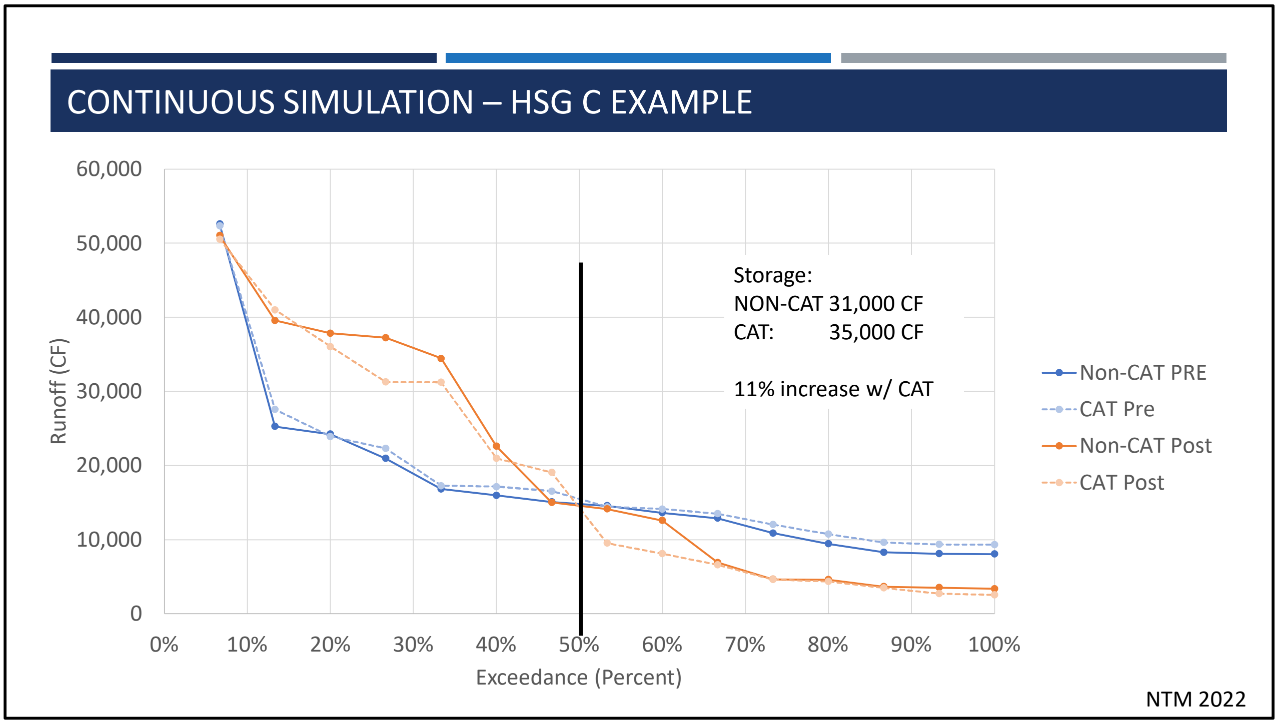


A SWMM add-on tool that the new PCSM manual recommends be used is the Climate Adjustment Tool (CAT). CAT adjusts the historic rainfall, temperature, and evaporation based on a downscaled Coupled Model Intercomparison Projection CMIP-3. Downscaling for CAT is done with CREAT 2.0 (Climate Resilience Evaluation and Analysis Tool).

Using a "Warm/Wet" assumption for outcome, the adjustment CAT provides represents the state of the science approach to adjusting the design of stormwater management for climate change.

There is a complex interaction between increased runoff and increased evaporation included in the SWMM-CAT methodology that results in what appears to be a smaller increase in runoff, but the basin adjustment is similar to the NRCS design storm method. Remember that the SWMM data uses rainfall from the most recent 15-years, so some adjustment for climate change is included in the model that is not included in an NRCS design storm model.

As with the NRCS design storm, CAT should be used for up to the 2-year storm event (a.k.a. 50% exceedance event).



As I said, the use of recent rainfall data (2005-2020) self adjusts to present conditions, whereas with NOAA depths we are adjusting were developed from decades older data. This increase the required storage, even before CAT is used.

With continuous simulation, compliance is judged based on the statistical runoff, not the rainfall event. This is referred to as the 50% exceedance runoff event.

In this graph smaller storms are to the right (smaller storms are more likely to be exceeded).

Because of the complex interplay between rainfall and evapotranspiration, the increase in runoff is not extreme with climate adjustments. Once again the question is; are we getting the larger cloud burst to the pond?

SUMMARY OF BASIN DESIGN SIZING RECOMMENDATIONS

- Use climate adjustment for up to the 2-year (50% exceedance storm).
  - Upper 90% confidence level NOAA depths for NRCS design storm.
  - Use SWMM CAT adjustment with continuous simulation.
    - Most recent 15 years of rainfall from a local weather station.

- Provide separate rate control facilities when feasible and for large sites.
  - Use NRCS design storm procedures for analysis.
  - Design rate control SCMs based on median NOAA rainfall depth.

(Read slide)

Recommendations for Inflow Design in DRAFT PCSM Manual

The capacity of the inflow components must be considered. Historically this has been neglected and has resulted in many SCMs that never reach capacity, even in large storms. With respect to climate change, an increase in inflow capacity is needed to account for anticipated rainfall intensity.

In addition to new facility design adaptation for climate change, improving inflow capacity can help adapt existing stormwater management facilities to handle climate changes.

KEY TAKE-AWAYS FOR INFLOW DESIGN

- Under sizing inflow components is an existing problem.
- The problem will become more pronounced with climate change.
- The design procedure proposed can be used to retrofit existing basins.

(Read Slide)

LARGER THUNDERSTORMS

- On July 8, 2019, a rain gauge at Ronald Reagan National Airport near Washington, D.C., recorded 3.30 inches of rain in one hour. The largest one-hour rainfall total over the past 60 years. (Rand 2021)
- Since Hurricane Floyd in 1999 it has been evident that rainfall intensity is increasing.

(Read Slide)

PEAK INTENSITY

Summary of precipitation intensity and return period estimates for a July 31, 2016 thunderstorm event in Virginia Beach – 100 to 200-year event.

