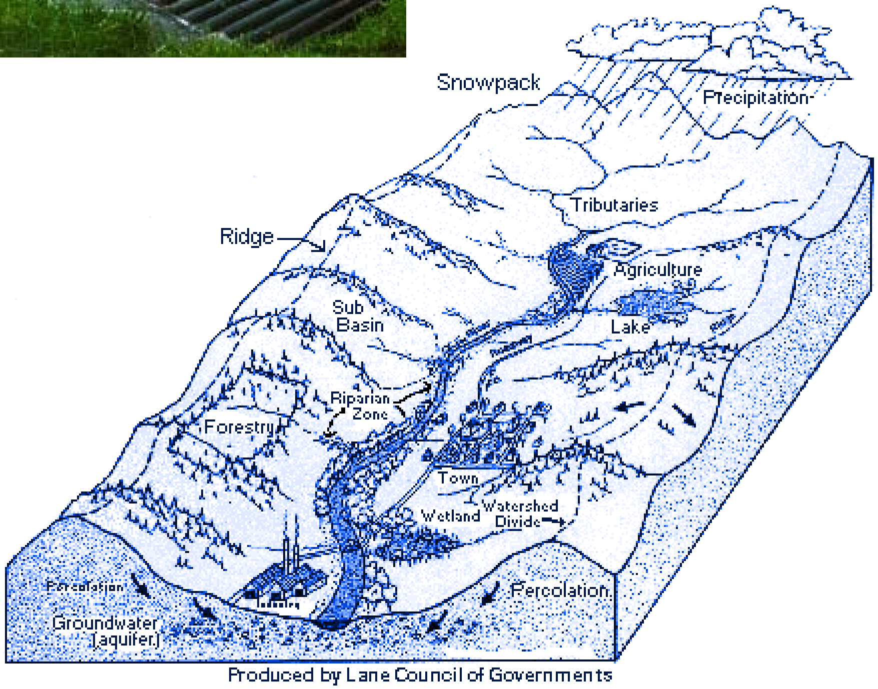
CE 374 K – Hydrology

Runoff Processes

Daene C. McKinney

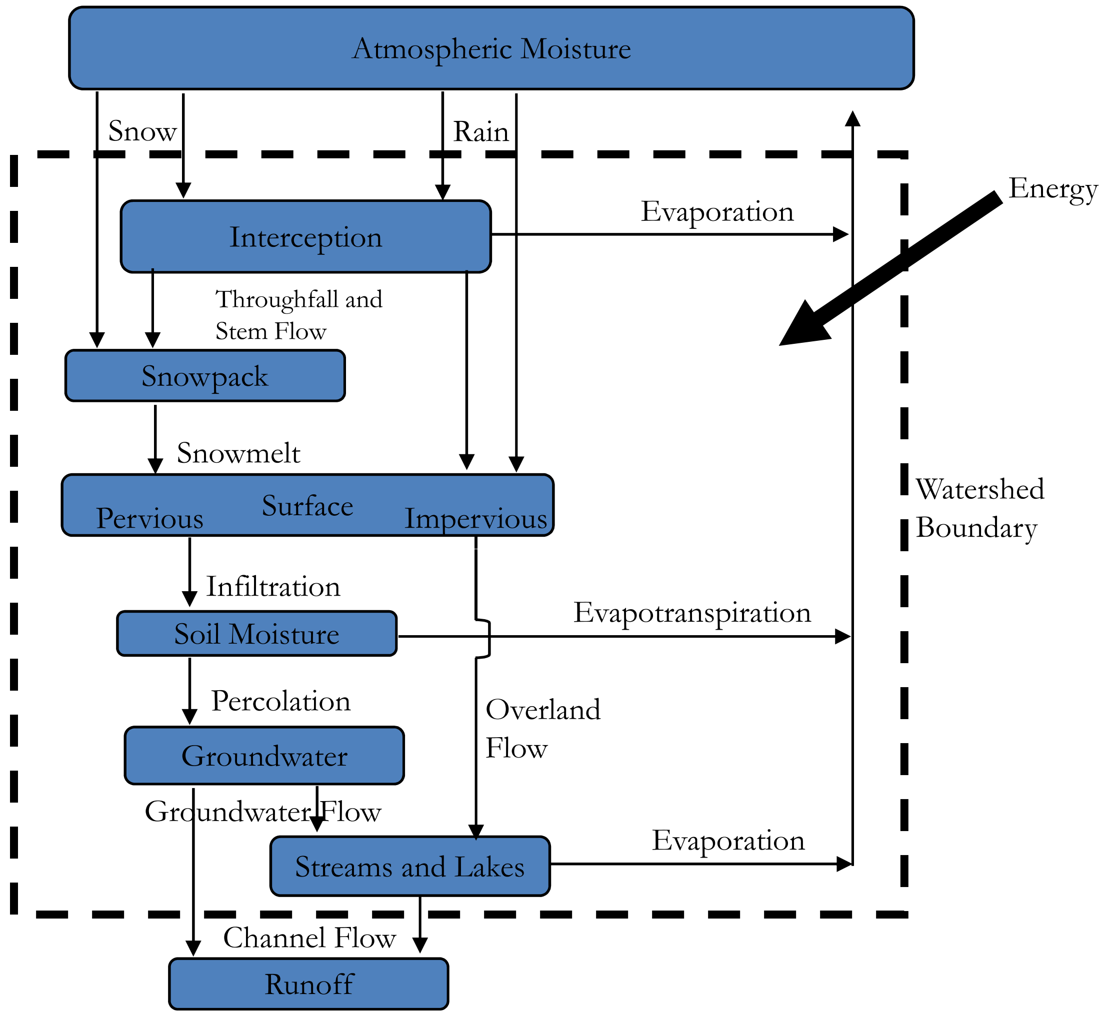
Watershed

- Watershed
  - Area draining to a stream
  - Streamflow generated by water entering surface channels
  - Affected by
    - Physical, vegetative, and climatic features
    - Geologic considerations
    - Stream Patterns
  - Dry periods
    - Flow sustained from groundwater (baseflow)

