Solutions Chapter 2

2.1. a) Explain the concept of the time-area method.

b) What physical factors affect the shape and timing of the UH?

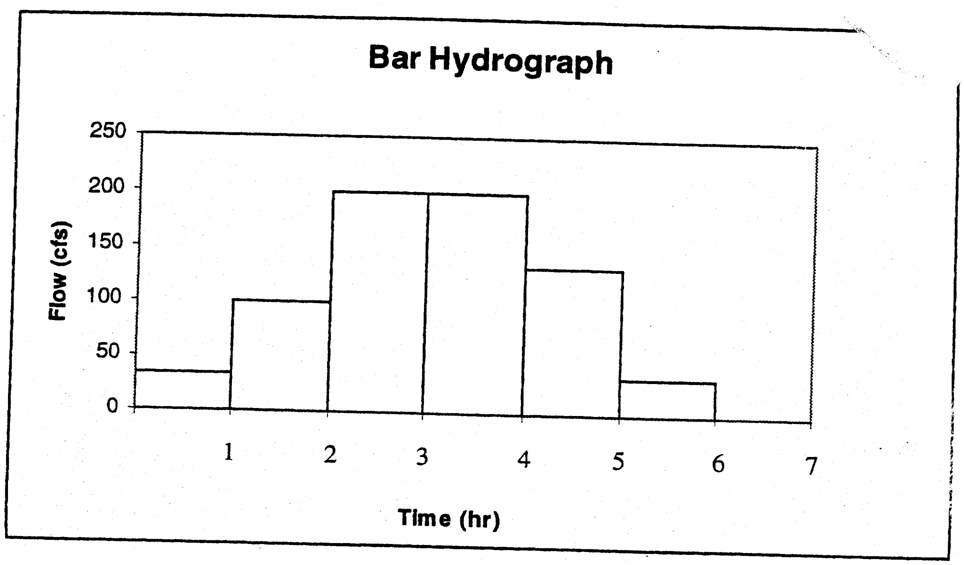
c) Rework Example 2.2 for a rainfall intensity of 0.33 in./hr falling uniformly for 3 hr. Develop the bar hydrograph.

a) The time- area method is used to construct an outflow hydrograph from a basin based on the arrival times of contributing areas and the rainfall. This method uses hydrograph convolution analogues to the until hydrograph times precipitation method except that a time- area histogram is used to weight the rainfall.

b) Basin size and shape as well as storage, types of lands use, slope, soil types, and percent imperviousness all affect the shape and timing of the unit hydrograph.

c)

Time (hr)	Hyetograph Ordinate (in/hr)	Basin	Time to Gage	Area (ac)	R_1 A_n (cfs)	R_1 A_n (cfs)	R_1 A_n (cfs)	Storm Hydrograph (cfs)
0								0
1	0.33	A	1	100	33.34			33.34
2	0.33	B	2	200	66.67	33.34		100
3	0.33	C	3	300	100	66.67	33.34	200
4		D	4	100	33.34	100	66.67	200
5						33.34	100	133.34
6							33.34	33.34
7								0

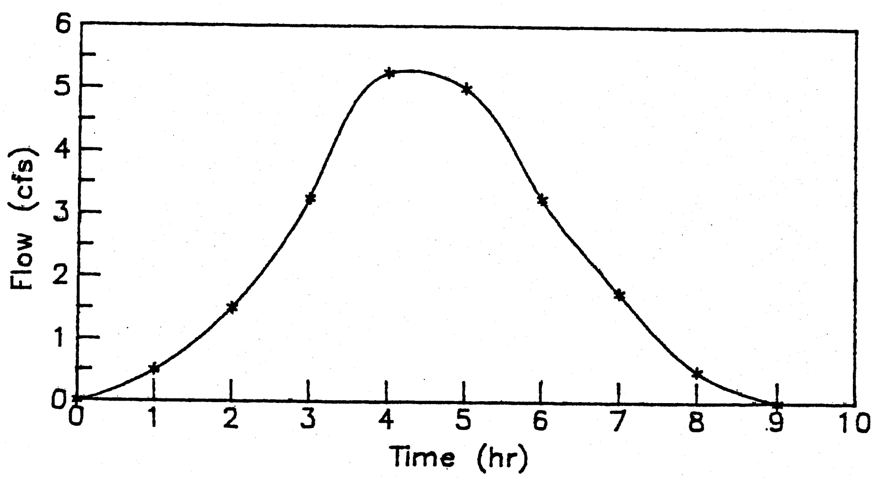


2.2. Determine the storm hydrograph resulting from the rainfall pattern in Fig. P2.2 (a) using the triangular 1-hr UH given in Fig. P2.2 (b).

Since the rainfall is given as net rainfall, we do not need to subtract any losses. The rainfall for each time period is multiplied by the unit hydrograph ordinates to obtain the storm hydrograph. This computational procedure is tabulated below.

Time (hrs)	UH		R_1U (cfs)	R_2U (cfs)	R_3U (cfs)	R_4U (cfs)		Q (cfs)
0	0		0	-	-	-		0
1	0.50		0.50	0	-	-		0.50
2	1.00		1.00	0.50	0	-		1.50
3	0.75		0.75	1.00	1.50	0		3.25
4	0.50		0.50	0.75	3.00	1.00		5.25
5	0.25		0.25	0.50	2.25	2.00		5.00
6	0		0	0.25	1.50	1.50		3.25
7			-	0	0.75	1.00		1.75
8			-	-	0	0.50		0.50
9			-	-	-	0		0

The storm hydrograph may then be plotted.



2.3. a) Given a triangular 1-hr UH with

T_B = 12 hr,

T_R = 4 hr,

Q_P = 200 cfs,

where

T_B = time base of the UH,

T_R = time of rise,

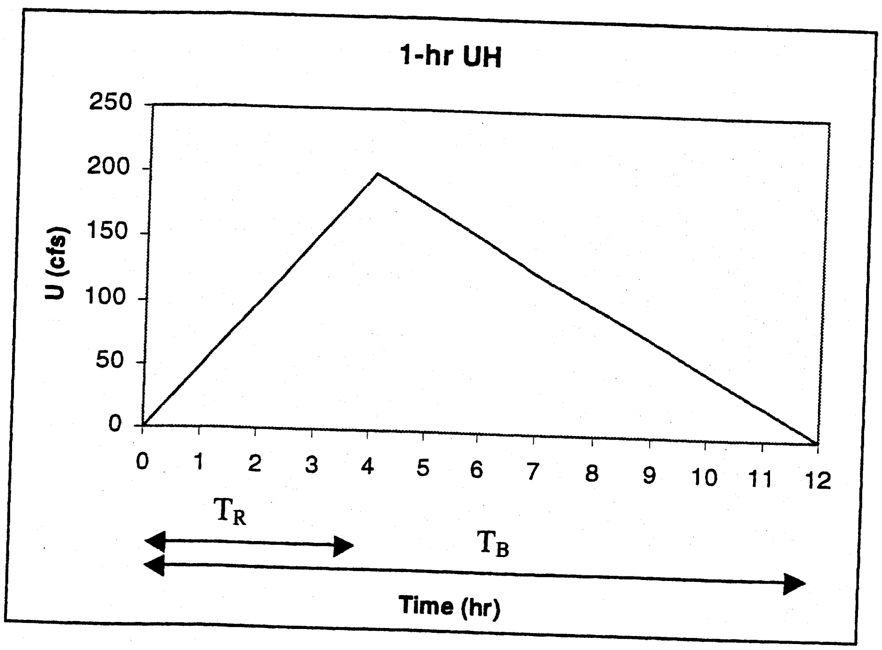
Q_P = peak flow,

Develop a storm hydrograph for hourly rainfall (in.) of P = [0.1, 0.5, 1.2].

b) Repeat the above problem for hourly rainfall (in.) of P = [0.2, 1.0, 2.4].

The UH ordinates are derived using 1 –hr time intervals:

U = [0, 50, 100, 150, 200, 175, 150, 125, 100, 75, 50, 25, 0] cfs



The storm hydrograph is developed for both cases (a) and (b) with the use of the convolution equation.

2.3. (cont) It is interesting to notice that in each time step, the precipitation (P_i) of the second rainfall is double the precipitation of the first rainfall. As expected, the resulting storm hydrograph of case (b) is double the storm hydrograph of case (a)

a)

Time	U (cfs)	P1*U	P2*U	P3*U	Q (cfs)
0	0	0			0
1	50	5	0		5
2	100	10	25	0	35
3	150	15	50	60	125
4	200	20	75	120	215
5	175	17.5	100	180	297.5
6	150	15	87.5	240	342.5
7	125	12.5	75	210	297.5
8	100	10	62.5	180	252.5
9	75	7.5	50	150	207.5
10	50	5	37.5	120	162.5
11	25	2.5	25	90	117.5
12	0	0	12.5	60	72.5
13			0	30	30
14				0	0

b)

Time	U (cfs)	P1*U	P2*U	P3*U	Q (cfs)
0	0	0			0
1	50	10	0		10
2	100	20	50	0	70
3	150	30	100	120	250
4	200	40	150	240	430
5	175	35	200	360	595
6	150	30	175	480	685
7	125	25	150	420	595
8	100	20	125	360	505
9	75	15	100	300	415
10	50	10	75	240	325
11	25	5	50	180	235
12	0	0	25	120	145
13			0	60	60
14				0	0

2.4. A small watershed has the characteristics given below. Find the peak discharge Q_P, the basin lag time t_p, and the time base of the unit hydrograph T_B, using Snyder's method.

$A = 150\ \text{mi}^2$,

$C_t = 1.70$,

$L = 27\ \text{mi}$,

$L_{ca} = 15\ \text{mi}$,

$C_p = 0.7$

Snyder's Method uses Eqs. 2.10 through 2.12. Equation 2.10 gives:

$$t_p = C_t\,(LL_c)^{0.3}$$
$$= (1.70)\,[(27)(15)]^{0.3}$$

$t_p = 10.3$ hr

Equation 2.11 gives:

$$Q_p = 640\ C_p\ A/t_p$$
$$= (640)(0.7)(150)/10.3$$

$Q_p = 6524$ cfs

The time based is found using Eq. 2.12

$$T_B = 4t_p$$

$T_B = 41.2$ hr

2.5. A sketch of the Buffalo Creek Watershed is shown in Fig. P2.5. Areas *A* and *B* are identical in size, shape, slope, and channel length. UHs (1 hr) are provided for natural and fully developed conditions for both areas.

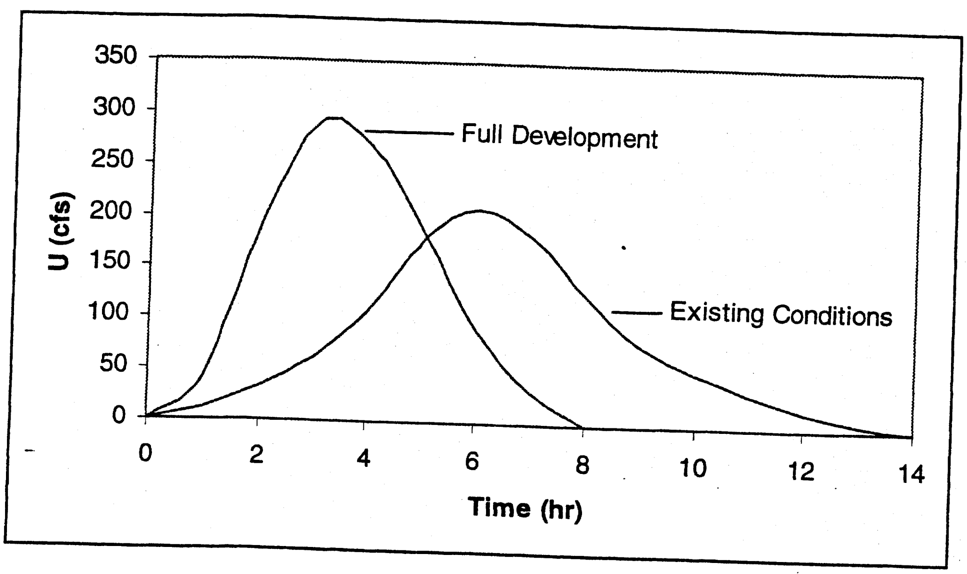
a) Assuming natural conditions for both areas, evaluate the peak outflow at point 1 if 2.5 in./hr of rain falls for 2 hr. Assume a total infiltration loss of 1 in.

b) Assume that area *B* has reached full development and area *A* has remained in natural conditions. Determine the outflow hydrograph at point 1 if a net rainfall of 2 in./hr falls for 1 hr.

c) Sketch the outflow hydrograph for the Buffalo Creek Watershed under complete development (*A* and *B* both urbanized) for the rainfall given in part (b).