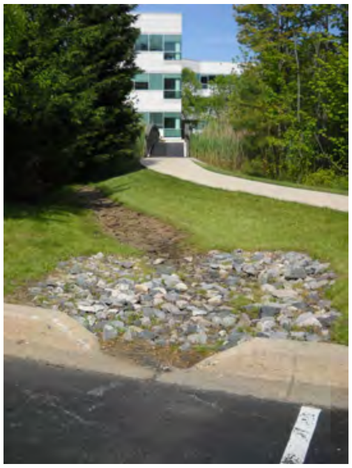
Duration	Maximum Rainfall Amount (in)	Estimated Return Period (yr)
15 min	1.18	5-10
30 min	1.97	10-25
1 hour	3.38	50-100
2 hour	6.66	500-1000
3 hour	7.19	500-1000
6 hour	7.19	100-200

The longer duration of intense rainfall rate is particularly striking.

Dewberry 2018

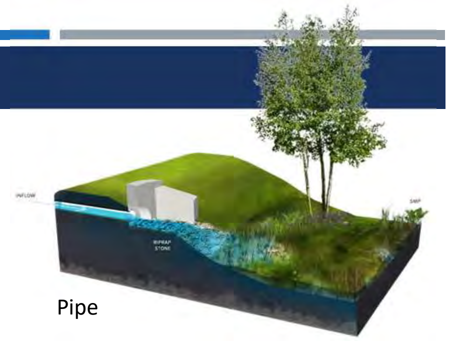
This table shows the peak intensities of a recent broad frontal thunderstorm. The Type IIA storm we use as a basis for design of basins is a broad frontal thunderstorm, but the design of inflow components is not, and the components may not be designed to direct these intensities to an SCM.

TYPES OF INFLOW COMPONENTS



Curb-Cut

Sheet Flow



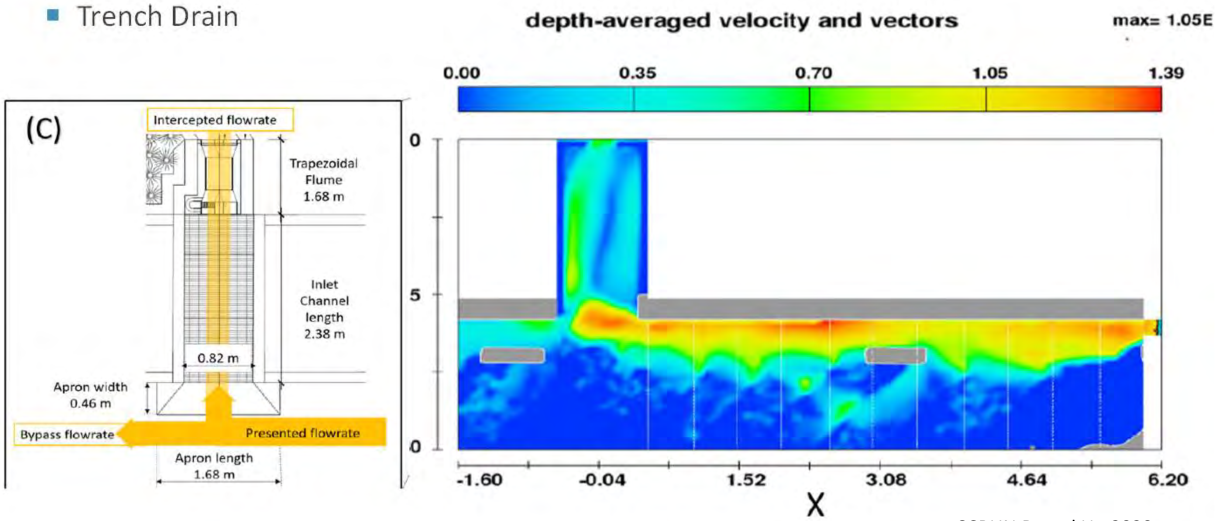
Pipe

Storm Drain Inlet

Here are some of the common configurations of inflow components. We will focus mostly on storm drain (lower right). Obviously, this one is clogged and will likely not pass the design flow.

INFLOW TO URBAN STORMWATER FACILITIES

- Trench Drain



CCRUN Drexel U - 2020

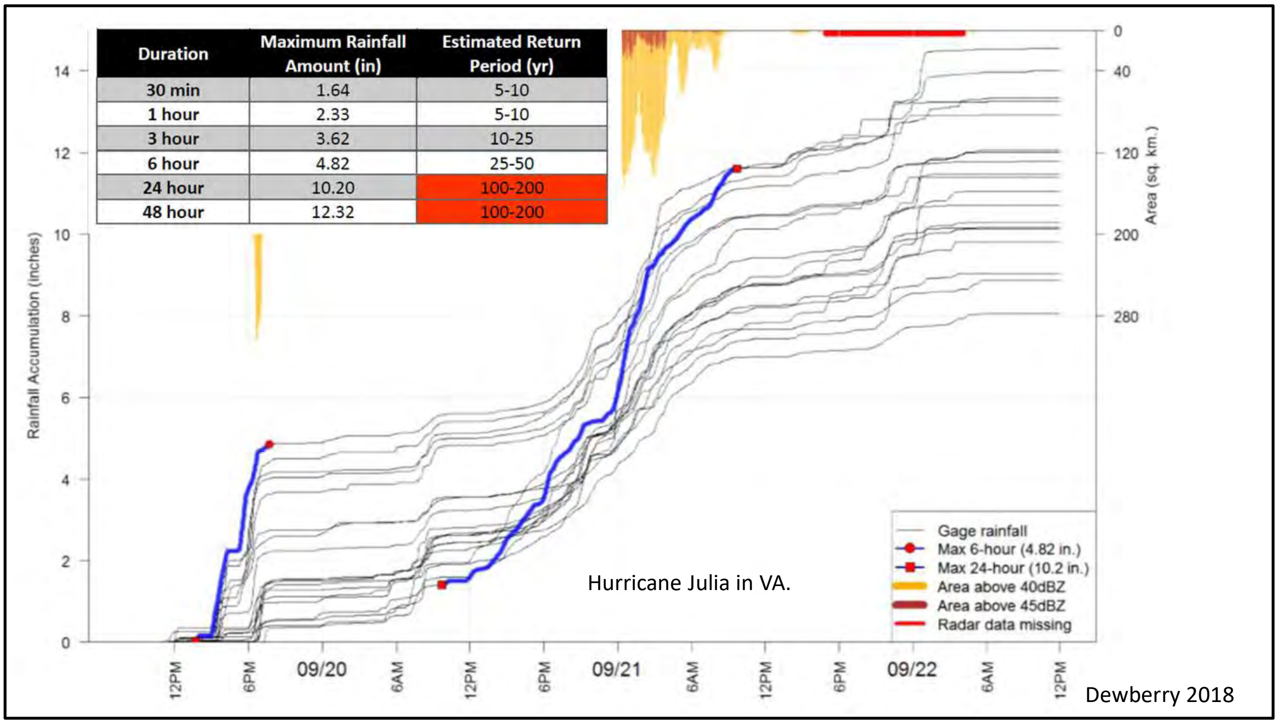
This is a depiction of flow entering a curb-cut and trench drain. It shows that in larger events there is a lot of bypass flow. Designs like this will not adapt well to climate change and may not even meet current design needs unless the bypass is included in the modeling.