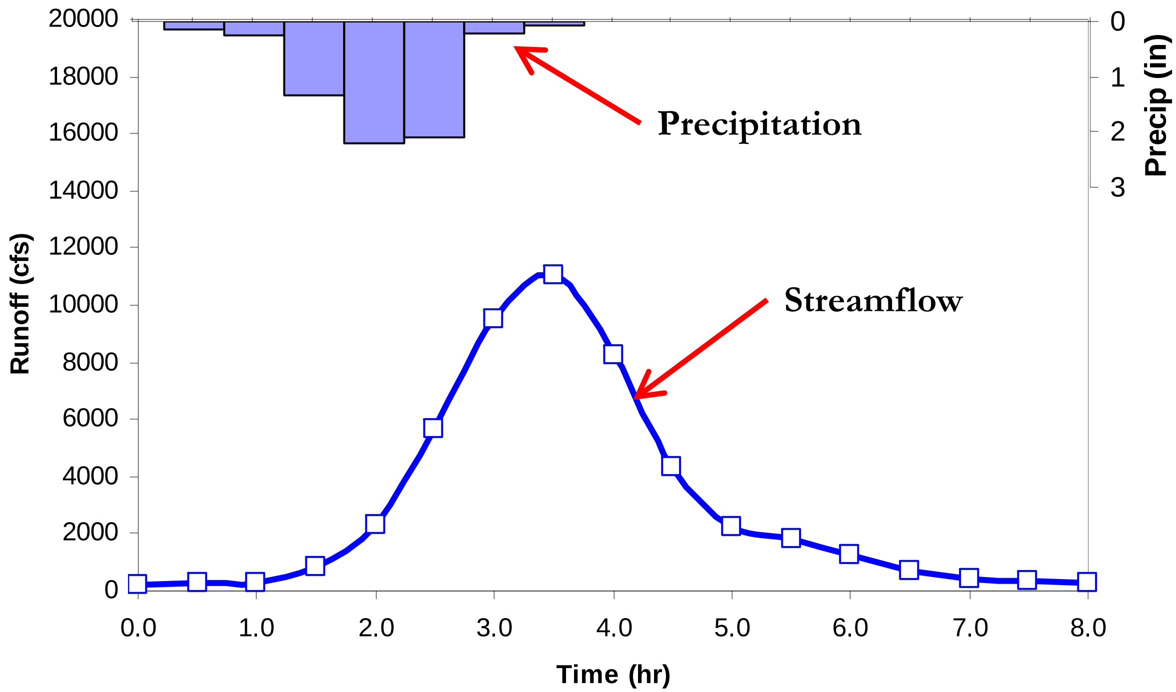


Streamflow

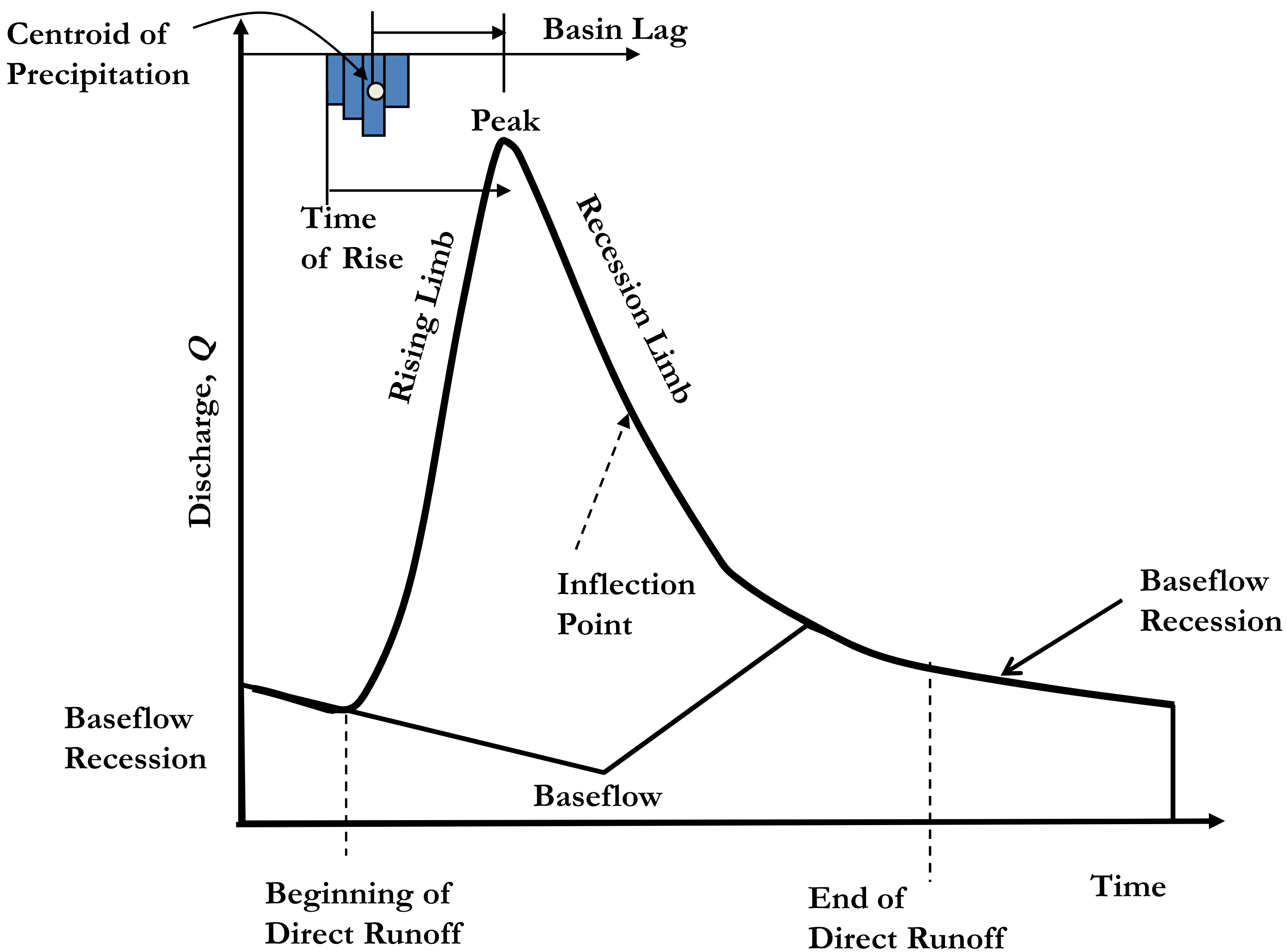
- Atmospheric Water
  - Evapotranspiration
  - Precipitation
- Subsurface Water
  - Infiltration
  - Groundwater
- <u>**Surface Water**</u>



