Appendix B: Peak Discharge Analysis:

**Peak Discharge ($q_p$) Calculations for Cascadilla Creek**:

I. **Cascadilla Creek Constants needed for all $q_p$ analyses**

a. Find Rainfall Intensity

$t = time\ (yrs) = 15 yrs$

$P\ = exceedance\ probability = 0.25$

$EP\ = exceedance\ probability\ in\ t\ years = 1-(1-P)^{1/t} = 0.019$

$T = 50\ yr\ rainfall\ event\ with\ 2\ hr\ duration = 1/EP\ \simeq 52\ yrs$

$i = Rainfall\ Intensity = depth/duration = [2.40\ in/2\ hrs] \cdot \frac{0.0254\ m}{1\ in} \cdot \frac{1\ hr}{3600\ sec} = 8.45 * 10^{-6}\ m/sec$

b. Use Kirpich method (1940) to find the time of concentration (see Appendix A):

$t_c = 0.0078 \cdot L^{0.77} \cdot S^{-0.385}$

$t_c = [0.0078 \cdot (48000)^{0.77} \cdot (3.03)^{-0.385}] \cdot \frac{1\ hr}{60\ min}$

$t_c = 1.99\ hrs \simeq 2\ hrs$

c. Area of the Cascadilla Creek Watershed

$A = 3.5 * 10^7 m^2$

d. Land Covering constants

$CN =\ NRCS\ Curve\ Number = 76.76$

$C = Rational\ Method\ Runoff\ Coefficient = 0.23$

II. **Rational Method (Lloyd-Davies Equation, 1800's)**

$q_p = CiA = 0.23 \cdot 8.45 * 10^{-6}\ m/sec \cdot 3.5 * 10^7 m^2$

$q_p = 67.2\ m^3/s$

III. **Curve Number (CN) Method with A Synthetic Triangular Hydrograph**

a. Curve Number Equation

$Q = (P - I_a)^2/(P - I_a + S)$

$Where:$

$Q = Runoff\ depth\ (in)$

$P\ = Rainfall\ depth\ (in) = 2.4\ in.\ (sourced\ from\ NRCC\ data)$

$I_a = Initial\ Abstraction\ (in)$

$S = Maximum\ Watershed\ Storage = (1000/CN) - 10\ (in) = 3.03\ in$

b. Using $I_a = 0.05S$ because it is recognized as more accurate than $I_a = 0.2S$

$I_a = 0.05S = 0.05 \cdot 3.03\ in = 0.15\ in$

$Q = [(2.4 - 0.15)^2/(2.4 - 0.15 + 3.03)] \cdot \frac{0.0254\ m}{1\ in}$

$Q = 0.0243\ m$

c. Find volume of watershed

$Q_v = volume\ of\ watershed\ (m^3) = 0.5 \cdot q_p \cdot (2.94 \cdot t_c)$

$Q_v = A \cdot Q = 3.5 * 10^7 m^2 \cdot 0.0243\ m = 850500\ m^3$

d. Use volume of watershed ($Q_v$) and the runoff depth ($Q$) to find peak discharge ($q_p$)