BASIC TENETS OF THE PROPOSED GUIDANCE

- The storm that the SCM is designed to manage must reach the basin.
  - Exception: Over-management to compensate.
- The inflow component must be sized to accept the SCM design storm.
- Either the inlets and pipe system must pass the SCM design storm, **and/or** an overland flow path for flows in excess of storm drain capacity is needed.

→ DUAL DRAINAGE CONCEPT

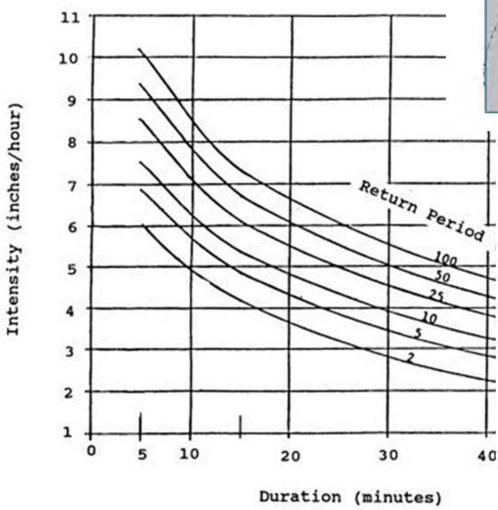
(Read Slide)

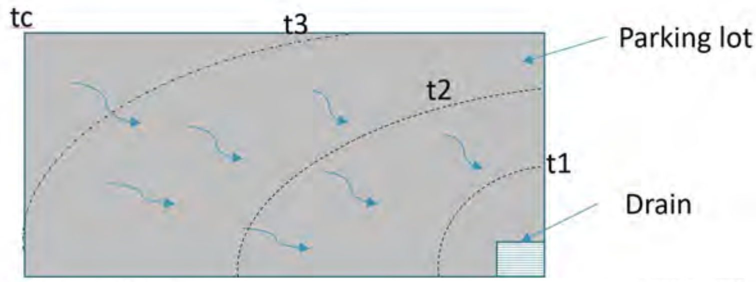


Duration	Maximum Rainfall Amount (in)	Estimated Return Period (yr)
30 min	1.64	5-10
1 hour	2.33	5-10
3 hour	3.62	10-25
6 hour	4.82	25-50
24 hour	10.20	100-200
48 hour	12.32	100-200

In large storms there are often periods of extreme intensity. The inflow components (combination of inlets and overland) taking flow to SCMs must pass these intense flows.

STORM DRAIN





Chapter 7 - Hydrology

Publication 584
2015 Edition

Table 7.2 Suggested Design Return Intervals (years)

Design Flood Selection Guidelines		
Functional Classification	**Maximum Exceedance Probability (%)**	**Minimum Return Period (years)**
Interstate and Limited Access Highways	2	50
Principal Arterial System	2	50
Minor Arterial System	4	25
Rural Collector System, Major	4	25
Other Collector System	10	10
Local Road and Street	10	10

Storm drain is the most common inflow component. The design storm for storm drain is usually not the same as for the SCM. Note that not even for the largest roadways is the design done for the 100-year storm.

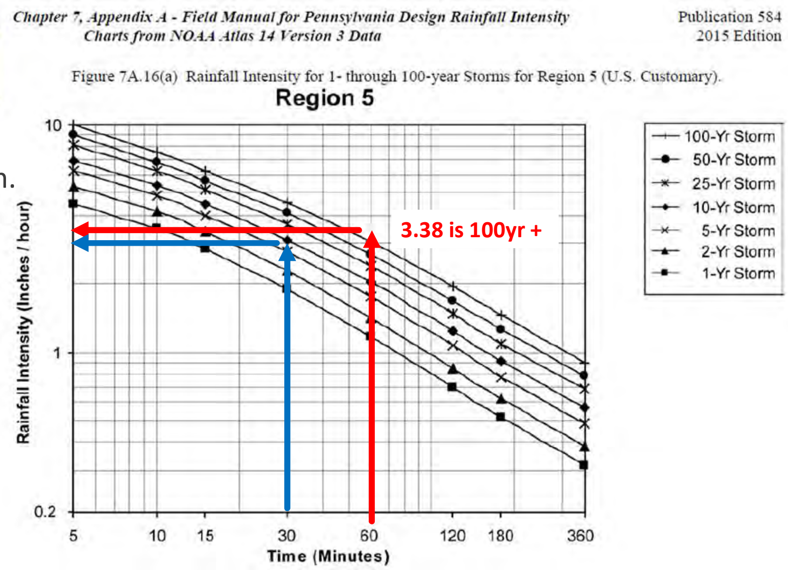
The intensity used in their design is dependent on the time of concentration (tc). Tc is the time when the maximum watershed contributes flow to the point of interest, in this case the inlet. This design criteria has little to do with the design storm for the SCM.