Shoal Creek Flood - 1981



Streamflow Hydrograph



Volume of Storm Runoff

- Depends on several factors
  - Large watersheds – previous storm events
  - Small watersheds – independent of previous storm
- Rainfall available for runoff – 3 parts
  - Direct runoff
  - Initial loss (before direct runoff begins)
  - Continuing loss (after direct runoff)

Baseflow Separation

- Depletion of groundwater during this period
- Continuity equation

$$\frac{dS}{dt} = I(t) - Q(t)$$

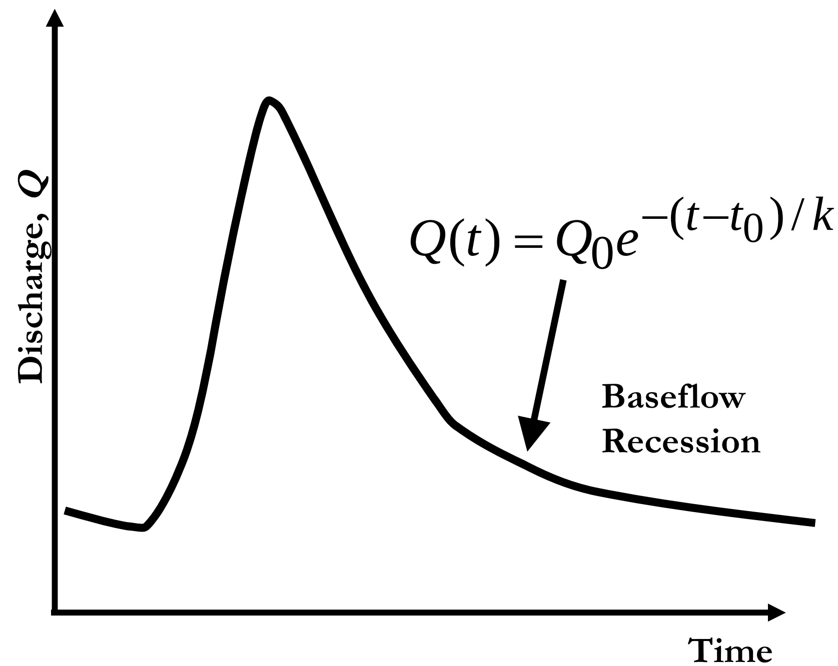
$$dS = -Q_0 e^{-(t-t_0)/k} dt$$

$$S(t) = kQ(t)$$

$Q(t) =$ flow at time t

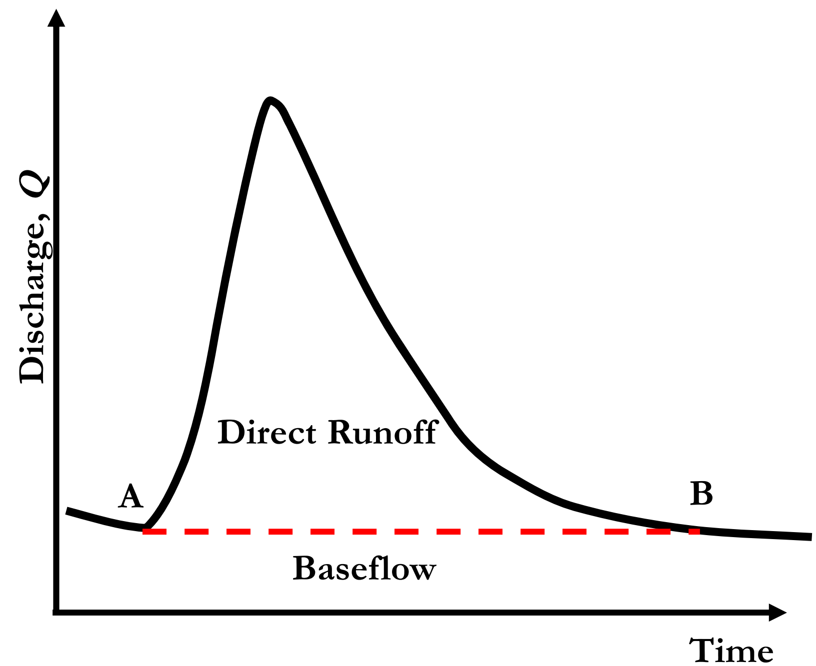
$Q_0 =$ flow at time t_0

$k =$ decay constant $[T]$



Baseflow Separation Techniques

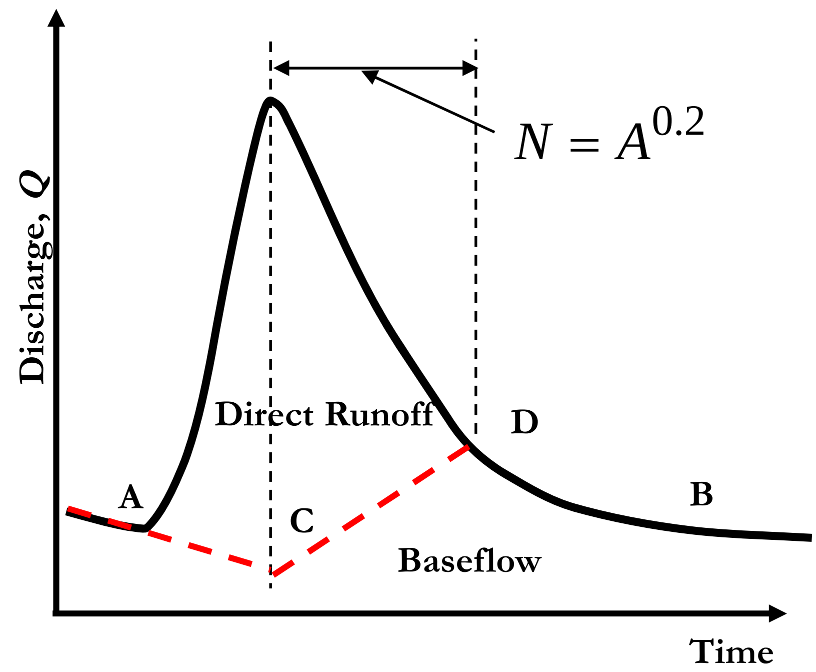
- **Straight – line method**
  - Draw a horizontal line segment (A-B) from beginning of runoff to intersection with recession curve



