DETENTION BASIN DESIGN USING RATIONAL HYDROGRAPHS

By Thomas F. Smith, P.E., P.L.S.
Bercek and Smith Engineering, Inc.
www.bercekandsmith.com
tfsmith2@bercekandsmith.com

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Topics Covered:

- The Rational Formula Explained
- Rational Hydrographs
- Rational Hydrographs in the Virginia Tech/ Penn State Urban Hydrology Model (VTPSUHM)
- Rational Hydrographs for Detention Basins and Infiltration design
- Comparison with NRCS Hydrographs

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The Rational Formula Explained

- Attributed to Emil Kuichling in 1889, also known as the Kuichling Formula for his use in sewer design in Rochester, New York. Original work started in 1674 by French Attorney.
- In British Isles it was concluded that the ratio of runoff to rainfall might be approximated as a coefficient, typically in the 0.4 - 0.6 range for natural catchments.
- The runoff coefficient is the first principle that would become known as the Rational Method.
- In 1851, Mulvaney presented second principle relating the time of concentration to the storm event.

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The Rational Formula Explained

- $Q = CI_{avg} A_{cont,}$ where in imperial units,
  - C = Dimensionless runoff to rainfall coefficient (0.0 to 1.0)
  - I_{avg} = rainfall intensity (inches/hour) averaged over the time of concentration and
  - A_{cont} = Contributing drainage area in acres.

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The Rational Formula Explained

- The units:
- C (dimensionless)* I (inches/hour)* A (Acres) = Acre inches/ hour

$$\frac{1 \text{ Acre in./hr} * 43560 \text{ SF/Ac}}{12 \text{ in/ft} \times 3600 \text{ sec/hr}} = 1.00833 \text{ CFS}$$

The method is “rational” by using the ratio of runoff to rainfall intensity.

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The Rational Formula Explained

- The assumptions
- C value:
  - Homogeneous watershed with evenly distributed rainfall and runoff (Using one weighted C value for the watershed).

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The Rational Formula Explained

- Time of Concentration and storm duration.
- Case 1 (the usual)
  - Set the storm duration equal to time of concentration, total watershed contributes to peak flow.
  - Usually, the maximum flow occurs when the rainfall duration is equal to the time of concentration.

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The Rational Formula Explained

- Case 2:
- For Storm duration longer than the Time of concentration,
  - Rainfall intensity is less, but total watershed contributing.
  - Less peak flow than Case 1.

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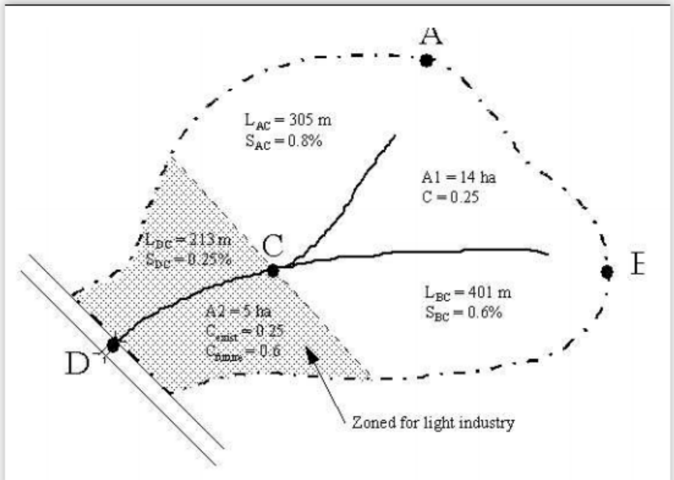
The Rational Formula Explained

- Case 3: (Partial Drainage area contribution)



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The Rational Formula Explained

- Case 3: (Partial Drainage area contribution)
- For storm duration less than Time of concentration
  - only part of the watershed (the downstream portion) contributes to the peak flow
  - Rainfall intensity is higher.
  - Peak flow may also be higher than Case 1.

