Chapter 2-ANSWER KEY

**Concept Check**

**2.1** What characterizes a watershed?

# ANSWER:

A watershed is the basic unit used in most hydrologic calculations relating to the water balance or computation of rainfall-runoff. It is characterized by one main channel and by tributaries that drain into a main channel at one or more confluence points. Larger watersheds can have many subareas that contribute runoff to a single outlet. The drainage area is another characteristic that reflects the volume of water that can be generated from rainfall.

**2.2** Describe the four assumptions made that are inherent to the unit hydrograph.

**ANSWER:**

1. Rainfall excesses of equal duration are assumed to produce hydrographs with equivalent time bases regardless of the intensity of the rain.
2. Direct runoff ordinates for a storm if given duration are assumed directly proportional to rainfall excess volumes. Thus, twice the rainfall produces a doubling hydrograph ordinates.
3. The time distribution of direct runoff is assumed independent of antecedent precipitation.
4. Rainfall distribution is assumed to be the same for all storms of equl duration, both spatially and temporally.

These assumptions can sometimes limit the application of a unit hydrograph in a given watershed.

**2.3** What physical factors affect the shape and timing of the unit hydrograph?

**ANSWER:**

The shape and timing of the hydrograph are related to duration and intensity of rainfall as well as the various factors governing the watershed area.

The meteorological factors that influence the hydrograph shape and volume of runoff include:

1. Rainfall intensity and pattern
2. Areal distribution of rainfall over the basin

The various factors that govern the watershed include:

1. Size and shape of the drainage area
2. Slope of the land surface and the main channel
3. Channel morphology and drainage type
4. Soil types and distribution
5. Storage detention in the watershed.

**2.4** Discuss the parameters that describe the main timing aspects of the hydrograph.

**ANSWER:**

The physical factors that will affect the shape and timing of the unit hydrograph are:

a. Duration of the rainfall excess: the time from start to finish of rainfall excess

b. Lag Time: the time from the center of mass of rainfall excess to the peak of the hydrograph.

c. Time of rise: the time from the start of rainfall excess to the peak of the hydrograph.

d. Time of concentration: the time for a wave (of water) to propagate from the most distant point in the watershed to the outlet. One estimate is the time from the end of net rainfall to the inflection point of the hydrograph.

**2.5** What two characteristics of the hydrograph do most methods for synthetic unit hydrographs relate?

**ANSWER:**

They relate hydrograph peak flow and timing to watershed characteristics.

**2.6** In order to determine which of the three excavation sites could have potentially contributed to the sedimentation of the three lakes, it is necessary to determine the watershed boundaries and the contributing drainage areas of the system of lakes. Catchment basins (watersheds) can be determined by connecting ridge lines and dividing lines. Ridge lines will follow the elevation isocontours and dividing lines are perpendicular to the elevation isocontours at the end and start at the confluences of streams.Using the map on the textbook website displaying the elevation data, determine the following:

a. How many confluences are displayed on the map?

b. Delineate the watersheds using the elevation isocontours. The total drainage area of the study area is approximately 238 acres.

c. Determine which of the three lakes may be affected by accelerated sedimentation.

d. Determine which of the three excavation sites may be responsible for the accelerated sedimentation of the lakes.

**ANSWER:**

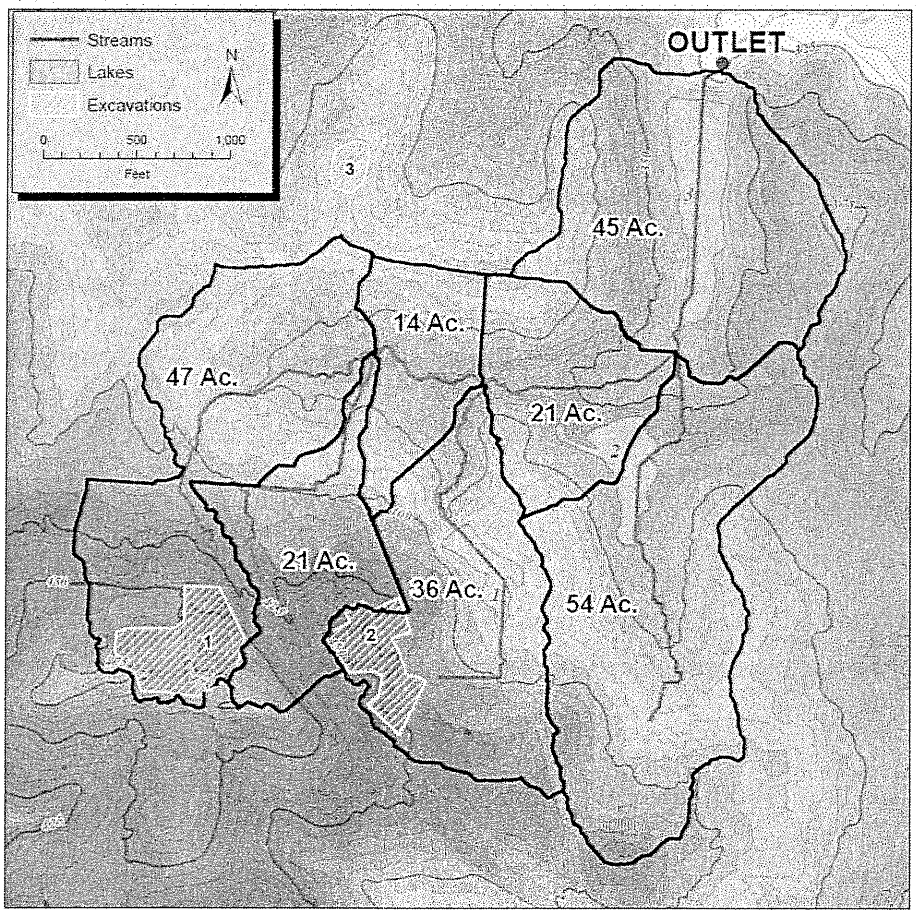
a. There are three confluence points

b. See picture below

c. Lakes 1 (lake 2 minimally) will be affected by the accelerated excavation.