Baseflow Separation Techniques

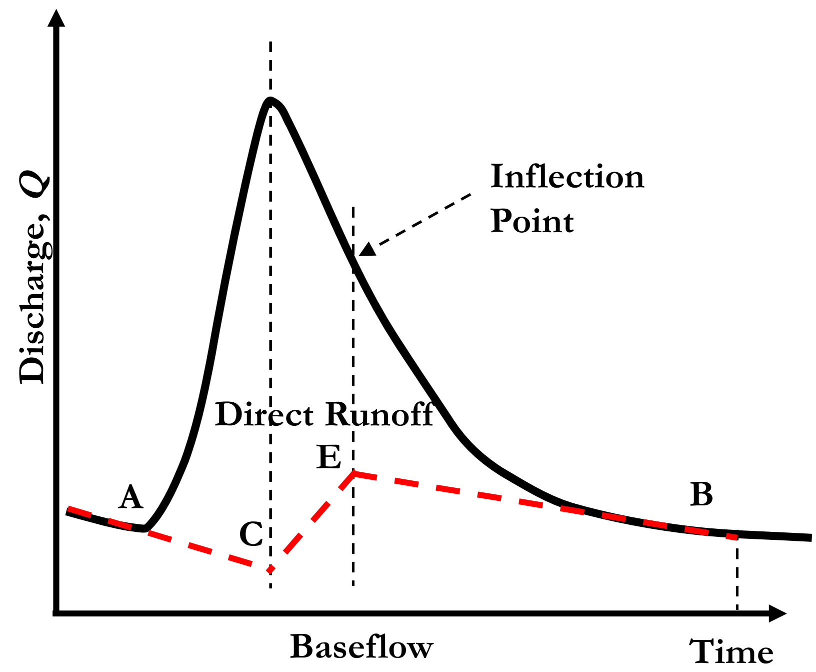
- **Fixed Base Method**
  - Draw line segment (A – C) extending baseflow recession to a point directly below the hydrograph peak
  - Draw line segment (C-D) connecting a point N time periods after the peak

$$N = A^{0.2}$$



Baseflow Separation Techniques

- **Variable Slope Method**
  - Draw line segment (A-C) extending baseflow recession to a point directly below the hydrograph peak
  - Draw line segment (B-E) extending baseflow recession backward to a point directly below the inflection point
  - Draw line segment (C-E)



Loss Estimation: Phi – Index Method

- Effective (excess) rainfall
  - Rainfall that is not retained or infiltrated
  - Becomes direct runoff
  - Excess rainfall hyetograph (excess rainfall vs time)
- Losses (abstraction)
  - Difference between total and excess rainfall hyetographs
- Phi – Index
  - Constant rate of loss yielding excess rainfall hyetograph with depth equal to depth of direct runoff

$$r_d = \sum_{m=1}^{M} \left(R_m - \phi \Delta t\right)$$

r_d = depth of direct runoff

R_m = observed rainfall

ϕ = Phi index

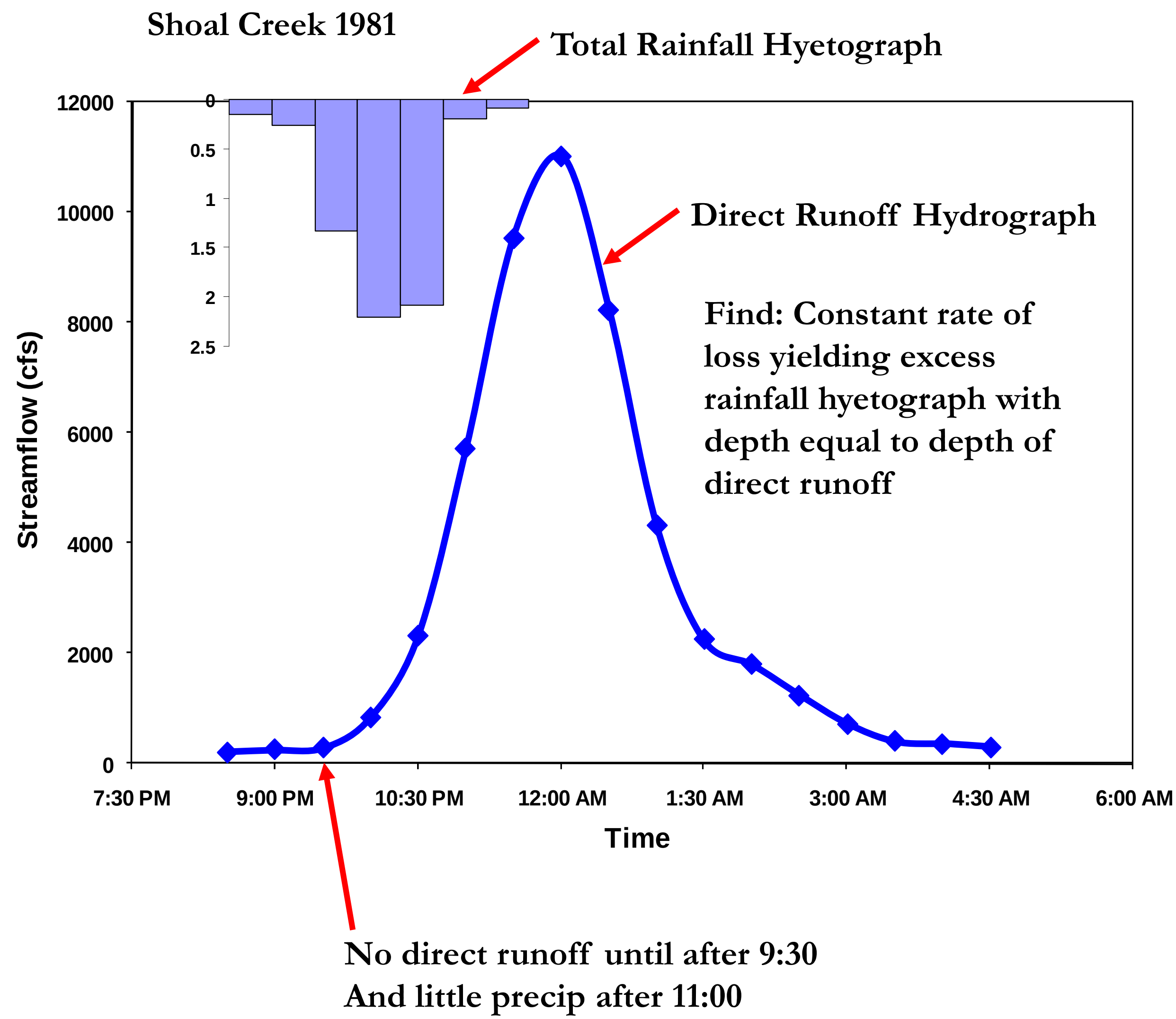
M = # intervals of rainfall contributing to direct runoff