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Runoff Coefficients (DEP E&S Manual)

TABLE 5.2
Runoff Coefficients for the Rational Equation*

LAND USE	A Soils[1]			B Soils[1]			C Soils[1]			D Soils[1]		
	< 2%	2 - 6%	>6%	< 2%	2 - 6%	>6%	< 2%	2 - 6%	>6%	< 2%	2 - 6%	>6%
Cultivated land	0.08	0.13	0.16	0.11	0.15	0.21	0.14	0.19	0.26	0.18	0.23	0.31
Pasture	0.12	0.20	0.30	0.18	0.28	0.37	0.24	0.34	0.44	0.30	0.40	0.50
Meadow	0.10	0.16	0.25	0.14	0.22	0.30	0.20	0.28	0.36	0.24	0.30	0.40
Forest	0.05	0.08	0.11	0.08	0.11	0.14	0.10	0.13	0.16	0.12	0.16	0.20
Residential lot size 1/8 acre	0.25	0.28	0.31	0.27	0.30	0.35	0.30	0.33	0.38	0.33	0.36	0.42
Residential lot size 1/4 acre	0.22	0.26	0.29	0.24	0.29	0.33	0.27	0.31	0.36	0.30	0.34	0.40
Residential lot size 1/3 acre	0.19	0.23	0.26	0.22	0.26	0.30	0.25	0.29	0.34	0.28	0.32	0.39
Residential lot size 1/2 acre	0.16	0.20	0.24	0.19	0.23	0.28	0.22	0.27	0.32	0.26	0.30	0.37
Residential lot size 1 acre	0.14	0.19	0.22	0.17	0.21	0.26	0.20	0.25	0.31	0.24	0.29	0.35
Industrial	0.67	0.68	0.68	0.68	0.68	0.69	0.68	0.68	0.69	0.69	0.69	0.70
Commercial	0.71	0.71	0.72	0.71	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
Streets	0.70	0.71	0.72	0.71	0.72	0.74	0.72	0.73	0.76	0.73	0.75	0.78
Open Space	0.05	0.10	0.14	0.08	0.13	0.19	0.12	0.17	0.24	0.15	0.21	0.28
Parking	0.85	0.86	0.87	0.85	0.86	0.87	0.85	0.86	0.87	0.85	0.86	0.87
Construction Sites - Bare packed soil, smooth	0.30	0.35	.040	0.35	.040	0.45	0.40	0.45	0.50	0.50	0.55	0.60
Construction Sites - Bare packed soil, rough	.020	0.25	0.30	0.25	0.30	0.35	0.30	0.35	0.40	0.40	0.45	0.50

* Runoff Coefficients for storm recurrence intervals less than 25 years

Adapted from McCuen, R.H., Hydrologic Analysis and Design (2004)

1. According to the USDA NRCS Hydrologic Soils Classification System

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The Rational Formula Explained

- Variables:
  - Runoff Coefficients relatively well defined, may not have a significant impact on peak flow.
  - C = 0.3 vs 0.25, peak varies 20%

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Rainfall Intensity NOAA Atlas 14, King of Prussia.