$q_p = 2 \cdot Q_v/(2.94 \cdot t_c)$

$$q_p = 2 \cdot 858500/(2.94 \cdot 2 \cdot 3600)$$
$$q_p = 80.9\ m^3/s$$

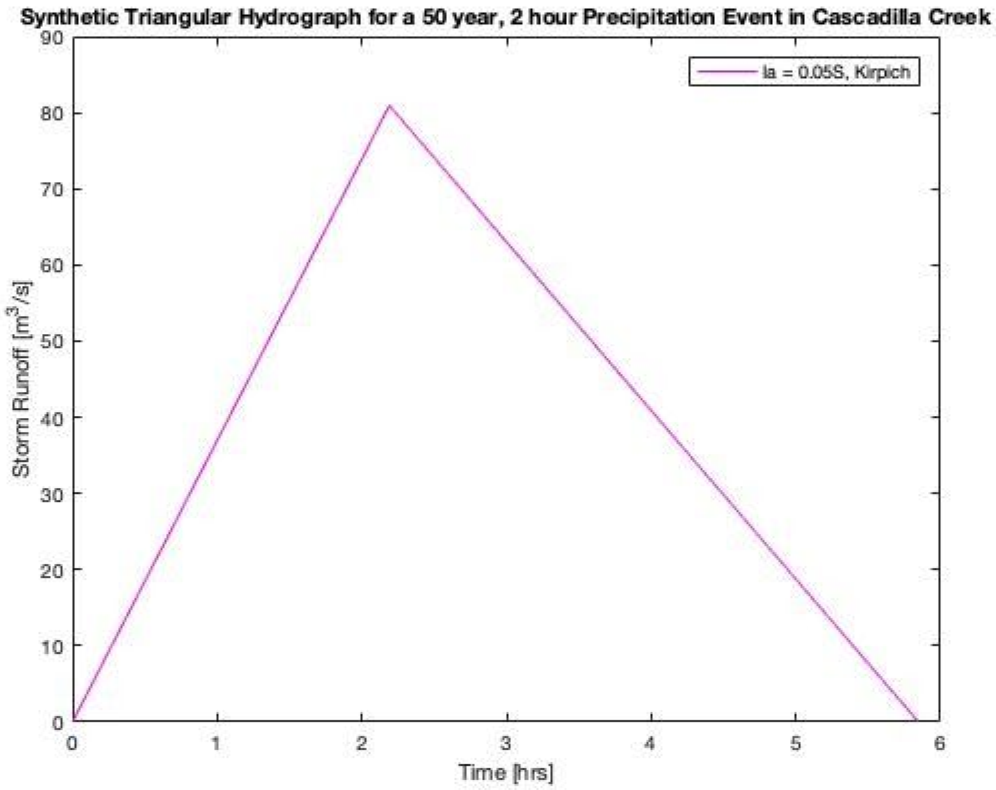


**Figure B.1:** Synthetic Triangular Hydrograph with the peak discharge of 80.9 $m^3/s$ for a 50 year, 2 hour precipitation event in Cascadilla Creek

To see the formulation of the graph in Fig. B.1 please see [MATLAB Appendix: Code for Peak Discharge Analysis of Cascadilla Creek]

## IV. Curve Number (CN) Method with a Composite Unit Hydrograph

a. Find the storm duration (D), time to peak ($t_p$), and recession time ($t_r$) for unit graph

$$D = \Delta = 0.133 \cdot t_c = 0.133 \cdot 2\ hr = 0.266\ hr$$
$$t_p = D/2 + 0.6 \cdot t_c = 0.266\ hr/2 + 0.6 \cdot 2\ hr = 1.33\ hr$$
$$t_r = 1.67 \cdot t_p = 1.67 \cdot 1.33 = 2.23\ hr$$

b. Find volume of watershed using a unit depth of 0.001 m

$$Q_v = 0.001\ m \cdot A = 0.001\ m \cdot 3.5 * 10^7 m^2 = 35000\ m^3$$

c. Use volume equation to solve for peak discharge ($q_p$) per unit:

$$q_p = 2 \cdot Q_v/(t_p + t_r)$$
$$q_p = [2 \cdot 35000\ m^3/(1.33\ hr + 2.23\ hr)] \cdot \frac{1\ hr}{3600\ sec}$$
$$q_p = 5.45\ m^3/s/unit$$