Δt = time interval

m = interval index

Example – Phi Index method

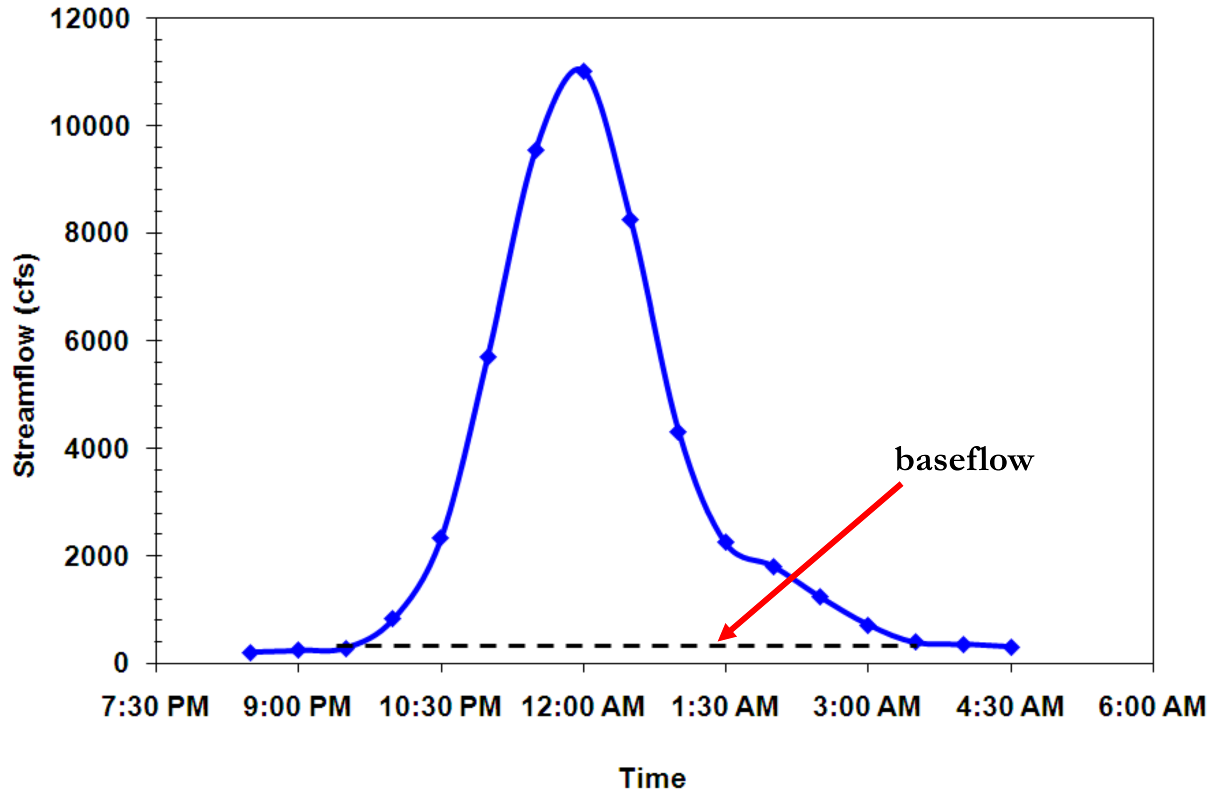
Time	Observed Rain	Flow
	in	cfs
8:30		203
9:00	0.15	246
9:30	0.26	283
10:00	1.33	828
10:30	2.2	2323
11:00	0.2	5697
11:30	0.09	9531
12:00		11025
12:30		8234
1:00		4321
1:30		2246
2:00		1802
2:30		1230
3:00		713
3:30		394
4:00		354
4:30		303



Basin area A = 7.03 mi2

Example – Phi Index Method (Cont.)

- Estimate baseflow (straight line method)
  - Constant = 400 cfs



Example – Phi Index Method (Cont.)

- Calculate Direct Runoff Hydrograph
  - Subtract 400 cfs

Date	Time	Observed Rainfall in	Observed Streamflow cfs	Time 1/2 hr	Direct Runoff cfs	Direct Runoff m3	
24-May	8:30 PM	0.15	203				
	9:00 PM	0.26	246				
	9:30 PM	1.33	283		428	770,400	
	10:00 PM	2.2	828	1	1,923	3,461,400	
	10:30 PM	2.08	2323	2	5,297	9,534,600	
	11:00 PM	0.2	5697	3	9,131	16,435,800	
	11:30 PM	0.09	9531	4	10,625	19,125,000	
25-May	12:00 AM		11025	5	7,834	14,101,200	
	12:30 AM		8234	6	3,921	7,057,800	
	1:00 AM		4321	7	1,846	3,322,800	
	1:30 AM		2246	8	1,402	2,523,600	
	2:00 AM		1802	9	830	1,494,000	
	2:30 AM		1230	10	313	563,400	
	3:00 AM		713	11			
	3:30 AM		394				
	4:00 AM		354				
	4:30 AM		303		**Total**	7.839E+07	**Volume of direct runoff**

$$r_d = \frac{V_d}{A} = \frac{7.839 * 10^7 \text{ ft}^3}{7.03 \text{mi} * 5280^2 \text{ ft}^2} = 4.80 \text{in}$$ **Depth of direct runoff**

Example – Phi Index Method (Cont.)