PDS-based precipitation frequency estimates with 90% confidence interva

Duration	Average recurrence interval (years)						
	1	2	5	10	25	50	100
5-min	**4.15** (3.82-4.52)	**4.94** (4.55-5.39)	**5.78** (5.30-6.30)	**6.38** (5.84-6.95)	**7.08** (6.46-7.70)	**7.56** (6.85-8.23)	**8.03** (7.24-8.75)
10-min	**3.31** (3.05-3.61)	**3.95** (3.64-4.30)	**4.63** (4.25-5.05)	**5.11** (4.67-5.56)	**5.65** (5.14-6.14)	**6.02** (5.45-6.55)	**6.37** (5.75-6.95)
15-min	**2.76** (2.54-3.01)	**3.31** (3.05-3.61)	**3.91** (3.58-4.26)	**4.30** (3.94-4.68)	**4.77** (4.35-5.19)	**5.08** (4.60-5.53)	**5.37** (4.85-5.86)
30-min	**1.89** (1.74-2.06)	**2.29** (2.10-2.49)	**2.78** (2.55-3.02)	**3.12** (2.86-3.39)	**3.53** (3.22-3.84)	**3.83** (3.47-4.17)	**4.11** (3.71-4.48)
60-min	**1.18** (1.09-1.29)	**1.44** (1.32-1.56)	**1.78** (1.63-1.94)	**2.03** (1.86-2.21)	**2.35** (2.14-2.56)	**2.59** (2.35-2.82)	**2.83** (2.56-3.09)
2-hr	**0.707** (0.646-0.775)	**0.858** (0.785-0.940)	**1.07** (0.976-1.17)	**1.23** (1.12-1.35)	**1.44** (1.30-1.58)	**1.61** (1.45-1.76)	**1.78** (1.59-1.95)
3-hr	**0.514** (0.470-0.565)	**0.624** (0.570-0.685)	**0.779** (0.710-0.855)	**0.898** (0.817-0.985)	**1.06** (0.954-1.16)	**1.18** (1.06-1.29)	**1.31** (1.17-1.43)
6-hr	**0.322** (0.294-0.354)	**0.389** (0.356-0.428)	**0.484** (0.442-0.532)	**0.561** (0.510-0.615)	**0.668** (0.603-0.732)	**0.754** (0.675-0.826)	**0.845** (0.750-0.926)
12-hr	**0.194** (0.178-0.215)	**0.235** (0.214-0.260)	**0.294** (0.268-0.325)	**0.343** (0.311-0.379)	**0.414** (0.372-0.456)	**0.474** (0.421-0.521)	**0.539** (0.473-0.593)
24-hr	**0.113** (0.104-0.124)	**0.136** (0.125-0.149)	**0.170** (0.156-0.187)	**0.199** (0.182-0.218)	**0.241** (0.219-0.262)	**0.276** (0.249-0.300)	**0.313** (0.281-0.341)

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The Rational Formula Explained

- Variables:
  - Computing Time of Concentration has greater impact on peak flow, especially for short duration storms.
  - Tc = 5 min vs 15 min. Intensity 8.03 in/hr, vs 5.37 in/hr (33% decrease)

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The Rational Formula Explained

- Storm sewer design principles:
  - The rainfall intensity is set based on a particular storm duration
  - the Duration is set equal to the time of concentration. You cannot have two different storms on the same watershed.
  - As you move down the watershed through pipes or other structures, you use the longest travel time to the next downstream point of interest (POI).

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Universal Rational Hydrographs

- Actual Rainfall intensity and depths used
- Uses 10 x Tc rainfall durations to develop the hydrograph.
- Peak is placed at 3 x Tc, computed using the Tc duration intensity.
- Storm duration lengthens in relation to Tc. As Tc increases, total duration increases by 10 X.

Time (min)	Incr. (inches)	Total (inches)	Intensity (in/hr)	Flow (cfs)
0	0.00	0.00	0.00	0.00
10	0.20	0.20	1.22	2.45
20	0.43	0.63	2.57	5.13
30	1.15	1.78	6.90	13.80
40	0.63	2.41	3.77	7.54
50	0.32	2.73	1.92	3.83
60	0.25	2.98	1.50	3.01
70	0.16	3.14	0.97	1.94
80	0.14	3.29	0.87	1.74
90	0.13	3.42	0.80	1.59
100	0.12	3.54	0.73	1.47

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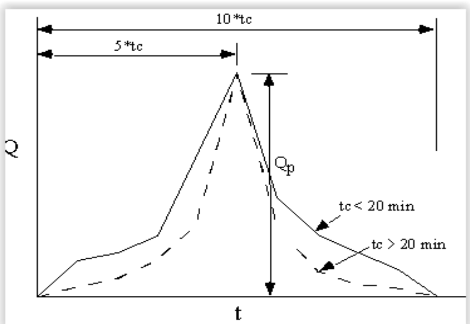
Dekalb Hydrographs

- Applies a Q/ Qp ratio to each ordinate (10 Tc increments)
- Peak placed in the middle (ordinate 5)
- Hydrograph duration lengthens as Tc increases.
- The total runoff volume is not equal to the 10 x Tc storm duration.



Dimensionless Time and Hydrograph Ordinates

t/t_c	Q/Q_p for $t_c < 20$ min	Q/Q_p for $t_c >= 20$ min
0	0.00	0.00
1	0.16	0.04
2	0.19	0.08
3	0.27	0.16
4	0.34	0.32
5	1.00	1.00
6	0.45	0.30
7	0.27	0.11
8	0.19	0.05
9	0.12	0.03
10	0.00	0.00

where:

- t_c = Time of concentration.
- Q = Flow at time t, in cfs.
- Q_p = Peak flow.