d. Solve for the ascending and descending slopes of the unit hydrograph

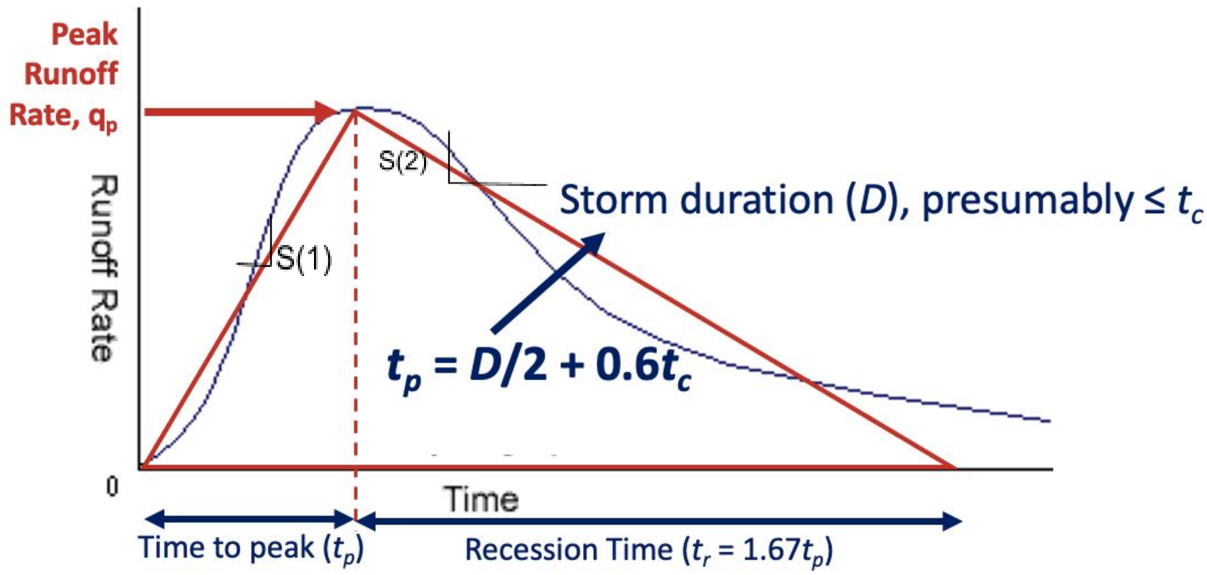


**Figure B.2**: Example unit hydrograph with time to peak (tp), recession time (tr), and peak runoff rate per unit defined. Slopes of each side of the unit triangle will be solved for in the equations below.

$S_1 = q_p/t_p = (5.45\ m^3/s/unit)/1.33\ hr = 4.09\ m^3/s/hr$

$S_2 = q_p/t_r = (5.45\ m^3/s/unit)/2.23\ hr = 2.45\ m^3/s/hr$

e. Build the Unit Hydrograph by finding the distribution of rainfall in time steps of $\Delta$. Graph $u(\Delta)$, where u is the peak discharge per unit per time step $\Delta$ up to $q_p$ and back down to 0

$u_{max} =$ *the incremental value for the u vector* $= t_p/\Delta = 1.33/0.266 = 5$

$u_{increment} = q_p/u_{max} = 1.0902$

$u_{vector\ ascending} = [0,\ 1,\ 2,\ 3,\ 4,\ 5] \rightarrow$ defined up to $u_{max}$

$x_{ascending} = \Delta \cdot u_{vector\ ascending} = [0,\ 0.266,\ 0.5320,\ 0.7980,\ 1.0640,\ 1.3300]$

$y_{ascending} = u_{increment} \cdot u_{vector\ ascending} = [0,\ 1.09,\ 2.18,\ 3.27,\ 4.36,\ 5.45]$

$u_{vector\ descending} = [5,\ 6,\ 7,\ 8,\ 9,\ 10,\ 11,\ 12,\ 13]$

$x_{descending} = \Delta \cdot u_{vector\ descending} = [1.33,\ 1.59,\ 1.86,\ 2.12,\ 2.39,\ 2.66,\ 2.92,\ 3.19,\ 3.45$

$y_{descending} = q_p - [(S_2 \cdot \Delta) \cdot [1,\ 2,\ 3,\ 4,\ 5,\ 6,\ 7\ ,8]]$

$y_{descending} = [5.46,\ 4,81,\ 4.15,\ 3.50,\ 2.85,\ 2.19,\ 1.54,\ 0.89,\ 0.24]$

Will now use $x_{ascending}$ and $y_{ascending}$ to graph the ascending portion of the unit hydrograph and $x_{descending}$ and $y_{descending}$ to graph the descending portion of the unit hydrograph, as seen in Fig. B.3.