- In general, a 10-year storm is used for the design of ditches.

(Read Slide)

PENNDOT

- Storm drain pipes are often designed for the 10-year storm.
- tc for the inlet are often between 5-minutes to 30-minutes.
- tc for the SCM might be up to 60-minutes



------ Intensity July 2016

------ Typical Storm Drain Design

This is the rainfall intensity chart used for storm drain design in Pennsylvania. It is based on NOAA 14 data.

(Read Slide)

What we can see in this graph is that slightly upsizing the design intensity could improve delivery of flows to the SCM, even with climate change.

TABULAR FORM

PDS-based precipitation frequency estimates with 90% confidence

Duration	Average recurrence interval (years)						
	1	2	5	10	25	50	1
5-min	**3.90** (3.50-4.32)	**4.63** (4.18-5.15)	**5.44** (4.90-6.02)	**6.04** (5.42-6.67)	**6.76** (6.02-7.45)	**7.27** (6.46-8.02)	**7** (6.8
10-min	**3.11** (2.80-3.44)	**3.70** (3.34-4.10)	**4.35** (3.91-4.81)	**4.82** (4.33-5.33)	**5.37** (4.80-5.93)	**5.78** (5.13-6.38)	**6** (5.4
15-min	**2.59** (2.33-2.87)	**3.10** (2.79-3.44)	**3.67** (3.30-4.06)	**4.06** (3.65-4.49)	**4.54** (4.05-5.01)	**4.88** (4.33-5.38)	**5** (4.6
30-min	**1.77** (1.59-1.96)	**2.14** (1.93-2.37)	**2.60** (2.34-2.88)	**2.94** (2.64-3.25)	**3.36** (3.00-3.71)	**3.67** (3.26-4.05)	**3** (3.5
60-min	**1.11** (0.993-1.22)	**1.34** (1.21-1.49)	**1.67** (1.50-1.84)	**1.91** (1.72-2.11)	**2.23** (1.99-2.47)	**2.48** (2.20-2.74)	**2** (2.4

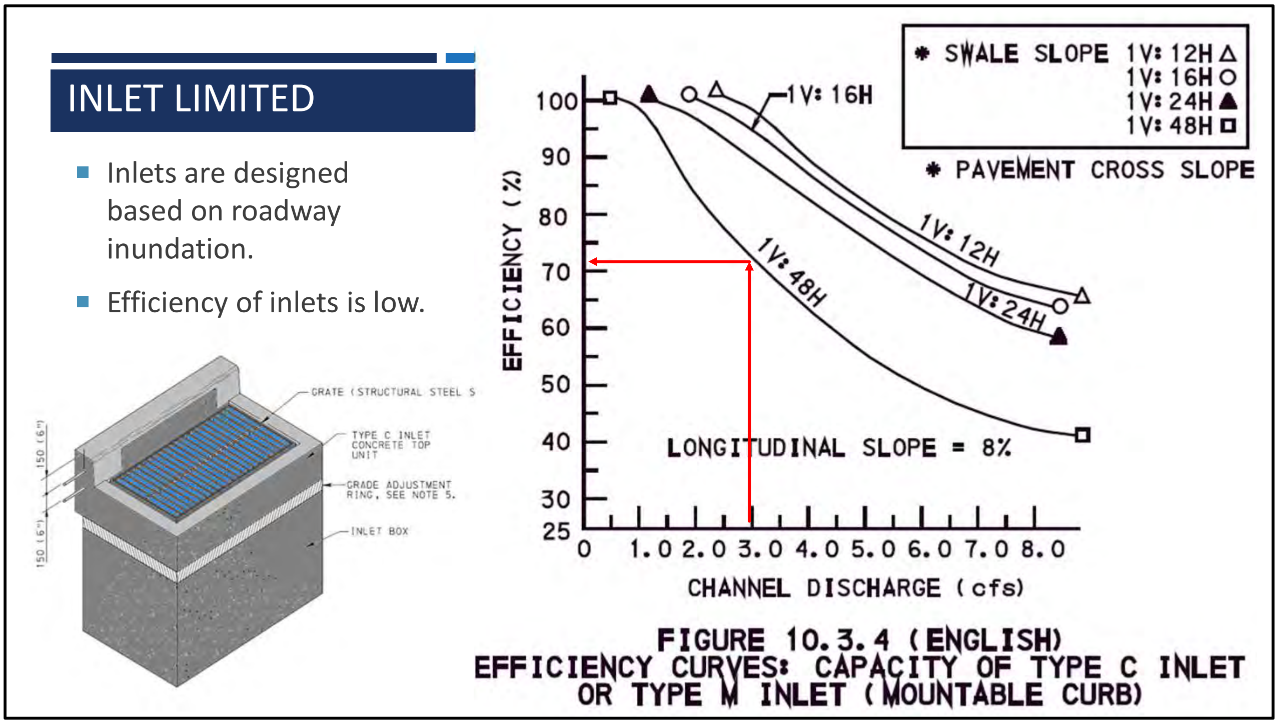
2.94
(2.64-3.25)

Precipitation Intensity – Partial Duration Series

Similar to the recommendation for the design for volume and water quality management using the NRCS design storm method, we are recommending designs for storm drains be based on the upper 90% confidence level intensity from the NOAA Atlas 14.

Note that this is a “Precipitation Intensity” table, that is a different expression of the “Precipitation Depth” used for SCM design.

Using this method to adjust storm drain design for climate change will improve pipe conveyance.