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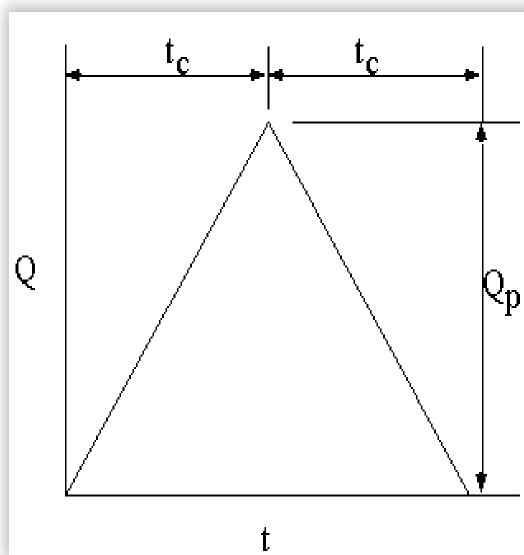
Triangular Hydrographs (Not conservative)

- Peak placed at Time of Concentration.
- Duration is 2 x Tc.
- Very small volume for detention storage.
- Some modifications use total duration = 3x Tc.



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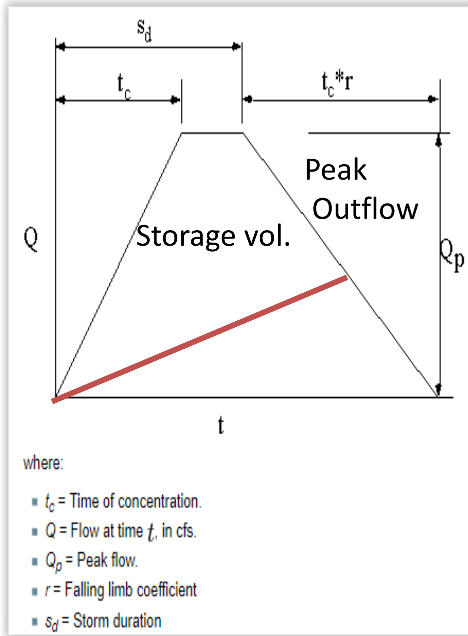
"Modified Rational Method" Hydrographs (T&E)

- Peak placed at Time of Concentration.
- Duration is increased with longer duration than Tc. Peak is lower..
- Falling limb duration typically 1 x Tc duration.
- Maximum outflow rate intersects descending limb.
- Compute Area between inflow & outflow hydrographs. Units CFS x seconds = CF storage.
- Use several durations to compute the maximum storage needed.
- Actual routing could change critical storm duration.



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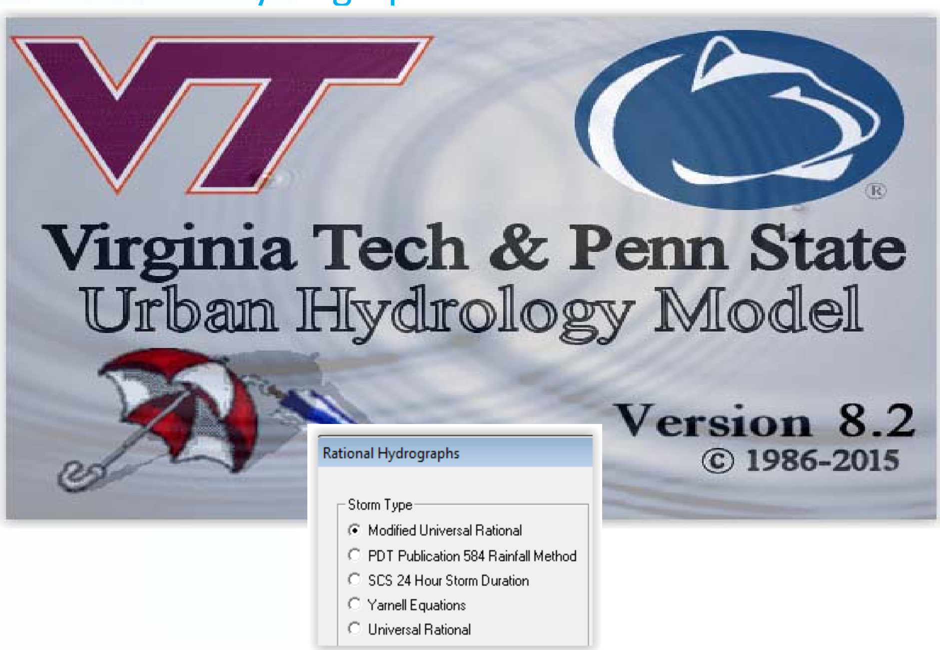
Rational Hydrographs VTPSUHM – 5 OPTIONS