Time (hr)	0	1	2	3	4	5	6	7	8
UH_{dev}(cfs)	0	40	196	290	268	185	90	30	0

Time (hr)	0	1	2	3	4	5	6	7	8
UH (nat)	0	12	32	62	108	180	208	182	126
Time (hr)	9	10	11	12	13	14			
UH (nat)	80	53	32	18	6	0			



2.5. (cont)

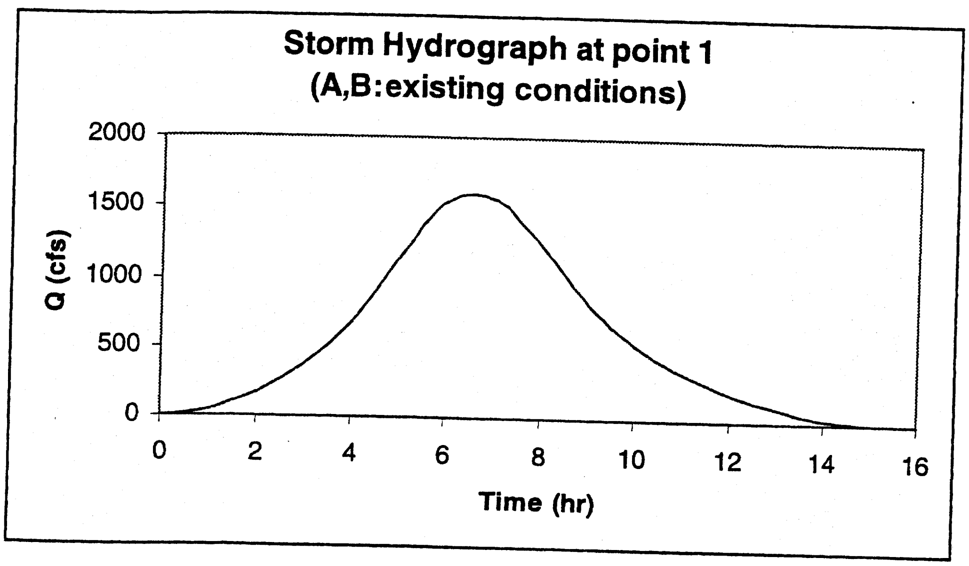
a) Assuming uniform loss, we get a loss rate of 0.5 in/hr.

Net rainfall intensity = 2.5 – 0.5 = 2 in/hr for 2 hours

The storm hydrograph at point 1 is found by combining the storm hydrographs for areas A and B.

Existing conditions for both areas } => $Q_A = Q_B$

Time (hr)	U_{exist}(cfs)	P1*U	P2*U	Q_A (cfs)	Q_B (cfs)	Q (cfs)
0	0	0		0	0	0
1	12	24	0	24	24	48
2	32	64	24	88	88	176
3	62	124	64	188	188	376
4	108	216	124	340	340	680
5	180	360	216	576	576	1152
6	208	416	360	776	776	1552
7	182	364	416	780	780	1560
8	126	252	364	616	616	1232
9	80	160	252	412	412	824
10	53	106	160	266	266	532
11	32	64	106	170	170	340
12	18	36	64	100	100	200
13	6	12	36	48	48	96
14	0	0	12	12	12	24
15	0	0	0	0	0	0



Qp = 1560 cfs at t = 7hr.

2.5. (cont)

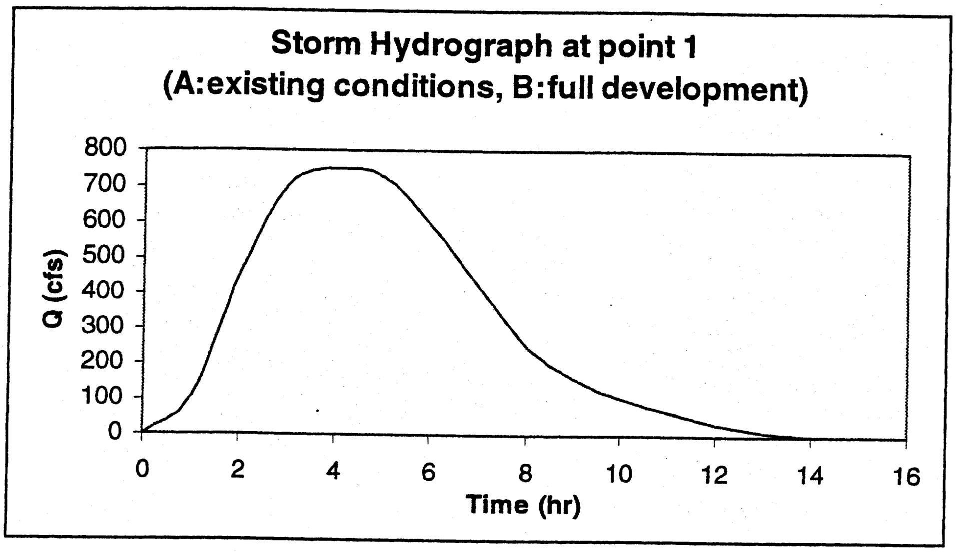
b) In this case we have to determine the storm hydrograph at point one for a 1 – hr duration rainfall.

$Q_A \rightarrow$ natural (existing) conditions

$Q_B \rightarrow$ full development

i = 2 in/ hr for 1 – hr.

Time (hr)	U_{exist}(cfs)	U_{devel} (cfs)	Q_A (cfs)	Q_B (cfs)	Q (cfs)
0	0	0	0	0	0
1	12	40	24	80	104
2	32	196	64	392	456
3	62	290	124	580	704
4	108	268	216	536	752
5	180	185	360	370	730
6	208	90	416	180	596
7	182	30	364	60	424
8	126	0	252	0	252
9	80		160		160
10	53		106		106
11	32		64		64
12	18		36		36
13	6		12		12
14	0		0		0



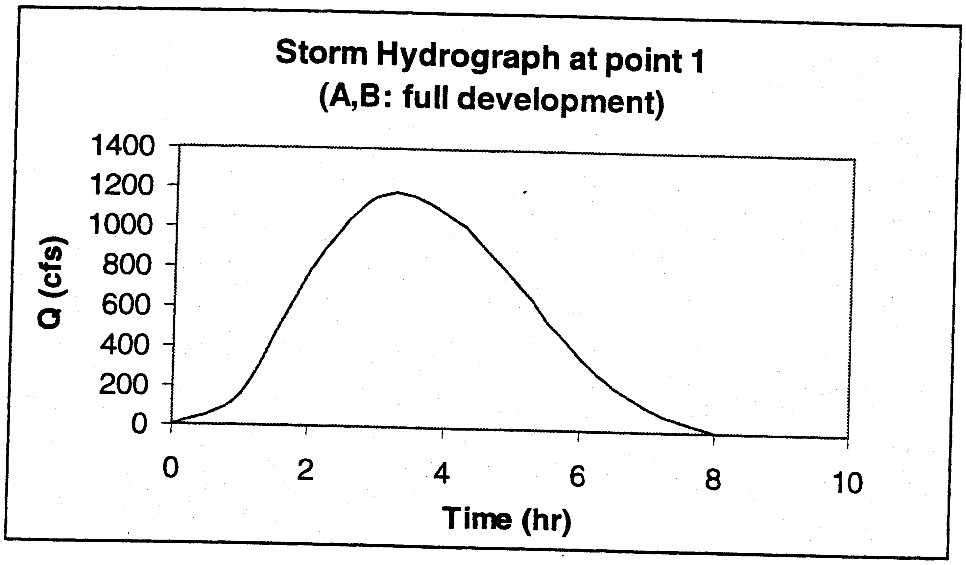
Q_p = 752 cfs at t = 4 hr

2.5. (cont)

c) Full Development for both areas} => $Q_A = Q_B$

i = 2in/ hr for 1 hr

Time (hr)	U_{devel} (cfs)	Q_A (cfs)	Q_B(cfs)	Q (cfs)
0	0	0	0	0
1	40	80	80	160
2	196	392	392	784
3	290	580	580	1160
4	268	536	536	1072
5	185	370	370	740
6	90	180	180	360
7	30	60	60	120
8	0	0	0	0



Q_P = 1160 cfs at t= 3 hr

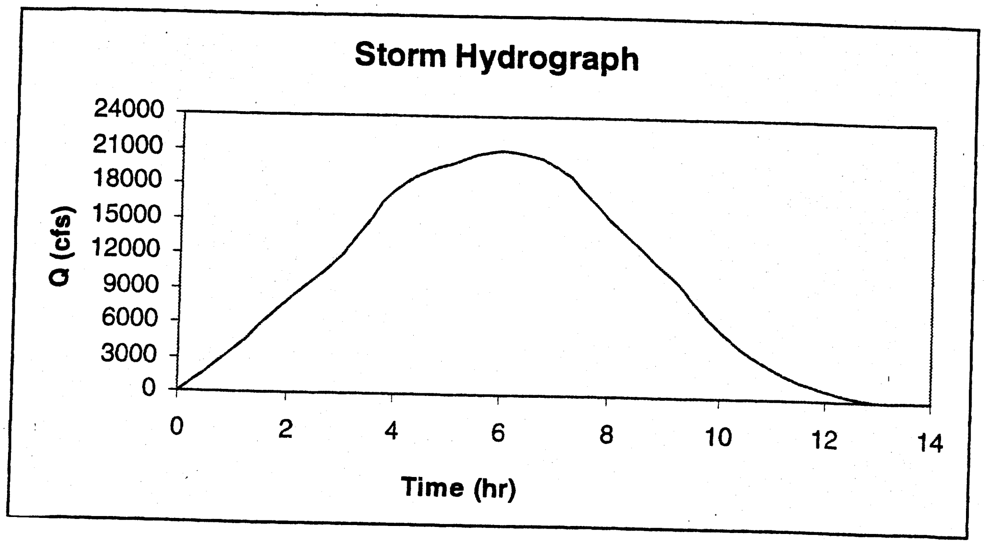
2.6. A watershed basin is approximately 43 square miles and has the following time-area relationship between its subbasins and the outlet.

TIME (hr)	AREA (sq mi)
1	9.5
2	6.7
3	5.2
4	8.0
5	6.6
6	7.0

STORM DATA

Time (hr)	Rainfall Excess (in./hr)
1	0.6
2	0.9
3	1.0
4	1.2
5	0.7
6	0.4
7	0.2

2.6. (cont) Use the storm measurements to produce an outflow hydrograph in cfs (ac-in/hr) using the time-area method. Use an Excel spreadsheet to perform calculations.