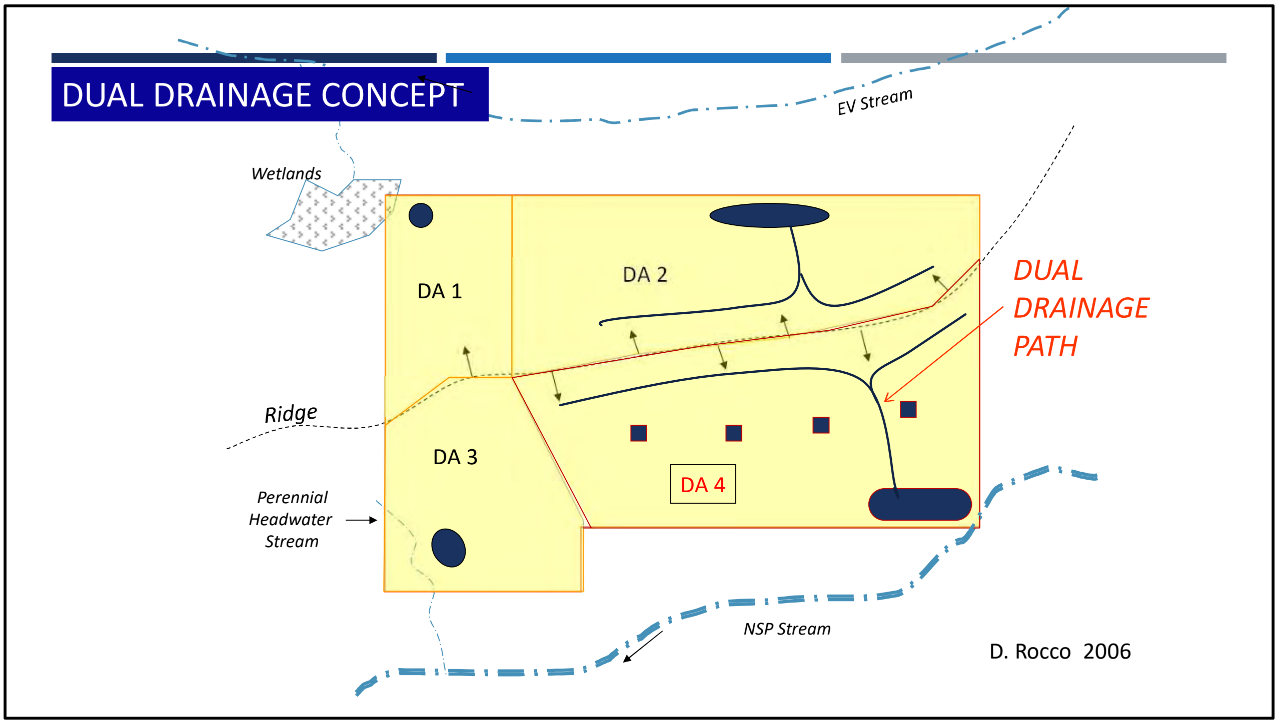


However, it is the design of inlets that are often the limiting factor.

They are spaced based on the spread of water into the travel lane or ponding in a parking lot. This has little to do with the design storm that the SCM is supposed to manage. Increasing the intensity used in inlet design will improve this some, but a provision for the direction of flow above the capacity of the inlet to the SCM may still be needed. This is called the DUAL DRAINAGE CONCEPT.

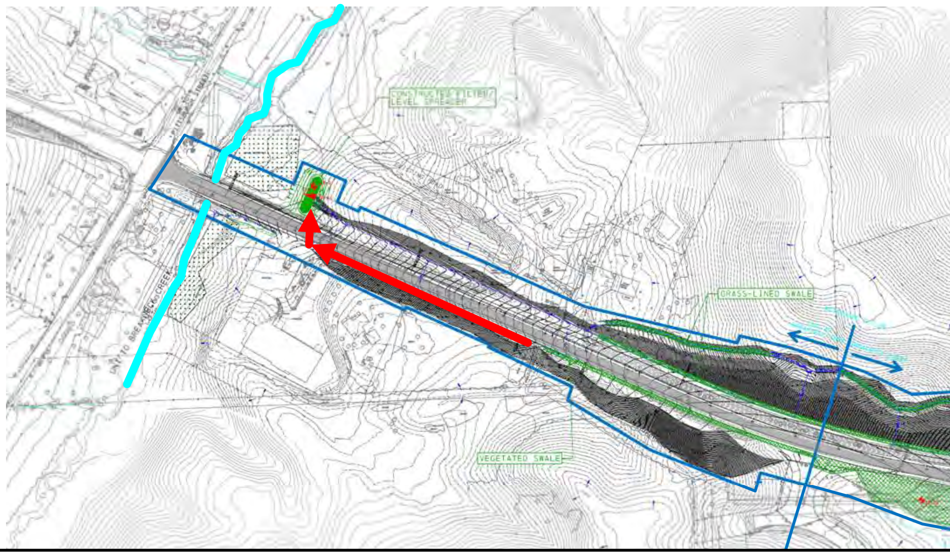
In addition, inlets are often not installed flush with the pavement causing higher bypass than expected. (Discuss Chart)

The lack of inlet and storm drain capacity is a current design flaw existing in many designs that will only become worse with climate change without implementing the proposed rainfall intensity adjustments included in the draft PCSM Manual.



The alternative to increasing storm drain and inlet capacity is providing an overland flow path. DUAL DRAINAGE CONCEPT