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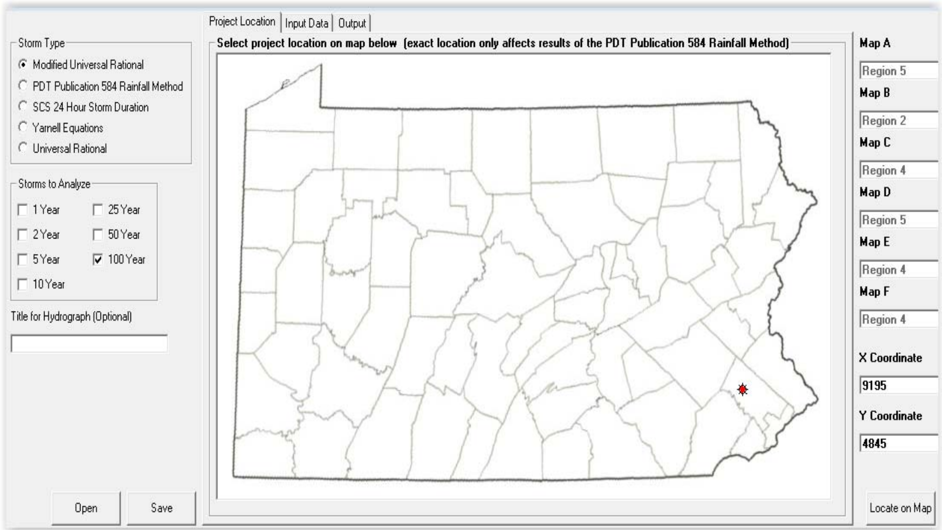
Rational Hydrographs VTPSUHM Input Screens

Project Location Screen – Map used for PDT Pub 584 method only.



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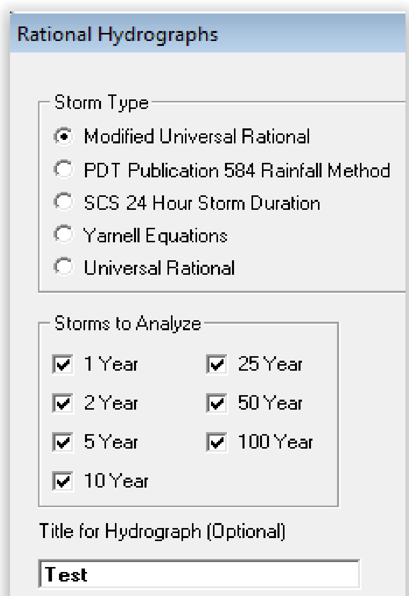
Rational Hydrographs VTPSUHM Input Screens

Project Location Screen

- Select Storm type
- Can analyze multiple storms at once
- Modified Universal Rational is newest method (7/2014).