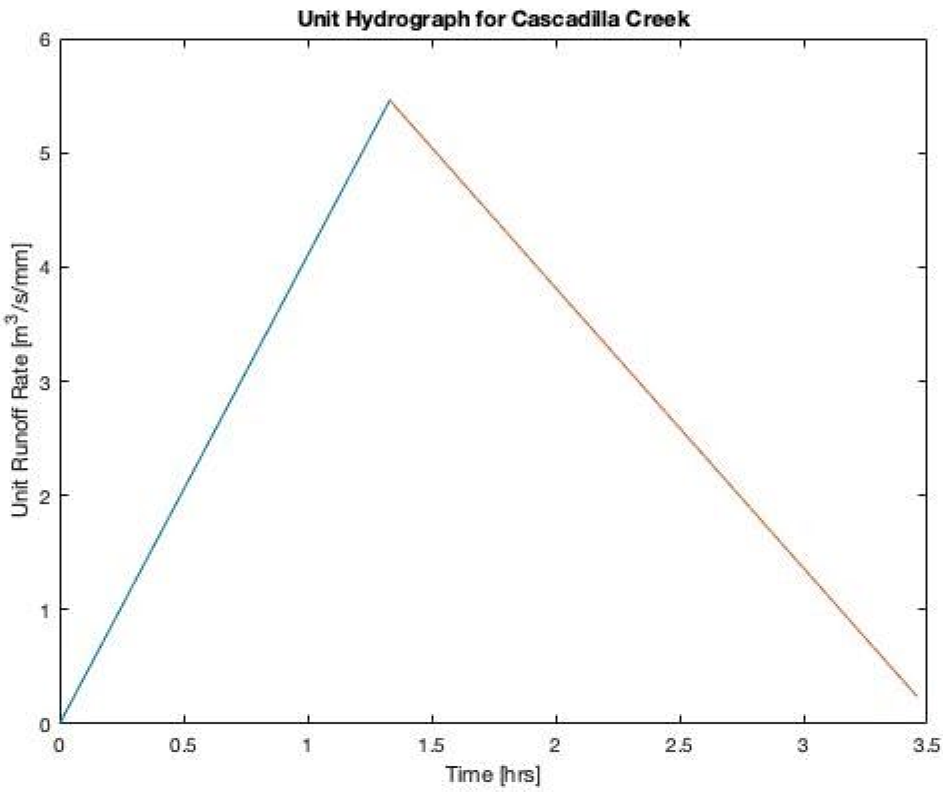


**Figure B.3:** Unit Hydrograph for Cascadilla Creek Watershed.

f. Build the Composite Unit Hydrograph using the Unit Hydrograph and graph
$delta = [x_{ascending}\ x_{descending}] \rightarrow$ builds a vector of all the x values from the unit hydrograph
$U = [\ y_{ascending}\ y_{descending}] \rightarrow$ builds a vector of all the y values from the unit hydrograph
Next, find the vector of rainfall depths (P) in order to solve the CN equation:
$Q = (P - I_a)^2/(P - I_a + S)$
It is known that the rainfall depth is $P = 2.4\ in$ from NRCC data. Therefore, need to divide up that rainfall depth into composite segments to build a composite set of Q values to solve the CN equation:
$\Delta P\ = step\ change\ for\ the\ rainfall\ depth = P/10 - steps = 0.24\ in/step$
$P_{vector} =\ [1, 2, 3, 4, 5, 6, 7, 8, 9, 10] \cdot \Delta P\ = [0.24, 0.48, 0.72, 0.96, 1.20, 1.44, 1.68, 1.92, 2.16, 2.40]\ (in)$
$S = Maximum\ Watershed\ Storage = (1000/CN) - 10\ (in) = 3.03\ in$
$I_a = 0.05S = 0.05 \cdot 3.03\ in = 0.15\ in$
Now, solve for the incremental runoff depths for each time step:

$Q = (P_{vector} - I_a)^2/(P_{vector} - I_a + S) = [0, 0.032, 0.089, 0.17, 0.26, 0.38, 0.51, 0.65, 0.80, 0.95]\ (in)$
It is also known that there will be no runoff unless $I_a > P$ , so there will be no Q values when the rainfall depth is less than the initial abstraction.
Now, to solve for the composite peak discharge $q_p$ , must multiply each Q value by the vector U, used to define all the y values. This results in a composite unit hydrograph as seen in Fig. B.4. For a more detailed explanation, with composite vectors shown, please refer to MATLAB Appendix: Code for Peak Discharge Analysis of Cascadilla Creek.