2.6. (cont)

Time (hr)	Area (mi^2)	Time to gage (hr)	Area (ac)	Intensity (in/hr)	R1*Area (cfs)	R2*Area (cfs)	R3*Area (cfs)	R4*Area (cfs)	R5*Area (cfs)	R6*Area (cfs)	R7*Area (cfs)	Q (cfs)
0												0
1	9.5	1	6080	0.6	3648							3648
2	6.7	2	4288	0.9	2572.8	5472						8045
3	5.2	3	3328	1	1996.8	3859.2	6080					11936
4	8	4	5120	1.2	3072	2995.2	4288	7296				17651
5	6.6	5	4224	0.7	2534.4	4608	3328	5145.6	4256			19872
6	7	6	4480	0.4	2688	3801.6	5120	3993.6	3001.6	2432		21037
7				0.2	0	4032	4224	6144	2329.6	1715.2	1216	19661
8						0	4480	5068.8	3584	1331.2	857.6	15322
9							0	5376	2956.8	2048	665.6	11046
10								0	3136	1689.6	1024	5850
11									0	1792	844.8	2637
12										0	896	896
13											0	0

2.7. The 1-hr UH in the accompanying table was recorded for a particular watershed. Determine the size of the watershed in acres and then convert the 1-hr UH into a 3-hr UH for the watershed.

TIME (hr)	0	1	2	3	4	5	6	7	8	9	10
U (cfs)	0	6	22	48	80	65	50	30	18	5	0

The area under the UH can be found by calculating the integral.

$$\int_0^{10} u(t)dt$$

Approximately, this equals to the sum

$$\sum_{L=1}^{10} u_i \Delta t \qquad \text{where } \Delta t = 1 \text{ hr}$$

By definition of the UH, the value of the area under the UH represents the direct run off of 1 in of rainfall excess over the watershed.

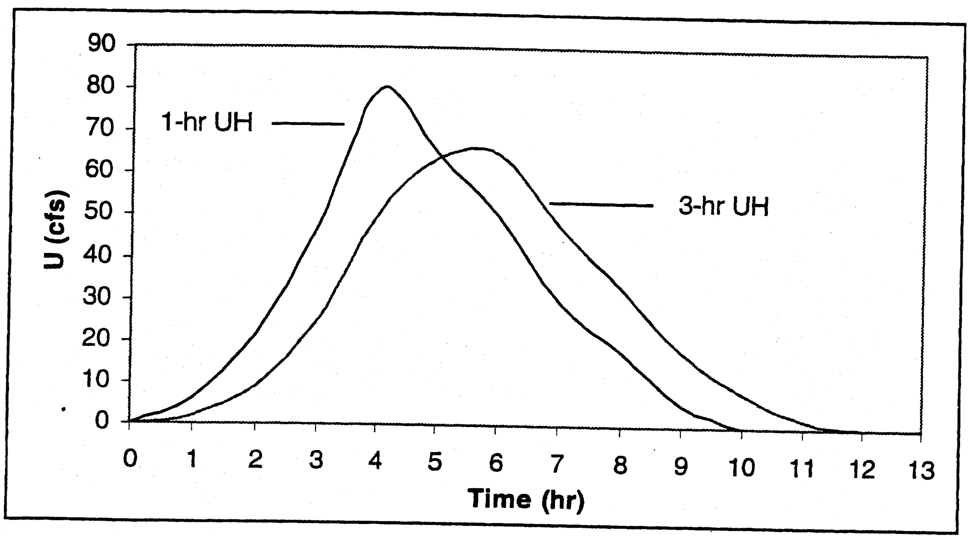
$$\sum_{L=1}^{10} u_i \Delta t = (1in)(Area) \Rightarrow Area = \frac{324ac - in}{1in} = 324ac$$

- ac-in≈cfs-hr

In order to calculate the 3 – hr UH, we add the ordinates of three 1 – hr UH's, the second and the third lagged by 1 – hr. Then we divide the result by 3.

2.7. (cont)

Time (hr)	1-hr UH (cfs)			3-hr UH (cfs)
0	0			0
1	6	0		2
2	22	6	0	9
3	48	22	6	25
4	80	48	22	50
5	65	80	48	64
6	50	65	80	65
7	30	50	65	48
8	18	30	50	33
9	5	18	30	18
10	0	5	18	8
11		0	5	2
12			0	0



2.8. The USGS recorded a major storm event on June 8-9, 2001 for Little Cypress Creek in Houston, TX. The incremental rainfall and measured hydrograph data for this storm are provided in Table P2-8 in 30-min increments. The drainage area for the basin is 3.35 mi^2. Assume base flow for Little Cypress is zero.

TIME (hr)	Precipitation (in)	Q (cfs)	TIME (hr)	Precipitation (in)	Q (cfs)	TIME (hr)	Precipitation (in)	Q (cfs)
15:30	0	0	3:30	0.11	321	15:30	0	72
16:00	0	0.4	4:00	0.01	340	16:00	0	66
16:30	0.01	0.4	4:30	0.01	358	16:30	0	61
17:00	0.05	0.4	5:00	0.01	372	17:00	0	56
17:30	0.05	0.5	5:30	0	375	17:30	0	51
18:00	0.04	0.5	6:00	0	367	18:00	0	47
18:30	0	0.5	6:30	0	344	18:30	0	43
19:00	0	0.6	7:00	0	320	19:00	0	39
19:30	0.37	4.2	7:30	0	293	19:30	0	36
20:00	0.08	14	8:00	0	269	20:00	0	33
20:30	0.01	27	8:30	0	246			
21:00	0	43	9:00	0	225			
21:30	0.05	58	9:30	0	207			
22:00	0.42	74	10:00	0	189			
22:30	0.18	93	10:30	0	173			
23:00	0.1	112	11:00	0	159			
23:30	0.28	134	11:30	0	146			
0:00	0.3	163	12:00	0	133			
0:30	0.15	196	12:30	0	122			
1:00	0.06	229	13:00	0	112			
1:30	0.14	255	13:30	0	103			
2:00	0.19	273	14:00	0	94			
2:30	0.23	288	14:30	0	86			
3:00	0.45	303	15:00	0	79			

2.8. (cont.)

a. Using the storm hydrograph, estimate the volume of runoff that occurred in inches over the watershed.

b. Estimate the volume of infiltration in inches for this storm event based on the measured rainfall.

c. Estimate the time to peak t_p for this watershed for the entire storm event. Comment.

a) In order to calculate approximately the volume of the direct runoff (cfs – hr ≈ ac – in) we do the following:

i) Add the resulting flow measurements

ii) Multiply the sum by ½ since our measurements are recorded every half hour.

From table P2.8

Total flow = 8206.5 cfs

Volume of Direct Runoff = 8206.5 cfs • ½ hour = 4103.25cfs • hr = 4103.25 ac – in

Area of watershed = 3.35 mi^2 = 2144 acres

$$P_{NET} = \frac{DRO}{\text{Area of Watershed}} = \frac{4103.25 \text{ ac} - \text{in}}{2144 \text{ ac}} = \mathbf{1.91\ in}$$

b) By adding the data of the incremental precipitation column, we find that the gross rainfall is 3.3 in. over the watershed.

Thus: $F = P_{GR} - P_{NET}$ = 3.3-1.91= **1.39 in** over the watershed

c) Estimate the time to peak t_p for this watershed for the entire storm event.

$$\sum_{i=0}^{29} P_i t_i \Big/ \sum_{i=0}^{29} P_i = 8.6 \text{ hours} = \text{Time to center of mass of rainfall}$$

Time of Peak Flow - Time to CM of Rainfall = 14.5-8.6 = **5.9 hours**

2.9. Storm data (Fig. P2.9) were recorded for a storm over a 205-acre basin on September 1, 1999. Approximations for the rainfall and runoff cumulative mass curves are shown by the black dots in the figure.

a) Determine the duration and average intensity of the rainfall.

b) What is the time to peak for this storm?

c) Find the ϕ index for this storm using the rainfall and hydrograph data.

d) Develop a UH for this watershed using the duration of part (a).

a) Duration = 17.25 hr – 16.25 hr = 1 hr
Intensity of gross rainfall = 2.6 in/hr

b) Center of mass of rainfall : 16.75 hr
Time of peak discharge : 17.3 hr
Time to peak, tp = 17.3 hr – 16.75 hr = 0.55 hr

c) $\phi = \dfrac{2.6\text{ in} - 1.4\text{in}}{1\text{ hr}} = 1.2\text{in/hr}$

d) In order to get the 1 hr UH, we multiply the storm hydrograph ordinates by 1/1.4

Time (hr)	Q (cfs)	U (cfs)
0	0	0
0.25	45	32
0.5	90	64
0.75	120	86
1	135	96
1.25	128	91
1.5	120	86
1.75	103	74
2	90	64
2.25	77	55
2.5	60	43
2.75	45	32

Time (hr)	Q (cfs)	U (cfs)
3	28	20
3.25	20	14
3.5	14	10
3.75	8	6
4	6	4
4.25	4	3
4.5	3	2
4.75	2.9	2
5	2.2	2
5.25	1.4	1
5.5	0.7	1
5.75	0	0

2.10. Plot the hydrograph for the storm data given in problem 1.3 (flow rate vs. time). Label the following:

a) peak flow Q_p,

b) time to peak t_p (distance from center of mass of rainfall to peak flow),

c) time of rise T_R (distance from start of discharge to peak flow),

d) time base T_B (distance from start of discharge to end of discharge).

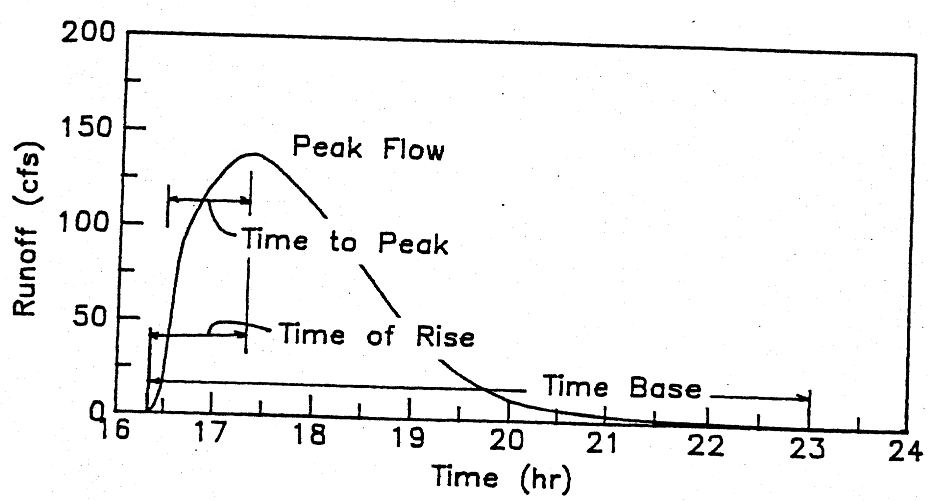
The hydrograph is plotted below.

a) Q_p = 138 cfs

b) t_p = 0.85 hr

c) T_R = 1.1 hr

d) T_B = 7.75 hr



2.11. A watershed has the following characteristics:

A = 2600 ac,

L = 4 mi,

S = 53 ft/mi,

I = 40%,

And the channel is lined with concrete.

The watershed is a residential area with 1/4-ac lots. The soil is categorized as soil group B. Assume that the average watershed slope is the same as the channel slope. Determine the UH for this area for a storm duration of 1 hr using SCS triangular UH method.

From Table 2.1, we get a curve number of 75.

S= (1000/CN) - 10

= (1000/75) – 10

S=3.33.