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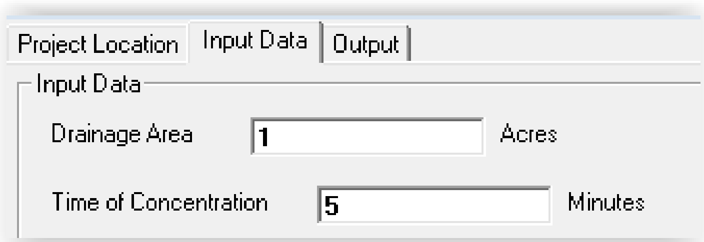
Rational Hydrographs VTPSUHM Input Data

- Input Drainage area in acres
- Input Time of Concentration in minutes



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Rational Hydrographs VTPSUHM Input Data

- Input Weighted C factor (can use constant for each storm)

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Rational Hydrographs VTPSUHM Input Data

- Input Rainfall intensity and Total rainfall for each design storm (From NOAA Atlas 14)
- Excel Spreadsheet helps with data interpolation

Modified Universal Rational NOAA Atlas 14 Storm Inensities------Total Rainfall for 2.08 Hour Design Storm

1 Year Storm		in/hr	25 Year Storm		in/hr	1 Year Storm		in	25 Year Storm		in
2 Year Storm	4.67	in/hr	50 Year Storm		in/hr	2 Year Storm	1.40	in	50 Year Storm		in
5 Year Storm		in/hr	100 Year Storm	9.11	in/hr	5 Year Storm		in	100 Year Storm	3.24	in
10 Year Storm		in/hr				10 Year Storm		in			

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Rational Hydrographs VTPSUHM Input Data

- Excel Spreadsheet helps with data interpolation

NOAA ATLAS 14, VOLUME 2 RAINFALL INTERPOLATION SPREADSHEET **DEVELOPED BY THOMAS F. SMITH, PE AND CLAYTON C. HODGES, PE**

Point precipitation frequency estimates (inches/hour)
NOAA Atlas 14 Volume 2 Version 3
Data type: Precipitation intensity
Time series type: Partial duration
Project area: Ohio River Basin
Location name (ESRI Maps): Centre Hall
Station Name: -
Latitude: 40.8000°
Longitude: -77.7000°
Elevation (USGS): 1283.3 ft

Copy Data

Point precipitation frequency estimates (inches)
NOAA Atlas 14 Volume 2 Version 3
Data type: Precipitation depth
Time series type: Partial duration
Project area: Ohio River Basin
Location name (ESRI Maps): Centre Hall
Station Name: -
Latitude: 40.8000°
Longitude: -77.7000°
Elevation (USGS): 1283.3 ft

Duration	Rainfall Intensities (inches/hr.) for Return period in years						
(hours)	1	2	5	10	25	50	100
0.083	3.91	4.67	5.68	6.47	7.50	8.29	9.11
0.167	3.04	3.65	4.42	4.99	5.74	6.29	6.86
0.250	2.48	2.97	3.61	4.09	4.72	5.19	5.68
0.500	1.64	1.99	2.47	2.84	3.34	3.71	4.10
1.000	1.00	1.22	1.55	1.81	2.16	2.44	2.74
2.000	0.57	0.69	0.88	1.03	1.25	1.42	1.61
3.000	0.41	0.50	0.63	0.73	0.88	1.01	1.15
6.000	0.25	0.31	0.38	0.44	0.53	0.61	0.69
12.000	0.16	0.19	0.23	0.27	0.33	0.38	0.43
24.000	0.09	0.11	0.14	0.16	0.20	0.22	0.25
48.000	0.05	0.07	0.08	0.09	0.11	0.13	0.15

Duration	Rainfall Depth (inches) for Return period in years						
(hours)	1	2	5	10	25	50	100
0.083	0.326	0.39	0.47	0.54	0.63	0.69	0.76
0.167	0.51	0.61	0.74	0.83	0.96	1.05	1.14
0.250	0.62	0.74	0.90	1.02	1.18	1.30	1.42
0.500	0.82	0.99	1.24	1.42	1.67	1.85	2.05
1.000	1.00	1.22	1.55	1.81	2.16	2.44	2.74
2.000	1.14	1.39	1.76	2.06	2.49	2.85	3.22
3.000	1.23	1.49	1.88	2.19	2.65	3.03	3.44
6.000	1.52	1.83	2.28	2.66	3.20	3.65	4.13
12.000	1.89	2.27	2.82	3.28	3.95	4.52	5.14
24.000	2.25	2.70	3.36	3.90	4.69	5.36	6.09
48.000	2.61	3.13	3.88	4.51	5.42	6.20	7.05