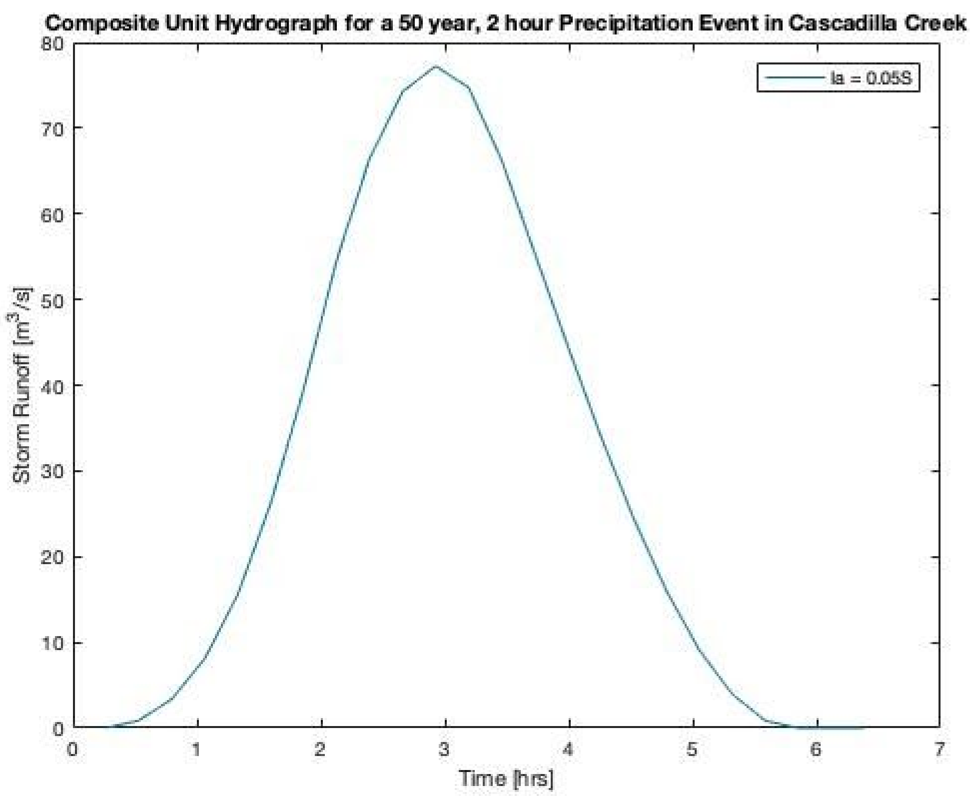


**Figure B.4**: Composite Unit Hydrograph for the Cascadilla Creek Watershed

## V. 24-hour Unit Hydrograph - Uniform distribution

Instead of looking at a 2-hr duration storm, will now analyze a 50 year, 24-hr duration storm. This method is very similar to the Composite Unit Hydrograph method except the D value is no longer $D = \Delta = 0.133t_c$. Now, the D value, or time step, will be $D = 0.2\ hrs$ .
This method is less sensitive to area issues and a 24-hr duration rainfall is easier to measure than a 2-hr rainfall event.
The rainfall depth (P) also changes for this analysis as it is no longer considering the depth at 2-hrs, but instead at 24-hrs. Therefore, $P = 4.98\ in\ (sourced\ from\ NRCC\ data)$

For the detailed equations used, please see [Spreadsheet Appendix : Excel Spreadsheet for 24-Hour Hydrograph Analyses of Cascadilla Creek].
***This analysis results in a design rainfall distributed uniformly over 24 hours.***