Using this value, we get:

$t_p = l^{0.8}(S+1)^{0.7}/1900y^{0.5}$

$= [(21,120)^{0.8}(3.33+1)^{0.7}]/[(1900)(1.0)^{0.5}]$

$t_p = 4.23$ hr

$T_R = (D/2) + t_p$

$= (1/2) + 4.23$

$T_R = 4.73$ hr

$Q_p = 484A/T_R$

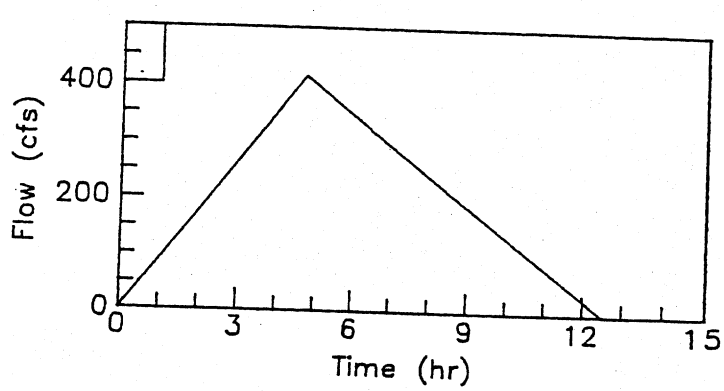
$= (484)(4.06)/4.73$

$Q_p = 415$ cfs

Vol = (1 in)(2600 ac) = 2600 cfs-hr

Vol = $(1/2)(Q_p)(T_R + B)$

$B = (2\ \text{Vol})/Q_p - T_R$



2.11. (cont)

= ((2*2600)/415) – 4.73

B = 7.8 hr

2.12. Using the convolution equation, develop a storm hydrograph for the rainfall intensity *i* and infiltration *f* given in the table (at the end of each time step) using the 30-min unit hydrograph *U* given below.

For each interval, the net rainfall intensity is as follows:

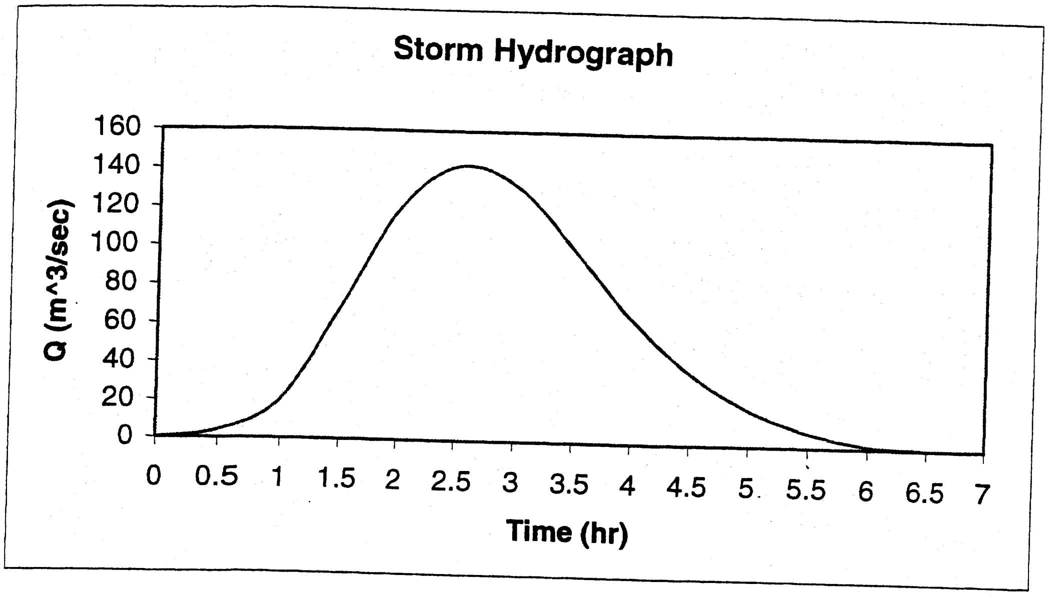
Time (hr)	Gross Rainfall Intensity (cm/hr)	Infiltration Rate (cm/hr)	Net Rainfall Intensity (cm/hr)
0-0.5	1	0.75	0.25
0.5-1	1.25	0.5	0.75
1-1.5	2.5	0.4	2.1
1.5-2	1	0.3	0.7

Then P_n = [0.125, 0.375, 1.05, 0.35]

Using an Excel Spreadsheet program, we develop the storm hydrograph.

Time (hr)	U (m^3/s)	P1*Un	P2*Un	P3*Un	P4*Un	Q (m^3/s)
0	0	0				0
0.5	33	4.125	0			4.125
1	66	8.25	12.375	0		20.625
1.5	80	10	24.75	34.65	0	69.4
2	75	9.375	30	69.3	11.55	120.225
2.5	55	6.875	28.125	84	23.1	142.1
3	35	4.375	20.625	78.75	28	131.75
3.5	20	2.5	13.125	57.75	26.25	99.625
4	10	1.25	7.5	36.75	19.25	64.75
4.5	4	0.5	3.75	21	12.25	37.5
5	0	0	1.5	10.5	7	19
5.5			0	4.2	3.5	7.7
6				0	1.4	1.4
6.5					0	0

2.12. (cont)

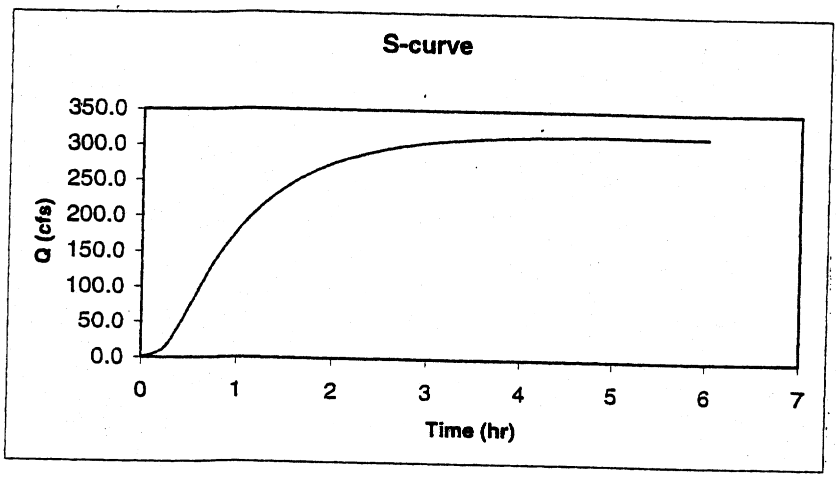


Storm Hydrograph
160
140
120
100
80
60
40
20
0
Q (m^3/sec)
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7
Time (hr)

2.13. Using Excel spreadsheet programs, develop the S-curve for the given 30-min UH, and then develop the 15-min UH from the 30-min UH.

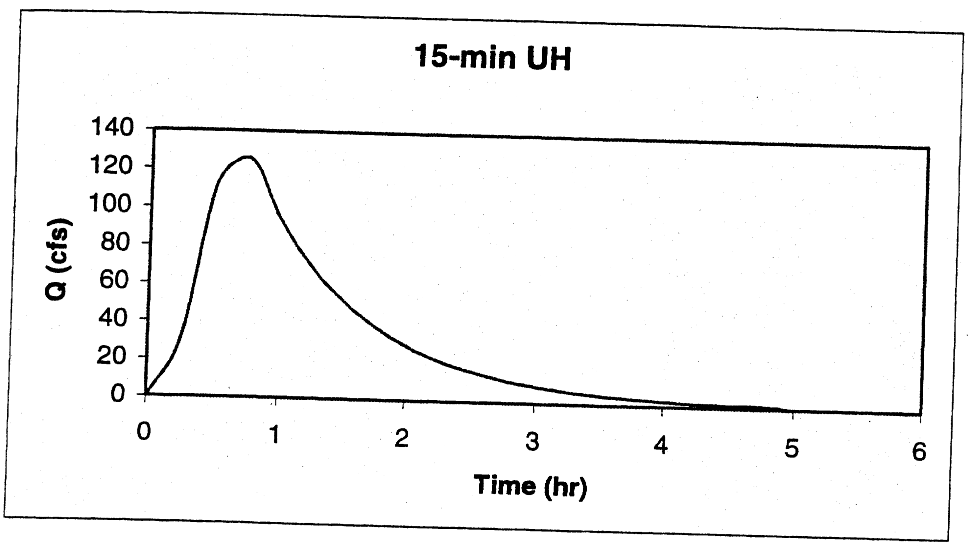
First, we create the S-curve using the 30 – min unit hydrograph.

Time	U	Half hour lagged UHs											S-curve
(hr)	(cfs)												
0	0.0												0.0
0.25	15.0												15.0
0.5	70.9	0.0											70.9
0.75	118.6	15.0											133.6
1	109.4	70.9	0.0										180.3
1.25	81.6	118.6	15.0										215.2
1.5	60.9	109.4	70.9	0.0									241.2
1.75	45.4	81.6	118.6	15.0									260.6
2	33.9	60.9	109.4	70.9	0.0								275.1
2.25	25.3	45.4	81.6	118.6	15.0								285.9
2.5	18.9	33.9	60.9	109.4	70.9	0.0							294.0
2.75	14.1	25.3	45.4	81.6	118.6	15.0							300.0
3	10.5	18.9	33.9	60.9	109.4	70.9	0.0						304.5
3.25	7.8	14.1	25.3	45.4	81.6	118.6	15.0						307.8
3.5	5.8	10.5	18.9	33.9	60.9	109.4	70.9	0.0					310.3
3.75	4.4	7.8	14.1	25.3	45.4	81.6	118.6	15.0					312.2
4	3.3	5.8	10.5	18.9	33.9	60.9	109.4	70.9	0.0				313.6
4.25	2.4	4.4	7.8	14.1	25.3	45.4	81.6	118.6	15.0				314.6
4.5	1.8	3.3	5.8	10.5	18.9	33.9	60.9	109.4	70.9	0.0			315.4
4.75	1.6	2.4	4.4	7.8	14.1	25.3	45.4	81.6	118.6	15.0			316.2
5	0.8	1.8	3.3	5.8	10.5	18.9	33.9	60.9	109.4	70.9	0.0		316.2
5.25	0.0	1.6	2.4	4.4	7.8	14.1	25.3	45.4	81.6	118.6	15.0		316.2
5.5		0.8	1.8	3.3	5.8	10.5	18.9	33.9	60.9	109.4	70.9	0.0	316.2
5.75		0.0	1.6	2.4	4.4	7.8	14.1	25.3	45.4	81.6	118.6	15.0	316.2
6			0.8	1.8	3.3	5.8	10.5	18.9	33.9	60.9	109.4	70.9	316.2



2.13 (cont.) Then, we lag the S-curve by 15 min. and we subtract it from the original S-curve. The result must be multiplied by the ratio of the duration of the original UH to the duration of the desired UH.