Tc (min):	5.0	Rainfall Intensity Interpolation routine					
Tc (Hours):	0.083	Storm Frequency (Years)					
Table durations	1	2	5	10	25	50	100
0.083	3.91	4.67	5.68	6.47	7.50	8.29	9.11
	COMPUTED RAINFALL INTENSITIES (INCHES/HOUR)						
0.000	**3.91**	**4.67**	**5.68**	**6.47**	**7.50**	**8.29**	**9.11**
0.167	3.04	3.65	4.42	4.99	5.74	6.29	6.86

Input the Time of concentration in the yellow cell

Rainfall Depth Interpolation routine							
Duration (hrs.)*	2.083	Storm Frequency (Years)					
Table durations	1	2	5	10	25	50	100
2.000	1.14	1.39	1.76	2.06	2.49	2.85	3.22
	COMPUTED RAINFALL DEPTHS (INCHES)						
0.083	**1.15**	**1.40**	**1.77**	**2.07**	**2.50**	**2.87**	**3.24**
3.000	1.23	1.49	1.88	2.19	2.65	3.03	3.44

* Total duration of storm is 25 X Tc

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Rational Hydrographs VTPSUHM Input Data

- Optional volume estimate - Can Input desired pond outflow to estimate storage required.
- Storage computed using parabolic outflow hydrograph method.

Desired Pond Outflow (Optional for Estimated Volume)

1 Year		CFS	25 Year		CFS
2 Year		CFS	50 Year		CFS
5 Year		CFS	100 Year	1	CFS
10 Year		CFS			

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Rational Hydrographs VTPSUHM Output Data

- One tab for each computed hydrograph.
- Volume estimate displayed if option used.
- Total hydrograph volume displayed below table
- Can print or save hydrographs

Hydrographs

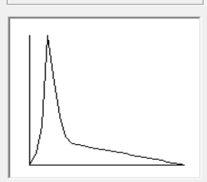
2 Year Storm | 100 Year Storm

Time (hrs)	Rainfall Increment (inches)	Total Rainfall (in)	Intensity (in/hr)	Flow (cfs)
0.000	0.00	0.00	0.00	0.00
0.083	0.08	0.08	0.91	0.46
0.167	0.23	0.30	2.73	1.37
0.250	0.76	1.06	9.11	4.56
0.333	0.48	1.54	5.78	2.89
0.417	0.28	1.83	3.40	1.70
0.500	0.16	1.99	1.97	0.99
0.583	0.12	2.12	1.50	0.75
0.667	0.12	2.24	1.42	0.71
0.750	0.11	2.35	1.34	0.67
0.833	0.11	2.45	1.26	0.63
0.917	0.10	2.55	1.18	0.59
1.000	0.09	2.64	1.10	0.55
1.083	0.09	2.73	1.02	0.51
1.167	0.08	2.81	0.95	0.47
1.250	0.07	2.88	0.87	0.43
1.333	0.07	2.94	0.79	0.39
1.417	0.06	3.00	0.71	0.35
1.500	0.05	3.06	0.63	0.32

Total Hydrograph Volume: 5,832 Cubic Feet, or 0.1339 Acre-Feet

Suggested Basin Volume

2486 Cubic Feet
or
0.0571 Acre-Feet



Save All Hydrographs | Save Hydrograph(s)

Print All Hydrographs | Print Hydrograph(s)

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Rational Hydrographs

Modified Universal Rational – Newest VTPSUHM Module (2014)

1. Peaks computed using Tc rainfall intensity.
2. Duration = 25 X Tc total rainfall depth.
3. Rainfall data obtained from NOAA Atlas 14.
4. Many new Act 167 Ordinances specify Atlas 14 Rainfall data.