DUAL DRAINAGE CONCEPT



D. Rocco 2006

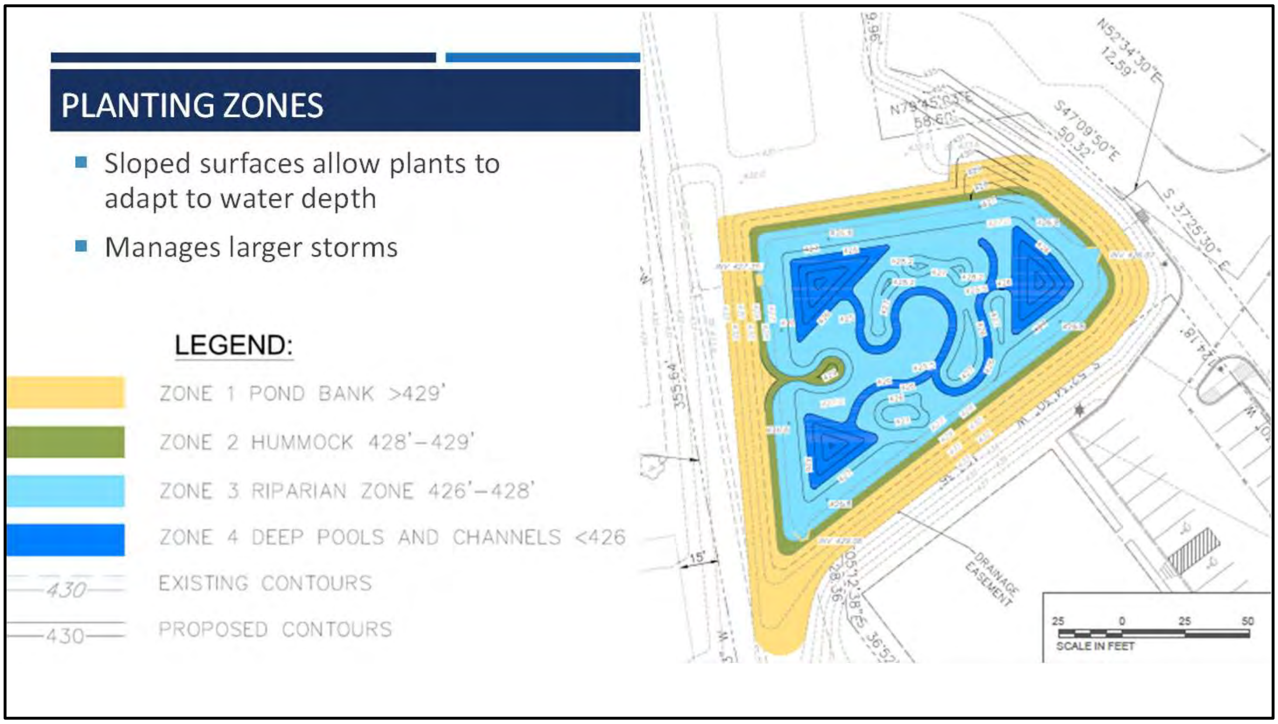
Roadside ditches sistering a storm drain may be a solution for many roadways. This is a roadway cut into a hill where the needed change is likely to increase a crossroad culvert at the bottom of the hill.

DRAFT PCSM Manual

Recommendations

for

Engineered Stormwater Treatment Wetlands



Climate change is expected to bring more days of rain, hotter days with higher evapotranspiration, and uncertainty about storm depth and intensity. Wetlands are well suited to adapt to uncertainty.

The frequency and depth of storms effect how plants in SCMs will grow. The varied surface elevations in engineered treatment wetlands allow the plant population to adjust to the depth of water and time of inundation. As climate change causes longer or shorter periods of inundation, the plants from higher or lower elevations will spread to the elevation with the right depth of water for them to survive. This makes an Engineered Treatment Wetland an ideal SCM in the face of climate change.

More evapotranspiration is a distinct possibility with climate change. The deep pools are designed to withstand 60-days of drought and provide for increased evapotranspiration.

IPCC–CLIMATE CHANGE 2022–IMPACTS, ADAPTATION AND VULNERABILITY

During periods with intense precipitation, low-lying urban parks and open space, engineered devices, and wetlands can play an important role in reducing stormwater runoff volumes, by providing places for water to be stored and infiltrate during heavy storms (Moore et al., 2016).

Investing in a diversity of NBS types may be important to maximize stormwater management and flood regulation as different types of engineered NBS have different strengths and weaknesses.

System	Mit. Pot.	Rest. Pot.	Best practices and adaptation benefits	Worst practices and negative adaptation tradeoffs	Additional societal benefits	References
Urban wetlands	Moderate*	Moderate	Integrated landscape management.		Recreation & aesthetics; stormwater absorption; heat mitigation; coastal flood protection	WGII Chapter 06

stormwater management, focusing on a combination of nature-based solutions, is shown to be highly effective and yields co-benefits at 3°C. However, these results were gained in a specific case study setting in a European city with limited generalizability (Figure 4.28).

Engineered Stormwater Treatment Wetlands are a Nature-Based Solution (NBS). These passages from the just released DRAFT 2022 International Panel on Climate Change suggests that Wetlands (both natural and constructed) are an ideal solution.

2014

This is an example engineered treatment wetland funded by a Growing Greener Grant used as a study for the recommendations included in the new PCSM Manual. I designed and constructed this basin in 2014 and have monitored its condition. Note in the next several slides you will see that the design includes trees and deep pools at the inlet and outlet.

2014

2015

2016

2017

2018

2019

ENGINEERED STORMWATER TREATMENT WETLANDS

- Will adapt to the uncertainty of rainfall depths and intensities.
- Guidance includes considerations for plant survival in the face of climate change.
- Will provide higher volume reduction through evapotranspiration as climate change increases temperatures.
- If designed with trees, deep pools, and reversed slope outfall pipe that draws stormwater from the middle of the deep pool, will provide thermal mitigation.
- Rate control can be included in one footprint without risking water quality/Volume management.
- Design is similar to Managed Release Concept SCMs.

(Read Slide)

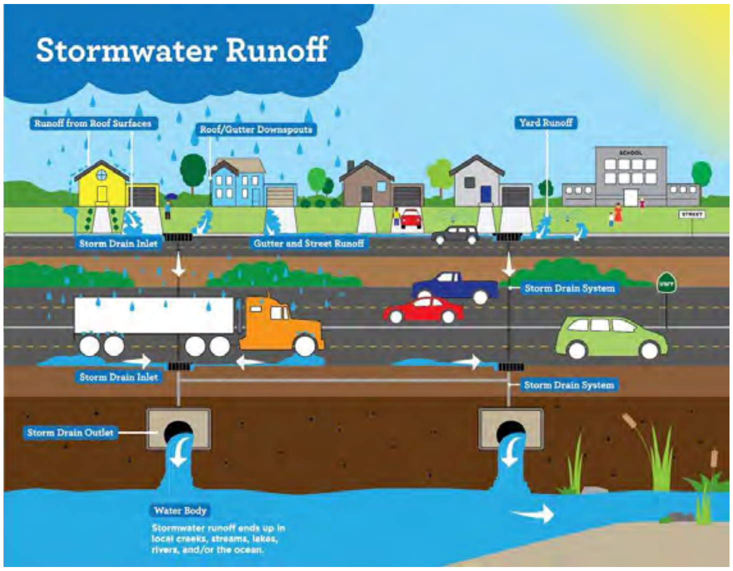
Actually, the Managed Release Concept (MRC) was developed by an engineer named Zachery Ranstead for engineered wetlands in 2008. He presented his concept to this audience during my presentation on evapotranspiration that year.