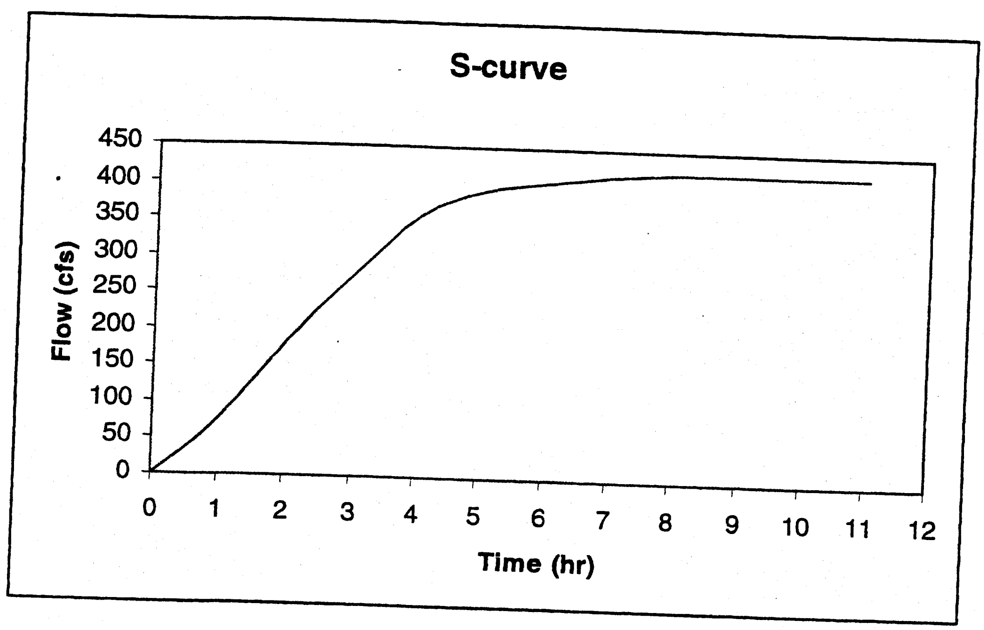
Time (hr)	S-Curve	S-Curve (lagged 0.25)	Difference	15min UH (D/D' =2)
0	0		0	0
0.25	15	0	15	30
0.5	70.9	15	55.9	111.8
0.75	133.6	70.9	62.7	125.4
1	180.3	133.6	46.7	93.4
1.25	215.2	180.3	34.9	69.8
1.5	241.2	215.2	26	52
1.75	260.6	241.2	19.4	38.8
2	275.1	260.6	14.5	29
2.25	285.9	275.1	10.8	21.6
2.5	294	285.9	8.1	16.2
2.75	300	294	6	12
3	304.5	300	4.5	9
3.25	307.8	304.5	3.3	6.6
3.5	310.3	307.8	2.5	5
3.75	312.2	310.3	1.9	3.8
4	313.6	312.2	1.4	2.8
4.25	314.6	313.6	1	2
4.5	315.4	314.6	0.8	1.6
4.75	316.2	315.4	0.8	1.6
5	316.2	316.2	0	0



2.14. Using Excel spreadsheet programs, develop the S-curve for the given 3-hr UH, and then develop the 2-hr UH from the 3-hr UH.

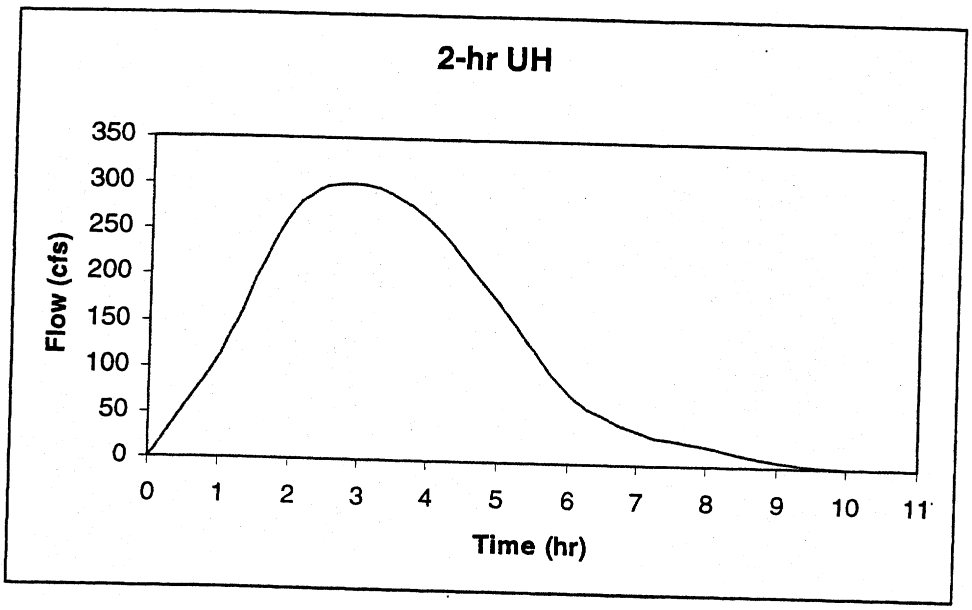
First we develop the S-curve using the 3 –hr UH.

Time	U	3hr lagged UHs			S-curve
(hr)	(cfs)				
0	0				0
1	75				75
2	180				180
3	275	0			275
4	280	75			355
5	210	180			390
6	130	275	0		405
7	60	280	75		415
8	30	210	180		420
9	15	130	275	0	420
10	5	60	280	75	420
11	0	30	210	180	420



2.14 (cont.) Then we lag the S-curve by two hours and we subtract it from the original S- curve. The result must be multiplied by the ratio of the duration of the original UH to the duration of the desired UH.

Time (hr)	S-curve	S-Curve (lagged by 2)	Difference	2hr UH (D/D'=1.5)
0	0		0	0
1	75		75	112.5
2	180	0	180	270
3	275	75	200	300
4	355	180	175	262.5
5	390	275	115	172.5
6	405	355	50	75
7	415	390	25	37.5
8	420	405	15	22.5
9	420	415	5	7.5
10	420	420	0	0



2.15. Repeat Example 2.8b using a spreadsheet program and an increased CN of 80.

Given CN = 80

$S = (1000/CN) - 10 = 2.5$

$I_a = 0.2*S = 0.5$

For each $P_i > I_a$ $F = ((S*(P_i\text{-}I_a))/P_i+S\text{-}I_a)$

At hr i, $P_{ei} = P_i\text{-}I_{ai}\text{-}F_i$

And exess RF = $P_{ej}\text{-}P_{ei}$ for time step j-i.

Time (hr)	Cumulative P (in)	Cumulative abstractions (in)		Cumulative Pe (in)	Excess RF Hyetograph
		Ia	F		
0	0	0	0	0.00	
1	0.3	0.3	0	0.00	
2	0.7	0.5	0.19	0.01	
3	1.4	0.5	0.66	0.24	0.22
4	2.8	0.5	1.20	1.10	0.86
5	4	0.5	1.46	2.04	0.94
6	4.5	0.5	1.54	2.46	0.42

2.16. Using the assumption of Eq. 2-19, and the definition of F and P_e, prove that Eq. 2-20 is correct as plotted in Fig. 2-14. Note that Q is a function of P and S.

Eq. 2-19: $F/S = Q/P_e$ $F = (P_e - Q)$ $P_e = (P - 0.2S)$

$FP_e/S = Q$ $F = (P - 0.2S - FP_e/S)$

$(F + FP_e/S) = (P - 0.2S)$

$F(1 + P_e/S) = (P - 0.2S)$

$F = (P - 0.2S)/(1 + P_e/S)$

$F = (P - 0.2S)/(1 + (P - 0.2S)/S)$

$(P - 0.2S)\bullet(P - 0.2S)/(1 + (P - 0.2S)/S)\bullet S = Q$

$\Rightarrow (P - 0.2S)^2/(P + 0.8S) = Q$

2.17.

Given the following 2-hr unit hydrograph, calculate the 1-hr unit hydrograph. Then back calculate and find the 2-hr unit hydrograph to prove that the method of calculation is accurate. Graph both unit hydrographs against time on the same plot.

TIME (hr)	0	1	2	3	4	5	6
FLOW (cfs)	0	33	100	200	400	500	433

TIME (hr)	7	8	9	10	11	12	13
FLOW (cfs)	367	300	233	167	100	33	0

- The following steps describe the procedure used to achieve the results summarized in the spreadsheet and graph below

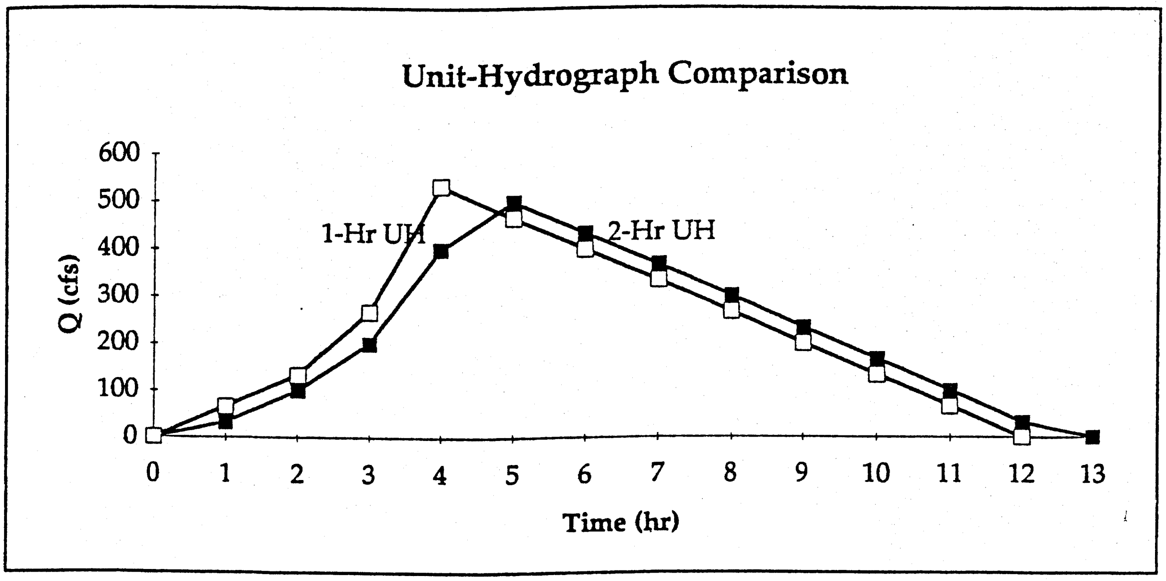
- Lag the 2 – hr unit hydrograph by 2 – hr increments to obtain the S –curve
- Then lag the S –curve by the time of duration of the new unit hydrograph – in this case, 1 –hr.
- Multiply the resulting ordinate values by the ratio D/D' where D is the original duration and D' is the desired duration. D/D = 2/1 = 2.

2.17. (cont.)

Time (hr)	2-Hr UH (cfs)							S-Curve	Lagged S-Curve	Difference (cfs)	1-Hr UH (cfs)
0	0							0		0	0
1	33							33	0	33	66
2	100	0						100	33	67	134
3	200	33						233	100	133	266
4	400	100	0					500	233	267	534
5	500	200	33					733	500	233	466
6	433	400	100	0				933	733	200	400
7	367	500	200	33				1100	933	167	334
8	300	433	400	100	0			1233	1100	133	266
9	233	367	500	200	33			1333	1233	100	200
10	167	300	433	400	100	0		1400	1333	67	134
11	100	233	367	500	200	33		1433	1400	33	66
12	33	167	300	433	400	100	0	1433	1433	0	0
13	0	100	233	367	500	200	33	1433	1433	0	

These results are graphed on the next page.

2.17. (cont)



Performing the process in reverse, we can verify our solution:

Note; D/D' = ½ for the reverse process.

Time (hr)	1-Hr UH (cfs)								S-Curve	Lagged S-Curve	Difference (cfs)	2-Hr UH (cfs)
0	0								0		0	0
1	66	0							66		66	33
2	134	66	0						200	0	200	100
3	266	134	66	0					466	66	400	200
4	534	266	134	66	0				1000	200	800	400
5	466	534	266	134	66	0			1466	466	1000	500
6	400	466	534	266	134	66	0		1866	1000	866	433
7	334	400	466	534	266	134	66	.	2200	1466	734	367
8	266	334	400	466	534	266	134	..	2466	1866	600	300
9	200	266	334	400	466	534	266	...	2666	2200	466	233
10	134	200	266	334	400	466	534	....	2800	2466	334	167
11	66	134	200	266	334	400	466	.....	2866	2666	200	100
12	0	66	134	200	266	334	400	......	2866	2800	66	33
13	0		66	134	200	266	334	....	2866	2866	0	0

This 2 – hr unit hydrograph is the same as given.

2.18. Repeat Example 2.4 using an Excel spreadsheet program.

WE ARE GIVEN THE 2 –HR UNIT HYDROGRAPH =

TIME (HR)	2 – HR UH ORDINATE (cfs)
0	0
1	75
2	250
3	300
4	275
5	200
6	100
7	75
8	50
9	25
10	0

- Lag the 2 – hr UH increments to obtain the S –Curve
- Lag the S – curve by the time of duration of the new Uh – in this case, 3 –hr
- Multiply the resulting ordinate values by the ratio D/D. where D is the original duration and D' is the desired duration; D/D' = 2/3.