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Rational Hydrographs

Modified Universal Rational

- Peaks computed using Tc rainfall intensity.
- Peak Q = ciA flow placed at 3 x Tc.
- Ordinates use 25 x Tc time steps
- The first 3 ordinates use the same Q/Qp ratios (Similar to Dekalb method)
  - ✓ Ordinate 1 = 0.1 x Qpeak (at 1 x Tc)
  - ✓ Ordinate 2 = 0.3 x Qpeak (at 2 x Tc)
  - ✓ Ordinate 3 = 1.0 x Qpeak (at 3 x Tc)

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Rational Hydrographs

Modified Universal Rational

- Total hydrograph duration = 25 X Tc
  - ✓ 5 minute Tc = 125 minute duration (2.08 hrs)
  - ✓ 15 minute Tc = 375 minute duration (6.25 hrs)
- Total runoff volume = runoff from the 25 X Tc storm duration.
- Area under the hydrograph = CFS x Seconds = CF.
- The calculations adjust the descending limb of the hydrograph, ending at 25 x Tc and maintaining the volume of runoff equal to the Total storm duration runoff.
- Each rainfall intensity and total runoff depth combination results in different hydrograph shapes.

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Detention basin design with Infiltration

1. Compute 2-year, 24-hour volumes using NRCS runoff Equations.
2. Set basin or bed lowest outlet orifice at or above the infiltration volume elevation.
3. Generate hydrographs using Rational Hydrograph method for post-development conditions to the BMP for the Tc duration storms.
4. Use modified-puls routing for each storm for peak rate control (2-year, 5-year, 10-year, 25-year, 50- year and 100-year storms.)

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Combining hydrographs for downstream BMP (SAME Tc for downstream BMP)

1. Compute hydrographs for the downstream condition or structure using the same Tc duration storm as the basin.
2. Use basin outflow hydrograph combination to add the ordinates from the basin outflow to the downstream inflow hydrographs.

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Combining hydrographs for downstream BMP (Longer Tc for downstream BMP)

1. Compute hydrographs for inflow hydrographs into the basin.
2. Use modified-puls routing for each storm and save outflow hydrographs for each storm.
3. Compute hydrographs for downstream condition or structure using the longer Tc duration storm.
4. Use basin outflow hydrograph combination to add the ordinates from the basin outflow to the downstream inflow hydrographs.

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WHY NOT JUST COMBINE HYDROGRAPHS FROM DIFFERENT Tc STORMS?

1. Remember, you are analyzing a STORM with a certain DURATION. A Storm Duration is NOT a Time of concentration!
2. You cannot combine the hydrographs from a 10 minute storm with a 30 minute storm!
3. Must use a consistent storm DURATION for each BMP. As is the proper procedure in designing storm sewers, the user always chooses the longest Tc (storm duration) as one moves downstream.
4. You essentially have 2 design storms in this case – the Tc storm for the basin outflow and the longer duration storm for the combined hydrographs.

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Comparing Rational Hydrographs with NRCS 24-hour Hydrographs

1. NRCS Hydrographs are from a 24- hour storm duration.
2. Rational Hydrographs vary from 2 X Tc duration to about 25 X Tc duration. (Example, for a 5 minute Tc, durations range from 10 minutes to 125 Minutes). Runoff volume will typically be less than NRCS methods.
3. Rainfall intensities based on local data (NOAA Atlas 14), whereas NRCS values based on 24-hour depths and the Type 2 Storm duration. Very conservative intensities result (13 inches per hour for 6 minute Tc and 7.2 inch rainfall).
4. NRCS peak discharges inaccurate for frequent storms and low CN values. (Under predicts).

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Comparing Rational Hydrographs with NRCS 24-hour Hydrographs

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2. Very conservative intensities result (13 inches per hour for 6 minute Tc and 7.2 inch rainfall).

100 Year Storm

Time (hrs)	Rainfall Increment (inches)	Total Rainfall (in)	Intensity (in/hr)	Flow (cfs)
0.000	0.00	0.00	0.00	0.00
0.100	0.13	0.13	1.28	0.64
0.200	0.37	0.50	3.68	1.84
0.300	1.30	1.80	13.05	6.52
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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Comparing Rational Hydrographs with NRCS 24-hour Hydrographs

- NRCS peak discharges inaccurate for frequent storms and low CN values. (Under predicts).
- NRCS peak discharges typically over-estimate for infrequent (50-year, 100-year) events, resulting in larger over-designed outflow culverts.
- Most storm sewer systems including downstream of basins being designed using the Rational Formula.
- Sound engineering judgement is needed in selecting the methodology based on site conditions, factors of safety and danger to life and property.

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QUESTIONS?

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