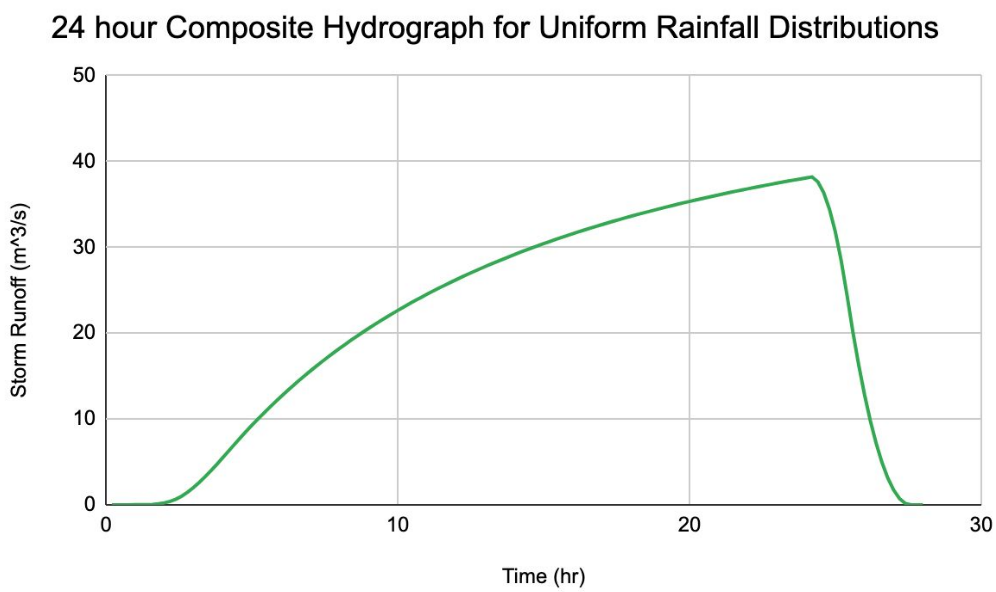


**Figure B.5:** 24-hr Composite Unit Hydrograph for a Uniform Rainfall distribution.

## VI. 24-hour Unit Hydrograph - NRCS Type II

For the detailed equations used, please see [Spreadsheet Appendix : Excel Spreadsheet for 24-Hour Hydrograph Analyses of Cascadilla Creek].
***This analysis results in a design rainfall distributed using NRCS distributions over 24 hours.***

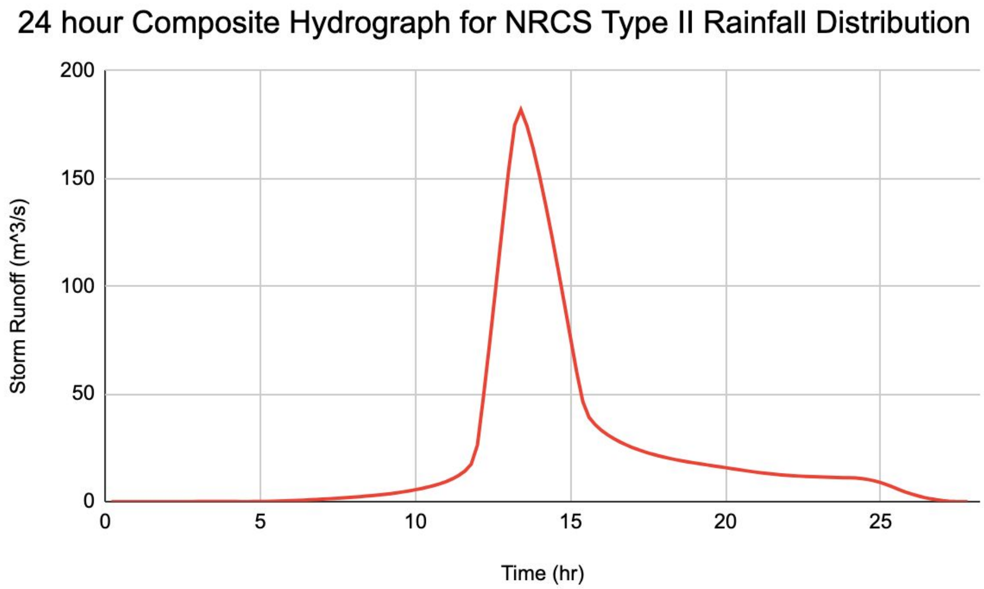


**Figure B.6:** 24-hr Composite Unit Hydrograph for NRCS Type II Rainfall distribution.

## VII. TR-55 Graphical Method

a. Have to use $I_a = 0.2S$ for the given C parameters of the TR-55 equation

   *$q_u$ = unit peak runoff factor ($m^3/s/cm$ runoff/$km^2$ watershed area)*

   $S_{0.2} = (1000/CN) - 10 = (1000/76.76) - 10 = 3.027\ in$

   $I_a = 0.2S = 0.6055\ in$

   $I_a/P = 0.6055\ in/4.98\ in = 0.1$

   For $I_a/P = 0.1$ the following parameters were obtained:

   $C_o = 2.55323$

   $C_1 = -0.61512$

   $C_2 = -0.16403$

   $ln\,(q_u) = 2.55323 + (-0.61512 * ln(1.99)) + (-0.16403 * [ln(1.990]^2) - 2.366$

   $ln\,(q_u) = -0.3142$

   $q_u = 0.7304\ \ m/s/cm\ runoff/km^2\ of\ watershed\ area$

*b.* Now solve for *$Q_{24}$ = runoff depth from a 24 hr rain event, CN method (cm)*

   $Q_{24} = (P - I_a)^2/(P - I_a + S)$

   $Q_{24} = (4.98 - 0.6055)^2/(4.98 - 0.6055 + 3.0276)$

   $Q_{24} = 2.58\ inches$

   $Q_{24} = 2.58in * 2.54cm/in = 6.57\ cm$

*c.* Find remaining values and solve for peak discharge $q_p$

   *A = watershed area = 35 $km^2$*

   *$F_p$ = wetland adjustment = 1*

   $q_p = q_u Q_{24} A F_p = (0.7304\ \ m/s/cm\ runoff/km^2\ of\ watershed\ area)(6.57\ cm)(35\ km^2\ )(1)$

   $q_p = 168\ m^3/s$

**Peak Discharge ($q_p$) Calculations for the 21 Tompkins Country Stream Crossings**:

## I. Using the CN Method with Synthetic Triangular Hydrograph

**Table B.1:** Values used to find the peak discharge (qp) for each Tompkins County Stream Crossing. The peak discharge (qp) can be found in the last column.

| Stream Crossing Road Name | Kirpich $t_c$ values (hrs) | P (in): duration=$t_c$ recurrence =50 | Curve Number (CN) | Maximum Watershed Storage S (in) | Area ($m^2$) | Runoff Depth Q (m) | Peak Discharge ($m^3$/s) |
|---|---|---|---|---|---|---|---|
| Bostwick Road | 0.1208 | 0.73 | 76.0 | 4.48 | 106000 | 0.0013 | 0.216 |
| Enfield Main Road | 0.6590 | 1.83 | 71.7 | 5.62 | 3108000 | 0.0085 | 7.598 |
| Connecticut Hill Road | 0.3713 | 1.37 | 77.6 | 4.10 | 1683000 | 0.0065 | 5.619 |
| Leonard Road | 0.3308 | 1.31 | 73.2 | 5.20 | 1580000 | 0.0045 | 4.040 |
| Butternut Creek Road | 0.3458 | 1.34 | 73.9 | 5.02 | 725000 | 0.0049 | 1.956 |
| Stonehaven Circle Road | 0.8958 | 2.09 | 74.2 | 4.93 | 6086000 | 0.0127 | 16.429 |
| Station Road | 0.1712 | 0.92 | 77.4 | 4.15 | 570000 | 0.0027 | 1.669 |
| Valley View Road | 0.4633 | 1.57 | 75.4 | 4.64 | 3445000 | 0.0076 | 10.709 |
| West Danby Road (34) | 0.4691 | 1.57 | 67.8 | 6.75 | 3496000 | 0.0048 | 6.797 |
| Smiley Hill Road | 0.2157 | 1.05 | 65.4 | 7.50 | 699000 | 0.0014 | 0.867 |
| Ekroos Road (1) | 1.5546 | 2.37 | 69.9 | 6.11 | 17068000 | 0.0132 | 27.318 |
| Ekroos Road (2) | 1.5546 | 2.37 | 75.4 | 4.62 | 17068000 | 0.0172 | 35.455 |
| Vanostrand Road (1) | 0.2085 | 1.05 | 73.4 | 5.14 | 285000 | 0.0027 | 0.697 |
| Vanostrand Road (2) | 0.2995 | 1.24 | 75.4 | 4.62 | 518000 | 0.0046 | 1.499 |
| Douglas Road | 0.3125 | 1.27 | 67.2 | 6.92 | 647000 | 0.0028 | 1.081 |
| Fishkill Road | 0.8356 | 2.02 | 77.0 | 4.25 | 4584000 | 0.0137 | 14.278 |
| Thomas Road | 0.2312 | 1.06 | 73.0 | 5.25 | 543897.5 | 0.0027 | 1.191 |
| Curry Road (1) | 2.6547 | 2.76 | 83.8 | 2.76 | 29784863.3 | 0.0325 | 68.682 |
| Curry Road (2) | 2.6547 | 2.76 | 73.2 | 5.19 | 29784863.3 | 0.0207 | 43.691 |
| Genung Road | 0.1786 | 0.93 | 69.7 | 6.16 | 212638.0 | 0.0014 | 0.327 |
| 38 North | 0.3952 | 1.41 | 59.0 | 9.89 | 751096.6 | 0.0020 | 0.710 |