2.18. (cont.)

Time (hr)	2-Hr UH (cfs)						S-Curve	Lagged S-Curve	Difference (cfs)	3-Hr UH (cfs)
0	0						0		0	0
1	75						75		75	50.0
2	250	0					250		250	166.7
3	300	75					375	0	375	250.0
4	275	250	0				525	75	450	300.0
5	200	300	75				575	250	325	216.7
6	100	275	250	0			625	375	250	166.7
7	75	200	300	75			650	525	125	83.3
8	50	100	275	250	0		675	575	100	66.7
9	25	75	200	300	75		675	625	50	33.3
10	0	50	100	275	250	0	675	650	25	16.7
11	0	25	75	200	300	75	675	675	0	0.0

The solution matches the example exactly.

Problem 2.19, 2.20 and 2.21 relate to the watershed shown in Fig. P2.19.

2.19. Develop storm hydrographs from UHs of subarea 1 and 2 for the given rainfall and infiltration.

Time (hr)	0	1	2	3	4	5	6	7	8	9
UH_1 (cfs)	0	200	400	600	450	300	150	0		
UH_2 (cfs)	0	100	300	450	350	250	150	100	50	0

Time Interval (hr)	**Gross Rainfall (in/hr)**	**Infiltration Capacity (in/hr)**	**Rainfall Excess (in/hr)**
0-1	0.5	0.4	0.1
1-2	1.1	0.2	0.9
2-3	3	0.2	2.8
3-4	0.9	0.2	0.7

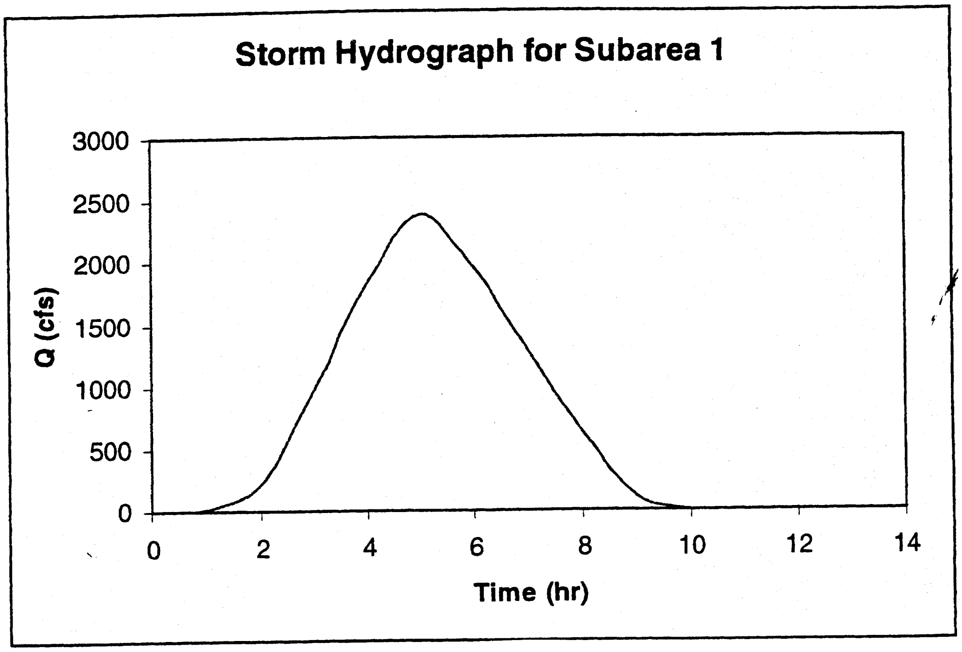
So P_N = [0.1, 0.9, 2.8, 0.7]

Using the convolution equation, we calculate the storm hydrograph for subareas 1 and 2.

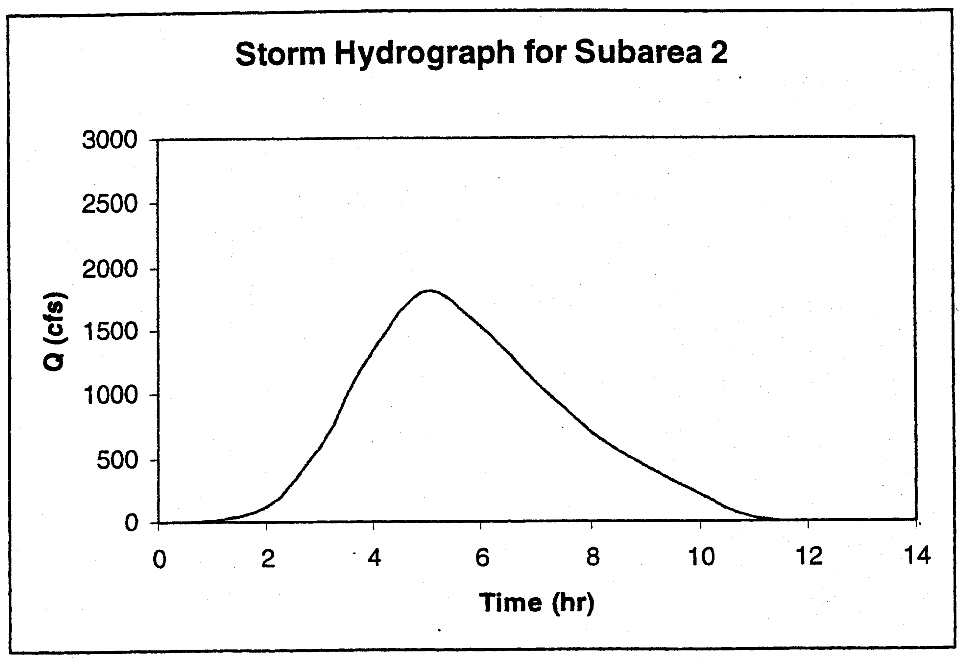
Time (hr)	**UH1**	**P1*UH1** (cfs)	**P2*UH1** (cfs)	**P3*UH1** (cfs)	**P4*UH1** (cfs)	**Q1** (cfs)
0	0	0				0
1	200	20	0			20
2	400	40	180	0		220
3	600	60	360	560	0	980
4	450	45	540	1120	140	1845
5	300	30	405	1680	280	2395
6	150	15	270	1260	420	1965
7	0	0	135	840	315	1290
8			0	420	210	630
9				0	105	105
10					0	0

Time (hr)	**UH2**	**P1*UH2** (cfs)	**P2*UH2** (cfs)	**P3*UH2** (cfs)	**P4*UH2** (cfs)	**Q2** (cfs)
0	0	0				0
1	100	10	0			10
2	300	30	90	0		120
3	450	45	270	280	0	595
4	350	35	405	840	70	1350
5	250	25	315	1260	210	1810
6	150	15	225	980	315	1535
7	100	10	135	700	245	1090
8	50	5	90	420	175	690
9	0	0	45	280	105	430
10			0	140	70	210
11				0	35	35
12					0	0

2.19. (cont.)



Storm Hydrograph for Subarea 1
3000
2500
2000
1500
1000
500
0
Q (cfs)
0
2
4
6
8
10
12
14
Time (hr)



Storm Hydrograph for Subarea 2
3000
2500
2000
1500
1000
500
0
Q (cfs)
0
2
4
6
8
10
12
14
Time (hr)

2.20. Develop a combined storm hydrograph at point A in the watershed (Fig. P2.19) and lag route (shift in time only) assuming that travel time from point A to B is exactly 2 hours.

We add the ordinates of Q_1 and Q_2 and develop the combined storm hydrograph at point A.

Time (hr)	Q1 (cfs)	Q2 (cfs)	Qa (cfs)
0	0	0	0
1	20	10	30
2	220	120	340
3	980	595	1575
4	1845	1350	3195
5	2395	1810	4205
6	1965	1535	3500
7	1290	1090	2380
8	630	690	1320
9	105	430	535
10	0	210	210
11		35	35
12		0	0

Then we lag route the combined hydrograph from point A to B

Lag 2 hr.

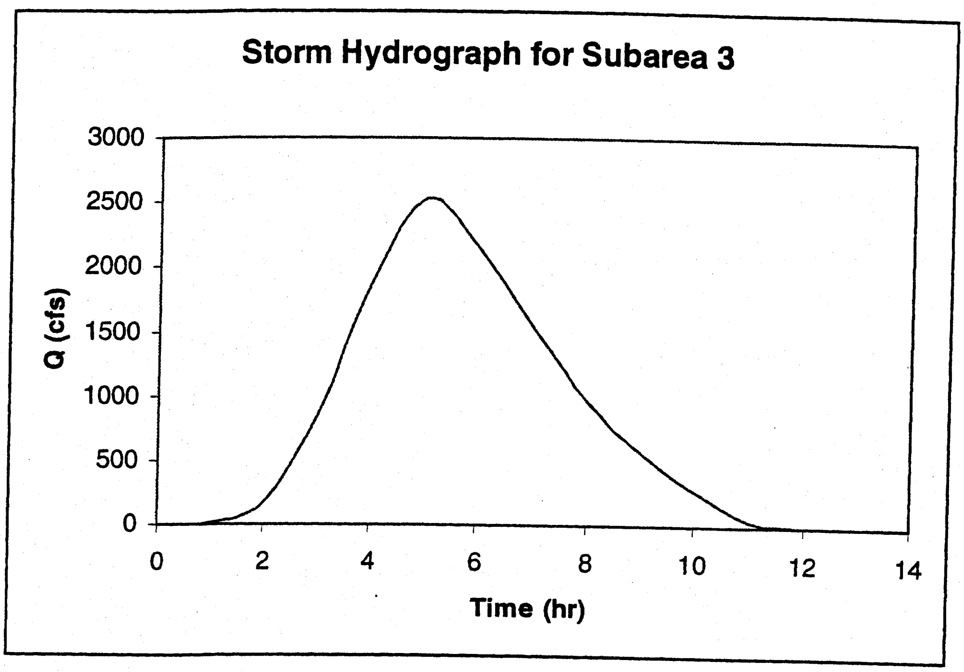
Time (hr)	Qab (cfs)
0	0
1	0
2	0
3	30
4	340
5	1575
6	3195
7	4205
8	3500
9	2380
10	1320
11	535
12	210
13	35
14	0

2.21. Develop a storm hydrograph for subarea 3 from the given UH, add to the combined hydrograph from problem 2.20, and produce a final storm hydrograph at the outlet of the watershed, *B*.

time (hrs)	UH_3 (cfs)	*t* (hr)	*i* (in./hr)	*f* (in./hr)
0	0	1	0.5	0.4
1	140	2	1.1	0.2
2	420	3	3	0.2
3	630	4	0.9	0.2
4	490			
5	350			
6	210			
7	130			
8	70			
9	0			

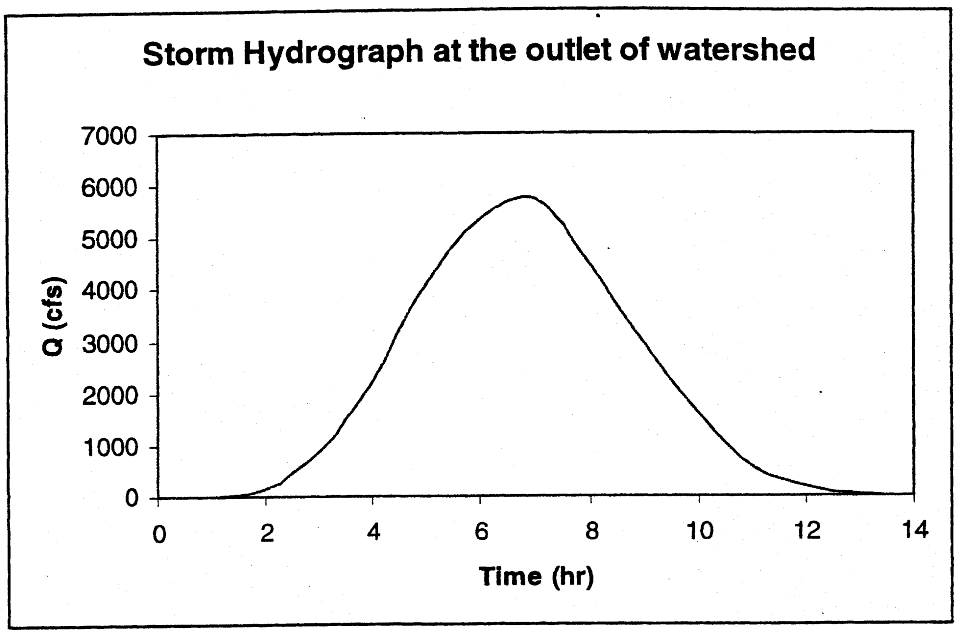
2.21. (cont.)