Conflicts

in

Regulations

WHICH REGULATIONS TO USE



One complication to implementing the guidance on addressing climate change contained in the new PCSM Manual will be figuring out which guidance has to be followed. This is nothing new but may become more difficult for you and the design engineers when the new PCSM manual is published.

PENNDOT AND MUNICIPALITIES SET DESIGN STORM FOR STORM DRAIN

Chapter 7 - Hydrology

Publication 584
2015 Edition

Table 7.2 Suggested Design Return Intervals (years)

Design Flood Selection Guidelines		
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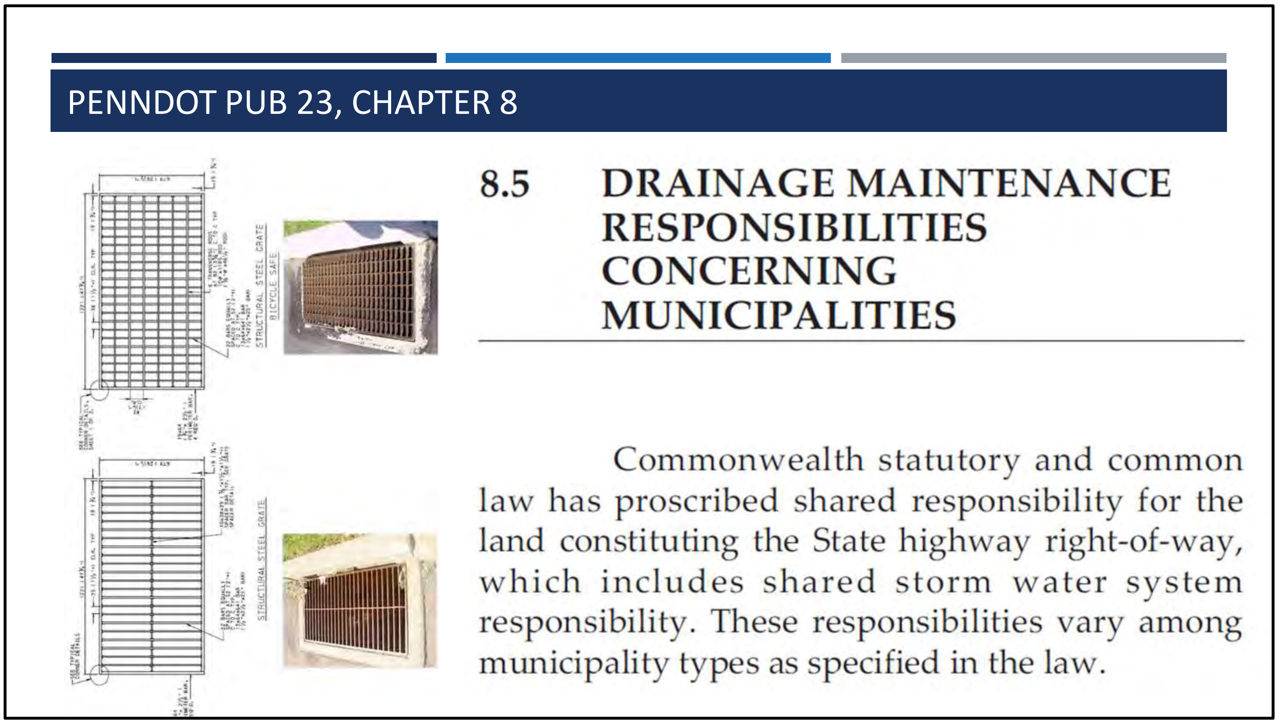
Rural Collector System, Major	4	25
Other Collector System	10	10
Local Road and Street	10	10

(Read the Slide)



PennDOT's publication 23 provides this insight:

(Read Slide)

Quite often PennDOT is responsible for the grates while a municipality is responsible for the pipes. Each might have design requirements that differ with PCSM guidance.

ARMY CORPS OF ENGINEERS' GUIDANCE

- Focus on those aspects of climate and hydrology relevant to the project's problems, opportunities, and alternatives.
- Include consideration of both past (observed) & changes

US Army Corps of Engineers

ENGINEERING AND CONSTRUCTION BULLETIN

No. 2018-14 **Issuing Office:** CECW-EC **Issued:** 10 Sep 18 **Expires:** 10 Sep 20

SUBJECT: Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects.

The Army Corps of Engineers provide this advice: (Read Slide)

CONCLUSION

- Climate change will affect stormwater management design.
- Storms smaller than the 2-year/24-hour storm need the most adjustment.
- The NRCS design storm method is conservative and will remain applicable for large storms.
- Inflow components are currently undersized, and design needs to be adjusted for climate change.
- Engineered Treatment wetlands are an ideal SCM.

Newell Tereska & Mackay Engineering

(Read Slide)

QUESTIONS

Mark Derham Bowen, PE, CFM, CCR
mbowen@ntmeng.com

Chesapeake Bay
Modified
IDF Curves

The Rand Corporation developed climate adaption recommendations for the Chesapeake Bay watershed that closely match those proposed for the new PCSM Manual.

The modifications they recommend confirm the magnitude of the adjustment we are recommending is appropriate.