- Neglect all precipitation intervals that occur before the onset of direct runoff (before 9:30)
- Select R_m as the precipitation values in the 1.5 hour period from 10:00 – 11:30

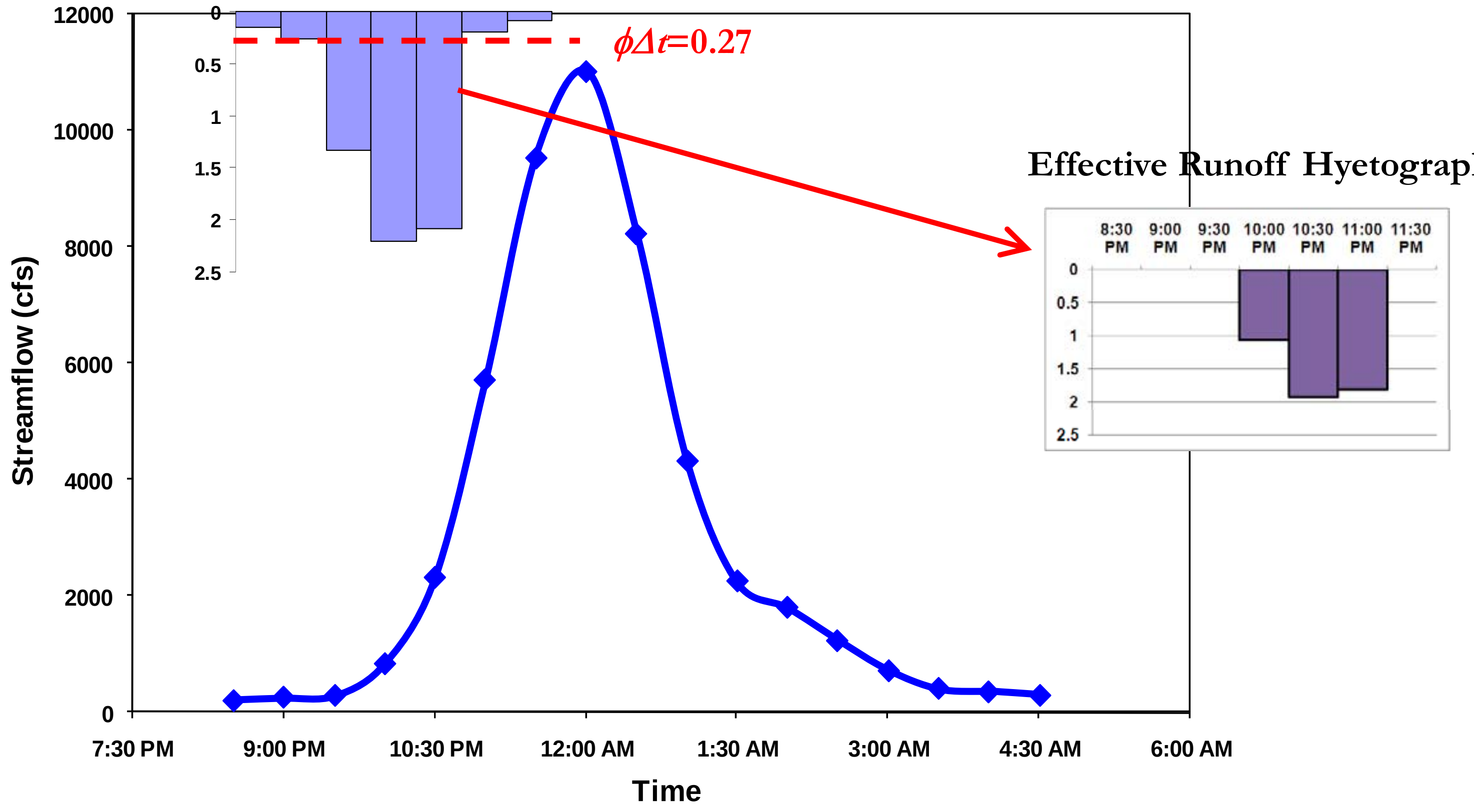
$$r_d = \sum_{m=1}^{M}\left(R_m - \phi\Delta t\right) = \sum_{m=1}^{3}\left(R_m - \phi 3 * 0.5\right)$$

$$4.80 = (1.33 + 2.20 + 2.08 - \phi * 3 * 0.5)$$

$$\phi = 0.54\,\text{in}$$

$$\phi\Delta t = 0.54 * 0.5 = 0.27\,\text{in}$$

Example – Phi Index Method (Cont.)

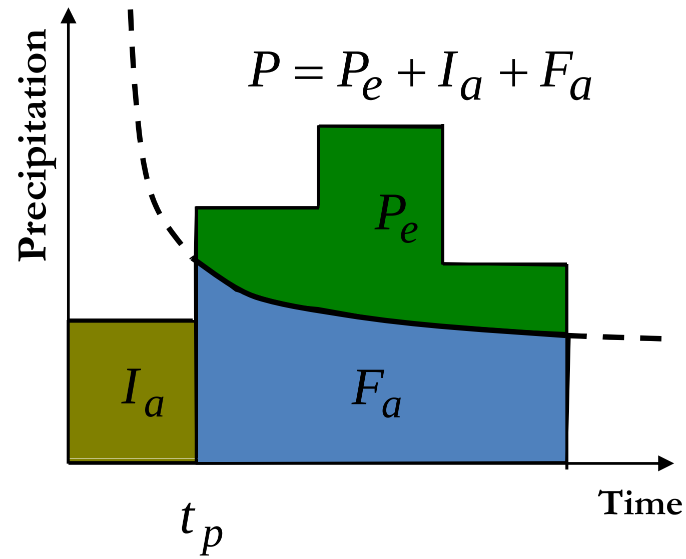


SCS Curve Number Method

- SCS Curve Number (CN) method
  - estimates excess precipitation as a function of
    - cumulative precipitation
    - soil cover
    - land use, and
    - antecedent moisture
- Developed for small basins (< 400 sq. mi.)
- Classify soils into four types
- Simple to use
- Converts basin storage into something simpler and more manageable (a “curve number” CN)

Losses – SCS Method

- Total rainfall separated into 3 parts:
  - Direct runoff
  - Continuing Loss
  - Initial Loss



- SCS Assumption

$$\frac{\text{Actual Storage}}{\text{Potential Storage}} = \frac{\text{Actual Runoff}}{\text{Potential Runoff}}$$

$$\frac{(P - I_a) - P_e}{S} = \frac{P_e}{P - I_a}$$

- Solve for Rainfall Excess

$$P_e = \frac{(P - I_a)^2}{P - I_a + S}$$

$P =$ Total Rainfall

$P_e =$ Excess Rainfall (Runoff)

$I_a =$ Initial Loss

$F_a =$ Continuing Loss

$S =$ Maximum Watershed Storage

SCS Method (Cont.)