Time	UH3	P1*UH3	P2*UH3	P3*UH3	P4*UH3	Q3
(hr)		(cfs)	(cfs)	(cfs)	(cfs)	(cfs)
0	0	0				0
1	140	14	0			14
2	420	42	126	0		168
3	630	63	378	392	0	833
4	490	49	567	1176	98	1890
5	350	35	441	1764	294	2534
6	210	21	315	1372	441	2149
7	130	13	189	980	343	1525
8	70	7	117	588	245	957
9	0	0	63	364	147	574
10			0	196	91	287
11				0	49	49
12					0	0



2.21. (cont.)

Time (hr)	Qab (cfs)	Q3 (cfs)	Qtotal (cfs)
0	0	0	0
1	0	14	14
2	0	168	168
3	30	833	863
4	340	1890	2230
5	1575	2534	4109
6	3195	2149	5344
7	4205	1525	5730
8	3500	957	4457
9	2380	574	2954
10	1320	287	1607
11	535	49	584
12	210	0	210
13	35		35
14	0		0



2.22. Redo Example 2.9a if the watershed is soil type B in good cover forest land. How does the forested area compare to the meadow UH?

From table 2.1, the SCS curve number is found to be 55. Therefore,

$$S = (1000/\ CN) - 10$$

$$= (1000/55) - 10$$

$$= 8.182 \text{ in.}$$

From example 2.9a

l = 95,040 ft

y = 1.9%

$t_p = (95{,}040^{0.8}\ (8.182 + 1)^{0.7} / 1900\ \sqrt{1.9}) = (45329.533/2618.97) = 17.3$ hr

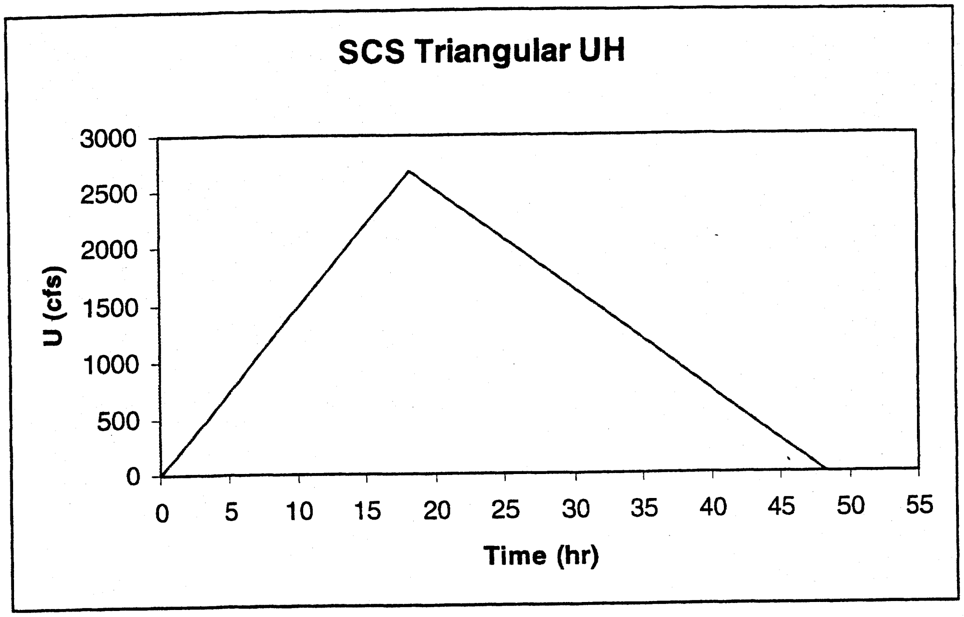
$T_R = D/2 + t_p = 1.6/2 + 17.3 = 18.1$

From Eq. 2.16

$Q_P = (484 \cdot A/T_R) = (484 \cdot 100/18.1) = 2674$ cfs

$B = 1.67 \cdot T_R = 30.2$

2.22. (cont.)



	Forested Area (Group B)	Meadow (Group D)
T_R	18.1	10.2
B	30.2	16.8
Q_p	2674	4745
S	8.182 in.	2.82 in.

From the table above, it is interesting to notice the following:

$$\frac{T_R\text{ (meadow)}}{T_R\text{ (forested)}} \approx 0.56$$

$$\frac{B\text{ (meadow)}}{B\text{ (forested)}} \approx 0.56$$

} The duration of the meadow UH is almost half the duration of the forested UH.

AND

$$\frac{Q_p\text{ (forested)}}{Q_p\text{ (meadow)}} \approx 0.56$$

The peak discharge of the forested UH is almost half the peak discharge of the meadow UH.

2.23. Sketch the SCS triangular and curvilinear UHs and the mass curve for a 100 mi^2 watershed which is 60% good condition meadow and 40% good cover forest land. The watershed consists of 70% soil group C and 30% soil group A. The average slope is 100 ft/mi, the rainfall duration is 3 hr, and the length to divide is 18 mi.

	Soil group		CN
Good condition meadow	C	0.6*0.7= 0.42	71
	A	0.6*0.3= 0.18	30
Good cover forest land	C	0.4*0.7= 0.28	70
	A	0.4*0.3= 0.12	25

The weighted CN is : $0.42 \bullet 71 + 0.18 \bullet 30 + 0.28 \bullet 70 + 0.12 \bullet 25 = 57.82 \approx 58$

$l = 18 \text{ mi} = 18 \text{ mi} \bullet 5280 \text{ ft/mi} = 95,040 \text{ ft}$

The slope is 100 ft/mi => $y = (100 \text{ ft/mi})(1\text{mi}/5280 \text{ ft})(100\%) = 1.9\ \%$

$S = (1000/CN) - 10 = (1000/58) - 10 = 7.24$ in

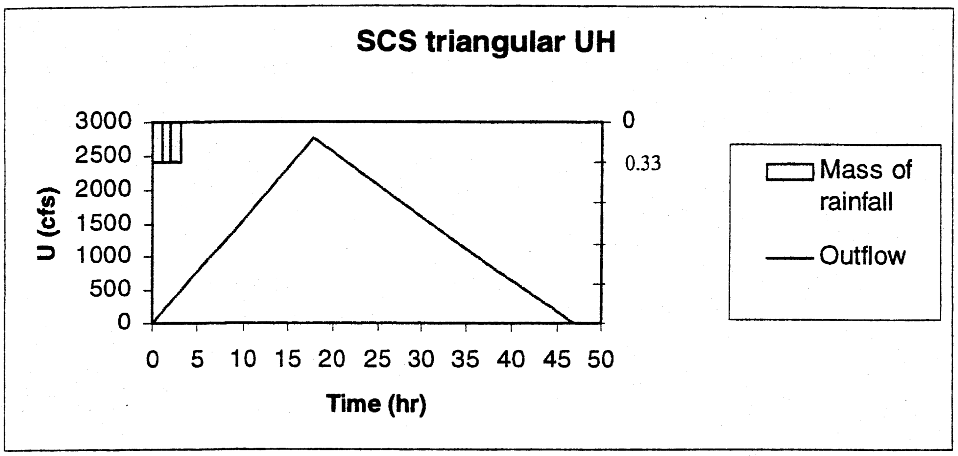
$t_p = (l^{0.8} \bullet (s + 1)^{0.7}/1900y^{1/2}) = (95{,}040^{\ 0.8}\ (7.24 + 1)^{\ 0.7}/1900\bullet\sqrt{1.9}) = 16.05$ hr

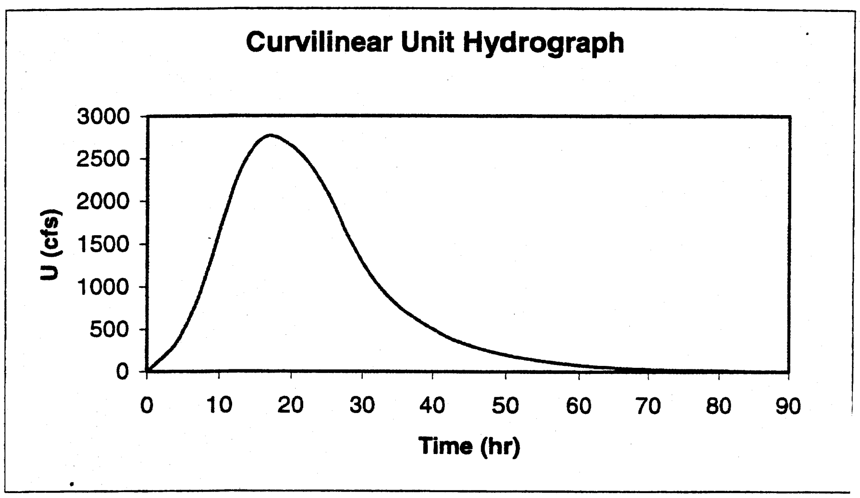
$T_R = D/2 + t_p = 1.5 + 16.05 = 17.55$ hr

$Q_P = (484 \bullet A/T_R) = (484 \bullet 100/17{,}55) = 2757.83$

$B = 1.67\ T_R = 1.67 \bullet 17.55 = 29.31$ hr

2.23. (cont.)


SCS triangular UH
3000
2500
2000
1500
1000
500
0
U (cfs)
0
0.33
0 5 10 15 20 25 30 35 40 45 50
Time (hr)
Mass of rainfall
Outflow


Curvilinear Unit Hydrograph
3000
2500
2000
1500
1000
500
0
U (cfs)
0 10 20 30 40 50 60 70 80 90
Time (hr)

2.24. For a 45 mi^2 watershed with C_t = 2.2, L = 15 mi, L_c = 7 mi, and C_p = 0.5, find t_p, Q_p, T_b, and D. Plot the resulting Snyder UH.