CHESAPEAKE BAY ADJUSTMENT

- Applicable to Atlas 14 circa 2006 only.
- This study recommends applying change factors calculated based on 24-hour rainfall depths across all rainfall durations in Atlas 14.
- Not recommended for Atlas 14 values that contain a different historical record or that have been updated to include more-recent data.
- Change Factors apply to:
  - 2, 5, 10, 50, and 100-year recurrence intervals
  - 1, 2,3, 6, 12, 18, and 24-hour durations

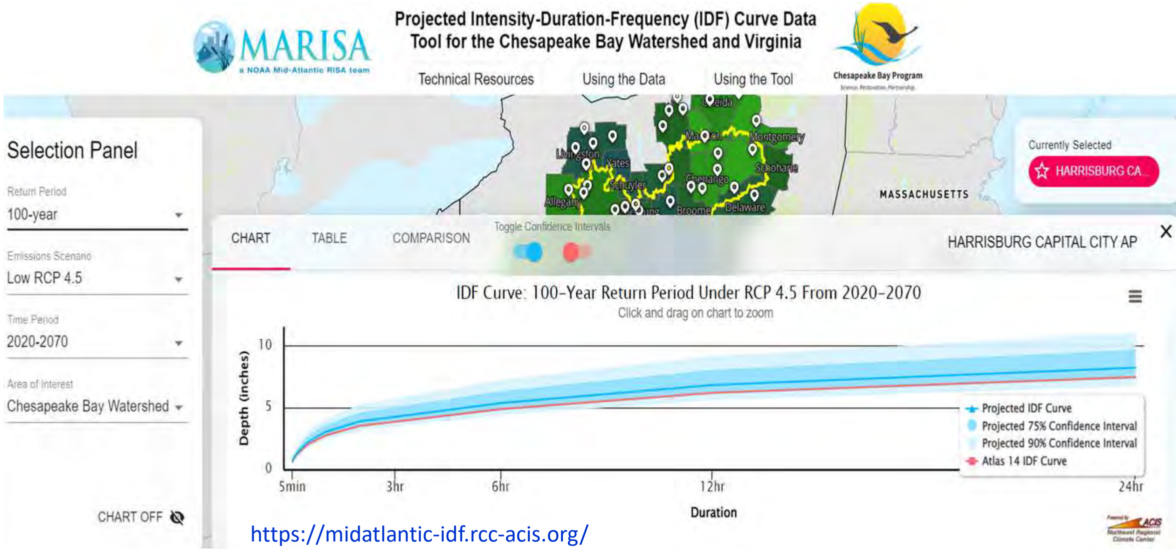
$$Change\ Factor_{2020-2069} = \frac{2yr{,}24hr\ rainfall\ depth_{2020-2069}}{2yr{,}24hr\ rainfall\ depth_{1950-1999}}$$

Rand 2021

(Read Slide)

The publication does not clearly state that these change factors can be used for storm drain design.

CHESAPEAKE BAY ADJUSTMENT TOOL



https://midatlantic-idf.rcc-acis.org/

Some designers are already using this online tool.

NOAA DEFINITIONS

DEPTH-DURATION-FREQUENCY (DDF) CURVE - Graphical depiction of precipitation frequency estimates in terms of depth, duration and frequency (ARI or AEP).

INTENSITY-DURATION-FREQUENCY (IDF) CURVE - Graphical depiction of precipitation frequency estimates in terms of intensity, duration and frequency.

INTENSITY – Inches per hour (in/hr) or millimeters per hour (mm/hr).

Their use of the term “IDF” is somewhat misleading, since they have actually modified DDF curves. These are related, but one needs to assume that an “S Curve” (see slide 15) applies to be able to convert DDF to IDF.

Rand’s guidance does not come with recommendations on how to apply the modification to sizing inflow components.

CHESAPEAKE BAY ADJUSTMENT

Table 5.1. Study Area Averaged Ensemble Median Change Factors for Each Recurrence Interval, RCP, Future Period, and Downscaled Climate Model Dataset

			2-Year	5-Year	10-Year	25-Year	50-Year	100-Year
LOCA	**RCP 4.5**	2020–2069	1.08	1.08	1.09	1.09	1.10	1.10
		2050–2099	1.11	1.11	1.11	1.12	1.12	1.13
	RCP 8.5	2020–2069	1.10	1.10	1.10	1.11	1.11	1.11
		2050–2099	1.18	1.18	1.18	1.18	1.18	1.18

Representative Concentration Pathways (RCPs)
- RCP 4.5 - optimistic future with low emissions
- RCP 8.5 – most used future with higher emissions

Localized Constructed Analogs (LOCA)
- LOCA includes 32 of the 35 GCMs in the CMIP-5 simulations for RCPs 4.5 and 8.5

Rand 2021

Rand’s recommendations include adjusting all storms, and the adjustments are larger for the larger storms.

This method does not account for how conservative the NRCS design storm method is for large storms.

(Discuss RCP)

OTHER SOURCES

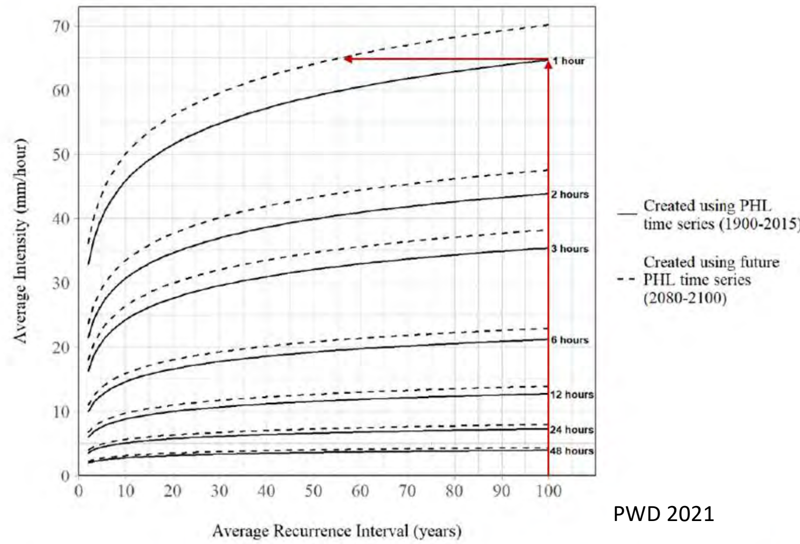
CCAP Precipitation Products: IDF Curves

NOAA

Office of Costal Management

Climate Change Adaption Program (CCAP)

https://coast.noaa.gov/ccapatlas/



Comparison of IDF curves generated by fitting GEV Type II distribution on AMS using PHL data (1900-2015) with future PHL time series based on the 2080-2100 storm set for RCP8.5

This is another source for adjusting rainfall intensity predictions for climate change.

(Read Slide)

This is a true Intensity Duration Frequency curve. The method predicts increases for all storms.