- Experiments showed

$$I_a = 0.2S$$

- So

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S}$$

$$S = \frac{1000}{CN} - 10$$

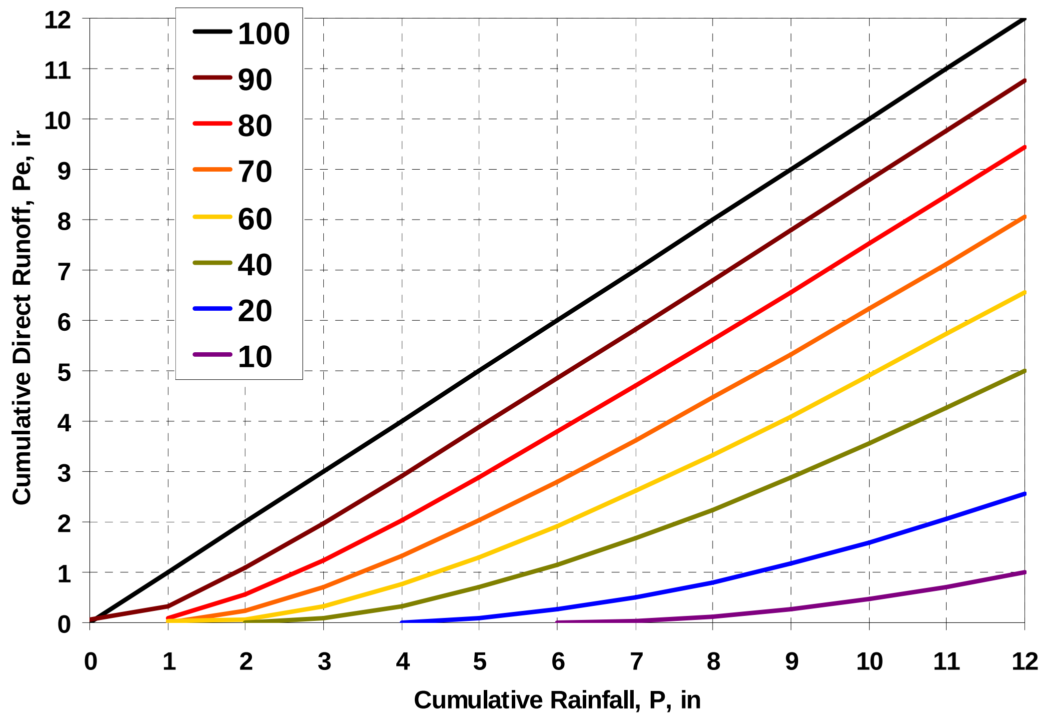
(American Units; $0 < \text{CN} < 100$)

$$S = \frac{25400}{CN} - 254CN$$

(SI Units; $30 < \text{CN} < 100$)

- Surface
  - Impervious: CN = 100
  - Natural: CN < 100

CN, Curve Number



SCS Method (Cont.)

- *CN* depends on previous (antecedent) rainfall
- Normal conditions, AMC(II)
- Dry conditions, AMC(I) $$CN(I) = \frac{4.2CN(II)}{10 - 0.058CN(II)}$$
- Wet conditions, AMC(III) $$CN(III) = \frac{23CN(II)}{10 + 0.13CN(II)}$$

	5-day antecedent rainfall (in)	
AMC Group	**Dormant season**	**Growing season**
I	< 0.50	< 1.4
II	0.5 -- 1.1	1.4 – 2.1
III	> 1.1	> 2.1

SCS Method (Cont.)

- *CN* depends on soil conditions

Group	Minimum Infiltration Rate (in/hr)	Soil type
A	0.3 – 0.45	High infiltration rates. Deep, well drained sands and gravels
B	0.15 – 0.30	Moderate infiltration rates. Moderately deep, moderately well drained soils with moderately coarse textures
C	0.05 – 0.15	Slow infiltration rates. Soils with layers, or soils with moderately fine textures
D	0.00 – 0.05	Very slow infiltration rates. Clayey soils, high water table, or shallow impervious layer

Example - SCS Method (1)

- Rainfall: 5 in.
- Area: 1000-acres
- Soils:
  - Class B: 50%
  - Class C: 50%
- Antecedent moisture: AMC(II) - Normal
- Land use
  - Residential
    - 40% with 30% impervious cover
    - 12% with 65% impervious cover
  - Paved roads: 18% with curbs and storm sewers
  - Open land: 16%
    - 50% fair grass cover
    - 50% good grass cover
  - Parking lots, etc.: 14%

Example (SCS Method 1, Cont.)

	Hydrologic Soil Group					
	B			C		
Land use	**%**	**CN**	**Product**	**%**	**CN**	**Product**
Residential (30% imp cover)	20	72	14.40	20	81	16.20
Residential (65% imp cover)	6	85	5.10	6	90	5.40
Roads	9	98	8.82	9	98	8.82
Open land: good cover	4	61	2.44	4	74	2.96
Open land: Fair cover	4	69	2.76	4	79	3.16
Parking lots, etc	7	98	6.86	7	98	6.86
Total	50		40.38	50		43.40

$$CN = 40.38 + 43.40 = 83.8$$

Example (SCS Method 1 Cont.)