$t_p = C_t (L \cdot L_c)^{0.3} = 2.2 \cdot (15 \cdot 7)^{0.3} = 8.9$ hr

$Q_p = (640 \cdot 0.5 \cdot 45/8.9) = 1618$ cfs

$T_D = 4 \cdot t_p = 4 \cdot 8.9 = 35.6$ hr

$D = t_p/ 55 = 1.6$ hr

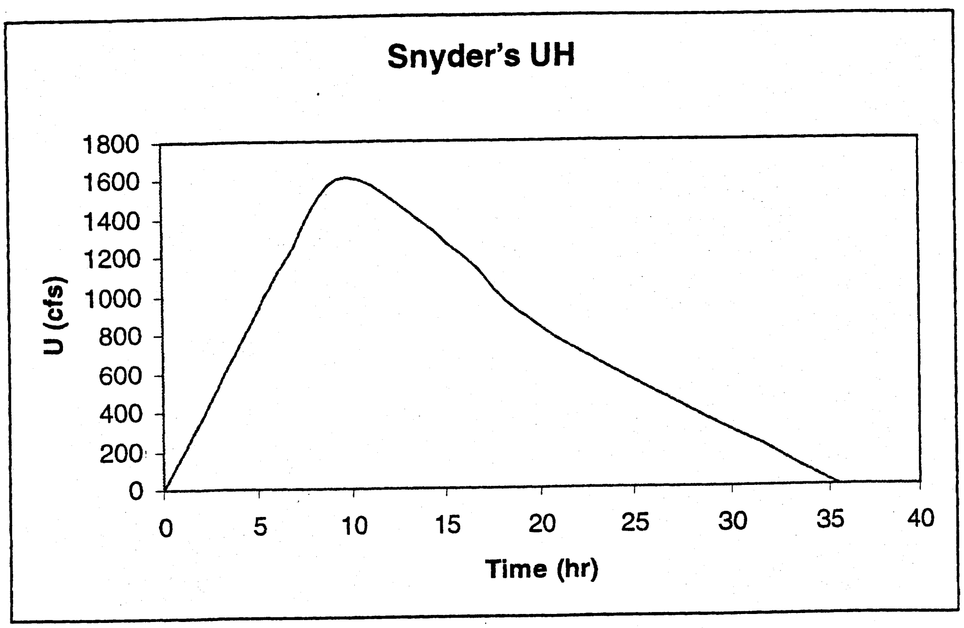
$W_{75} = 440\ (Q_p/A)^{-1.08} = 440 \cdot (1618/45)^{-1.08} = 9.2$ (3.1 before Q_p, 6.1 after Q_p)

$W_{50} = 770\ (Q_p/A)^{-1.08} = 770\ (1618/45)^{-1.08} = 16.1$ (5.4 before Q_p, 10.7 after Q_p)

The time of Q_p is = 8.9 + (1.6/2) = 9.7 hr

At t = 9.7 – 3.1 = 6.6 hr and t = 15.8 hr, Q = 1213.5 cfs

At t = 9.7 – 5.4 = 4.3 hr and t = 9.7 + 10.7 = 20.4 hr, Q = 809 cfs



2.25. Watershed data are provided on Fig. 2.1a for a small forested watershed that contains 7 subareas aa shown. Compute Snyder unit hydrographs for subarea B, based on length and areas from the figure. Assume that $C_t = 2.2$ and $C_p = 0.5$. Assume L = length along the stream in each subarea.

For Sub area B: A = 111 mi^2

$L_c = 9.2$ mi

L = 14.2 mi

<u>Development of UH for Sub area B:</u>

$t_p = C_t (L \cdot L_c)^{0.3} = 2.2 (14.2 \cdot 9.2)^{0.3} = 9.5$ hr

$Q_p = 640 C_p A / t_p$ $(640 \cdot 0.5 \cdot 11.1)/9.5 = 3739$ cfs

$T_b \approx 4 \cdot t_p = 4 \cdot 9.5$ hr $= 38$ hr

$D = t_p / 5.5 = 9.5/5.5 = 1.7$ hr

$W_{75} = 440(Q_p/A)^{-1.08} = 440 \cdot (3379/111)^{-1.08} = 9.9$ (3.3 before Q_p, 6.6 after Q_p)

$W_{50} = 770 (Q_p/A)^{-1.08} = 770 (3739/111)^{-1.08} = 17.3$ (5.8 before Q_p, 11.5 after Q_p)

The time of $Q_P = t_p + D/2 = 9.5 + 1.7/2 = 10.35$ hr

At t = 10.35 – 3.3 = 7.05 hr and t = 10.35 + 6.6 = 16.95 hr, Q = 2804.25 (75% of Q_p)

At t = 10.35 – 5.8 = 4.55 hr and t = 10.35 +11.5 = 21.85 hr, Q = 1869.5 (50% of Q_p)

Check volume of hydrograph = 1.0 inch

2.25. (cont.)

$W_{75} = 440\ (Q_p/A)^{-1.08} = 440\ (418/12.4)^{-1.08} = 9.9 < 3.3$ before Qp

6.6 after Qp

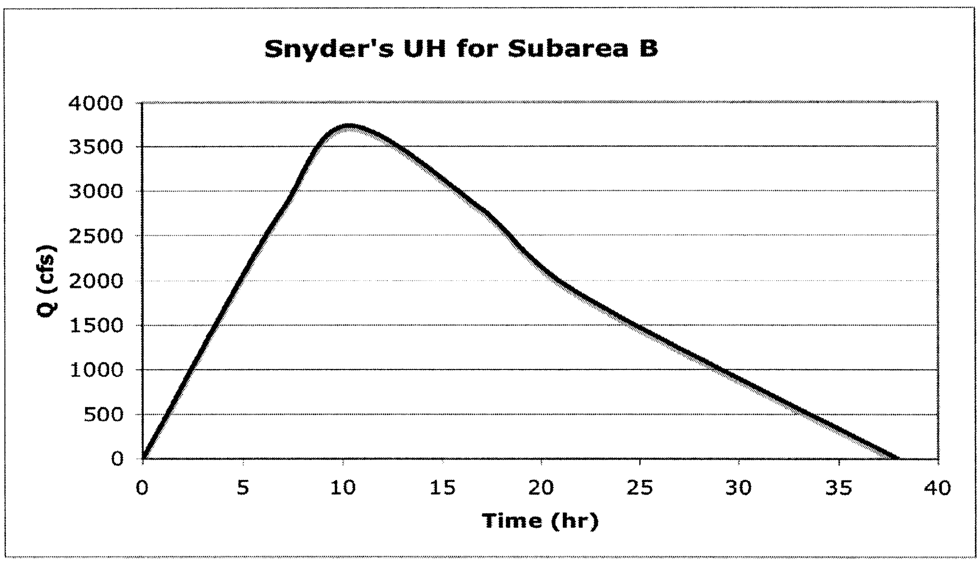
$W_{50} = 770\ (Qp/A)^{-1.08} = 770\ (418/12.4)^{-1.08} = 17.3 < 5.8$ before Qp

11.5 after Qp

Time of Qp is: 9.49 + 1.7/2 = 10.34 hr

At t= 10.34 – 3.3 = 7.04 and t = 10.34 + 6.6 = 16.94, Q = 314 cfs

At t = 10.34 – 5.8 = 4.54 and t = 10.34 + 11.5 = 21.84 hr, Q = 209 cfs



2.26. Watershed data are provided on Fig. 2.1a for a small forested watershed that contains 7 subareas as shown. Compute SCS UHs (dimensionless) for subarea B, based on lengths and areas from the watershed.

Assume a watershed slope of 0.5% and a CN = 70.

FOR SUB AREA B

$S = (1000/CN) - 10 = (1000/70) - 10 = 4.29$ in

$l = 21.6$ mi • 5280 ft/mi = 114,48 ft

$y = 0.5\%$

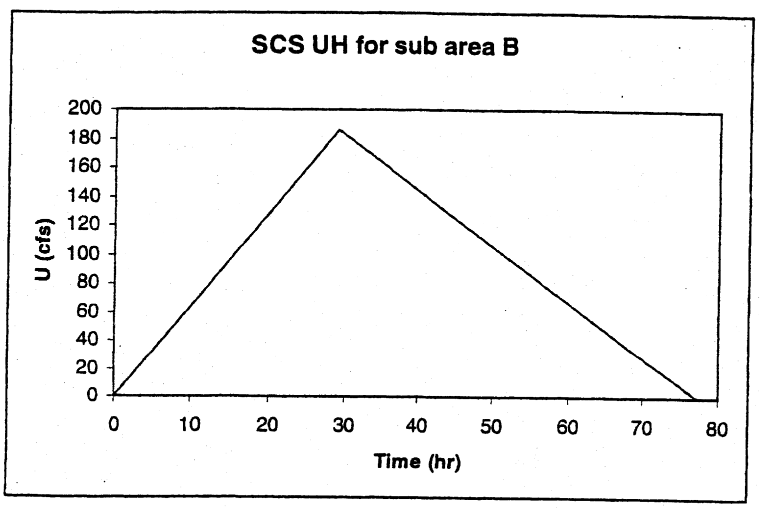
$$tp = \frac{(114,048)^{0.8}\,(4.29+1)^{0.7}}{1900\sqrt{0.5}} = 26.54 \text{ hr}$$

$D = tp/5.5 = 26.54 /5 .5 = 4.83$ hr

$T_R = (D/2) + t_p = (4.83/2) + 26.54 = 28.96$ hr

$Q_p = (4.84 \bullet 11.1/28.96) = 185.5$ cfs

$B = 1.67 \bullet TR = 1.67 \bullet 28.96 = 48.36$



2.26 (cont.)

For Sub Area E

$S = 4.29$ in

$L = 14.2$ mi• 5280 ft/mi = 74.976ft

$Y = 05.\%$

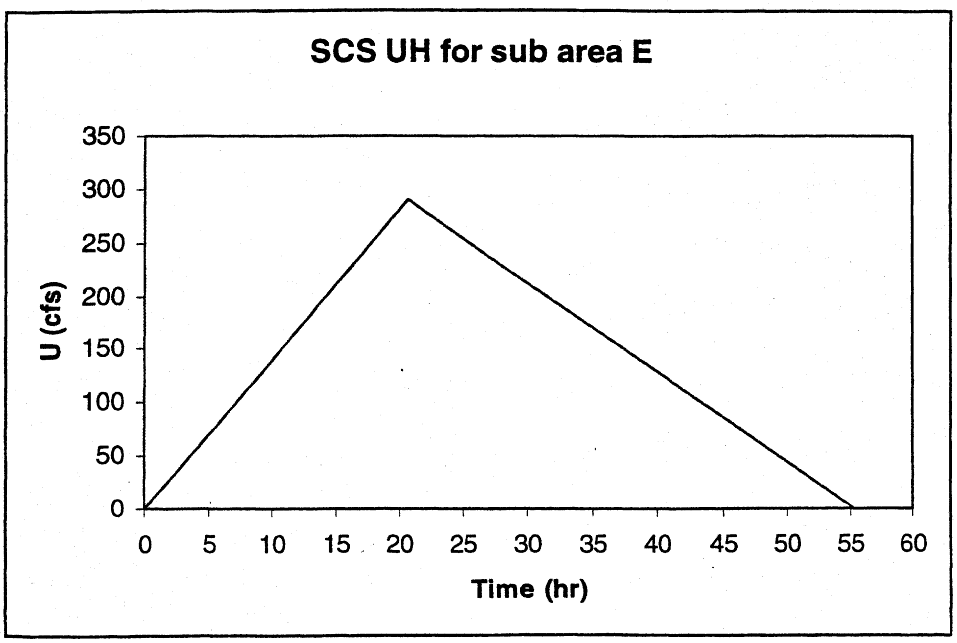
$T_p = ((74{,}976)^{0.8}(4.299 + 1)^{0.7} / 1900\ \sqrt{0.5}) = 18.97$ hr

$D = t_p / 5.5 = 18.97 / 5.5 = 3.45$hr

$T_R = (D/2) + tp = (3.45/2) + 18.97 = 20.7$ hr

$Q_p = (484 \bullet 12.4 / 20.7) = 290$ cfs

$B = 1.67 \bullet T_R = 1.67 \bullet 20.7 = 34.57$ hr



2.27. Develop a list of steps for hydrologic analysis for the watershed in Fig 2.1a. Indicate the order of computing subarea runoff from given rainfall, combining hydrographs at confluences, and flood routing (moving the hydrograph within the stream channel) through the four reaches, as shown in the figure. Begin at the upstream end (G), and proceed in a downstream direction to the outlet. A similar watershed will be formally analyzed later with computer models in Chapter 5.

O = Runoff

□ = Routing

▽ = Combination