a. The calculations for the stream crossing qp values were the same as those performed for Cascadilla Creek using the CN Method with Synthetic Triangualar Hydrograph.
   Curve Number Equation

$$Q = (P - I_a)^2/(P - I_a + S)$$

$$Where:$$

$$Q = Runoff\ depth\ (in)$$

$$P = Rainfall\ depth\ (in)$$

$$I_a = Initial\ Abstraction\ (in)$$

$$S = Maximum\ Watershed\ Storage$$

   Using $I_a = 0.05S$ because it is recognized as more accurate than $I_a = 0.2S$

$$I_a = 0.05S$$

   Find volume of watershed

$$Q_v = volume\ of\ watershed\ (m^3)$$

$$Q_v = A \cdot Q$$

   Use volume of watershed ( $Q_v$ ) and the runoff depth ( $Q$ ) to find peak discharge ( $q_p$ )

$$q_p = 2 \cdot Q_v/(2.94 \cdot t_c)$$

b. This analysis resulted in the composite Synthetic Triangular Hydrograph seen in Fig. B.7. See MATLAB Appendix: Code for Peak Discharge Analysis for Tompkins County Stream Crossings. In order to run this code, download data set (1) and data set (2).

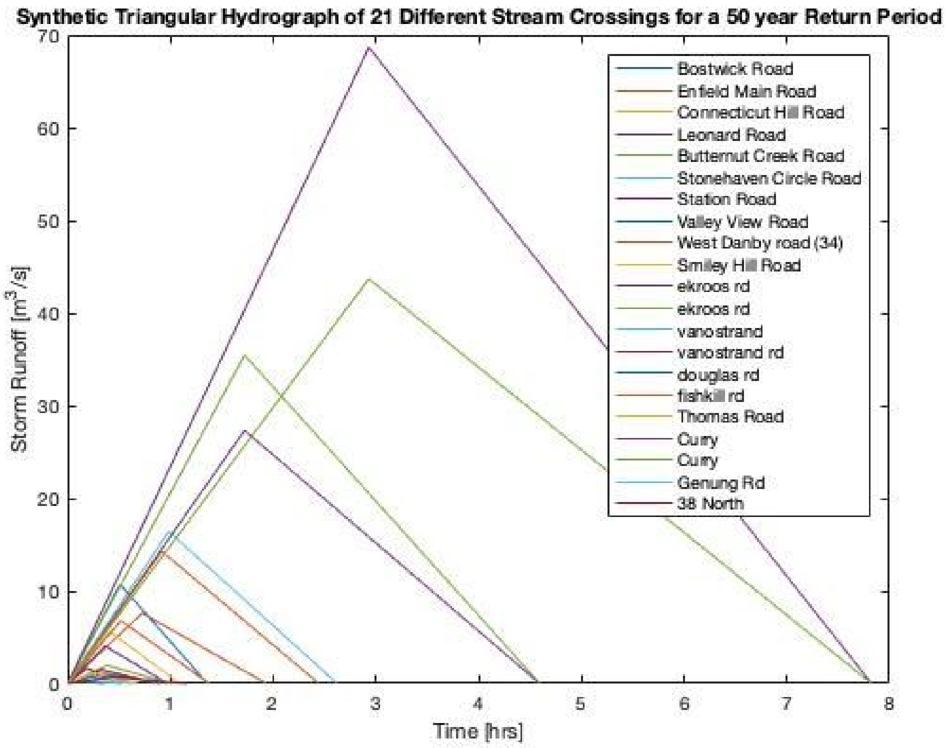


**Fig B.7:** Synthetic Triangular hydrographs for each Tompkins County Stream Crossing.