- Average AMC

$$CN = 83.8 \qquad S = \frac{1000}{CN} - 10$$

$$S = \frac{1000}{83.8} - 10 = 1.93\,\text{in}$$

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S} = \frac{(5 - 0.2*1.93)^2}{5 + 0.8*1.93} = 3.25\,\text{in}$$

- Wet AMC

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S} = \frac{(5 - 0.2*0.83)^2}{5 + 0.8*0.83} = 4.13\,\text{in}$$

Example (SCS Method 2)

- Given P, CN = 80, AMC(II)
- Find: Cumulative abstractions and excess rainfall hyetograph

Time (hr)	Cumulative Rainfall (in)	Cumulative Abstractions (in)		Cumulative Excess Rainfall (in)	Excess Rainfall Hyetograph (in)
	P	Ia	Fa	Pe	
0	0				
1	0.2				
2	0.9				
3	1.27				
4	2.31				
5	4.65				
6	5.29				
7	5.36				

Example (SCS Method – 2)

- Calculate storage $$S = \frac{1000}{CN} - 10 = \frac{1000}{80} - 10 = 2.50\,\text{in}$$
- Calculate initial abstraction $$I_a = 0.2S = 0.2 * 2.5 = 0.5\,\text{in}$$
- Initial abstraction removes
  – 0.2 in. in 1st period (all the precip)
  – 0.3 in. in the 2nd period (only part of the precip)
- Calculate continuing abstraction from SCS method equations

$$F_a = \frac{S(P - I_a)}{(P - I_a + S)} = \frac{2.5(P - 0.5)}{(P + 2.0)}$$

Time (hr)	Cumulative Rainfall (in)
	P
0	0
1	0.2
2	0.9
3	1.27
4	2.31
5	4.65
6	5.29
7	5.36

Example (SCS method –2, Cont.)

- Cumulative abstractions can now be calculated

Time (hr)	Cumulative Rainfall (in)	Cumulative Abstractions (in)	
	P	I_a	F_a
0	0	0	-
1	0.2	0.2	-
2	0.9	0.5	0.34
3	1.27	0.5	0.59
4	2.31	0.5	1.05
5	4.65	0.5	1.56
6	5.29	0.5	1.64
7	5.36	0.5	1.65

$$F_a = \frac{2.5(P-0.5)}{(P+2.0)}$$

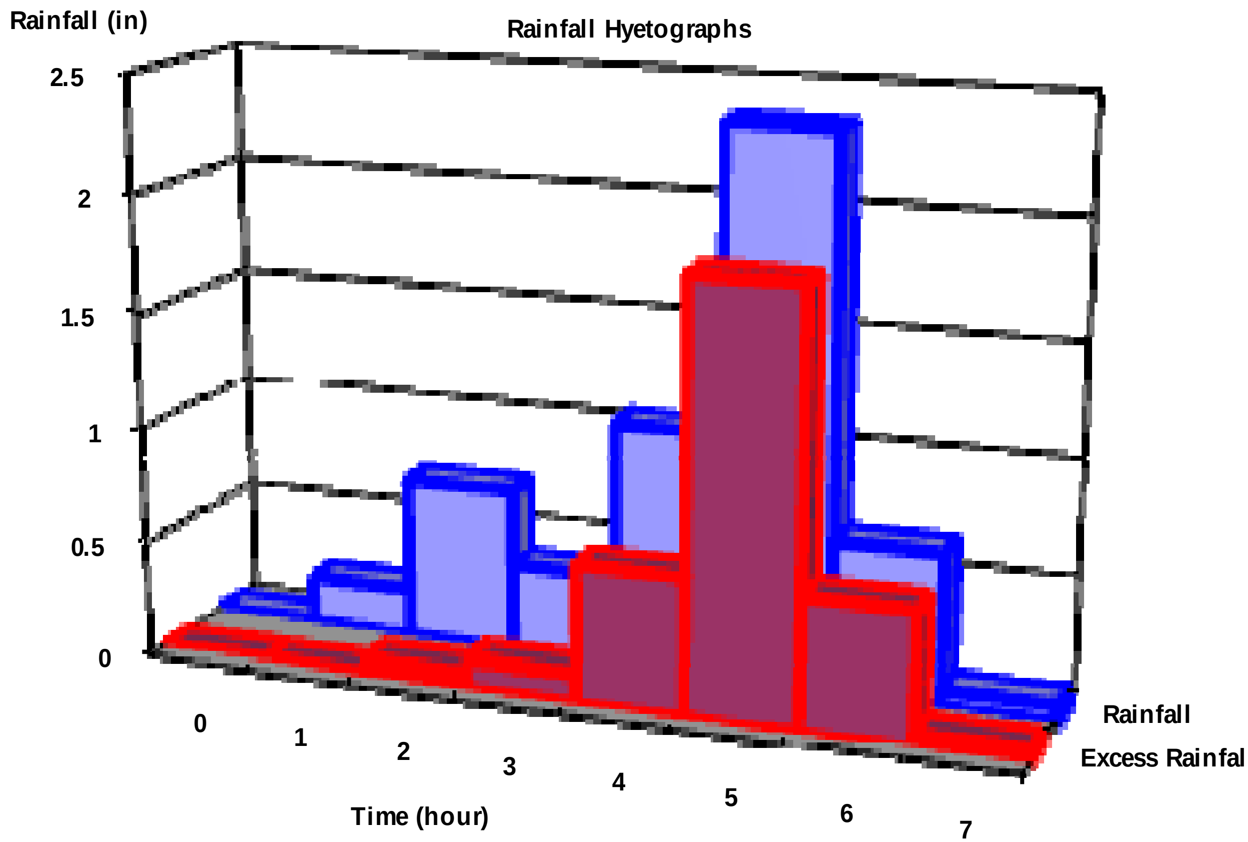
$$F_a(2\,\text{hr}) = \frac{2.5(0.9-0.5)}{(0.9+2.0)} = 0.34\,\text{in}$$

Example (SCS method 2, Cont.)

- Cumulative excess rainfall can now be calculated
- Excess Rainfall Hyetograph can be calculated

Time (hr)	Cumulative Rainfall (in)	Cumulative Abstractions (in)		Cumulative Excess Rainfall (in)	Excess Rainfall Hyetograph (in)
	P	I_a	F_a	P_e	ΔP_e
0	0	0	-	0	0
1	0.2	0.2	-	0	0
2	0.9	0.5	0.34	0.06	0.06
3	1.27	0.5	0.59	0.18	0.12
4	2.31	0.5	1.05	0.76	0.58
5	4.65	0.5	1.56	2.59	1.83
6	5.29	0.5	1.64	3.15	0.56
7	5.36	0.5	1.65	3.21	0.06

Example (SCS method 2, Cont.)



Time of Concentration

- Different areas of a watershed contribute to runoff at different times after precipitation begins
- Time of concentration
  - Time at which all parts of the watershed begin contributing to the runoff from the basin
  - Time of flow from the farthest point in the watershed