d. The sites that are responsible are sites 1 and 2. Three can be eliminated because it is outside the watershed.

2.6 cont'



Streams
Lakes
Excavations
N
0
500
1,000
Feet
OUTLET
45 Ac.
14 Ac.
47 Ac.
21 Ac.
21 Ac.
36 Ac.
54 Ac.
1
2
3

## HOMEWORK PROBLEMS

**2.7** A watershed has the following characteristics:

A = 2600 ac

L = 4 mi.

S = 53 ft/mi.

y = 1%

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 the SCS triangular UH method.

**ANSWER:**

From table 2-1 obtain the curve number with the given information.

CN = 75

S = (1000/CN) – 10 = (1000/75) – 10 = 3.33

L = 4 mi. = (4mi.)(5280 ft/mi.) = 21,120 ft.

Plug into equation:

$$t_p = \frac{L^{0.8}(S+1)^{0.7}}{1900\sqrt{y}}$$

$$t_p = \frac{(21{,}120)^{0.8}(3.33+1)^{0.7}}{1900\sqrt{1}} = \mathbf{4.23\ hr}$$

$T_R = D/2 + t_p = 1/2 + 4.23 =$ **4.73 hr**

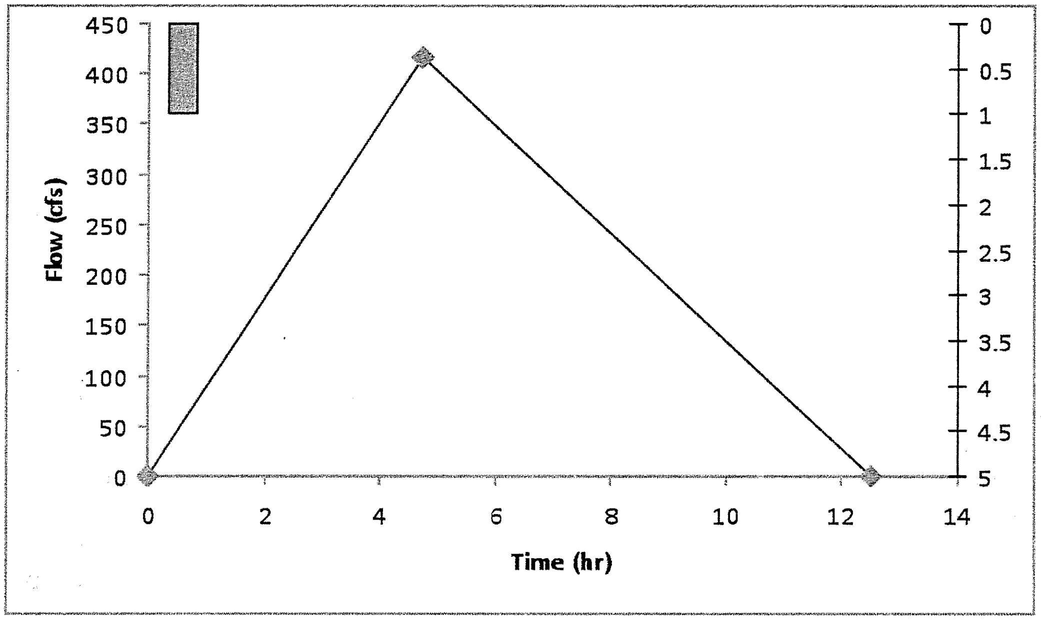
$$Q_p = \frac{484A}{T_R} = \frac{484 \cdot 2600ac \cdot \dfrac{1mi.^2}{640ac}}{4.73} = \mathbf{416\ cfs}$$

Vol = (1 in.)(2600 ac) = 2600 ac-in. ~ **2600 cfs-hr**

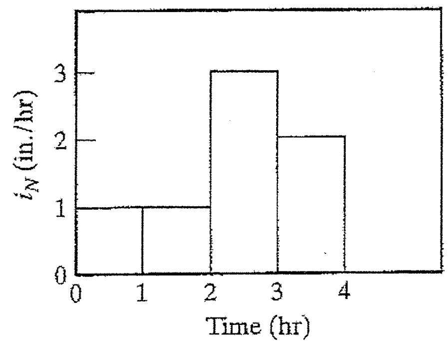
2.7 cont'

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

$$B = \frac{2Vol}{Q_P} - T_R = \mathbf{7.8\ hr}$$



**2.8** Determine the storm hydrograph resulting from the rainfall pattern in Fig. P2–8(a) using the triangular 1-hr UH given in Fig. P2–8(b).



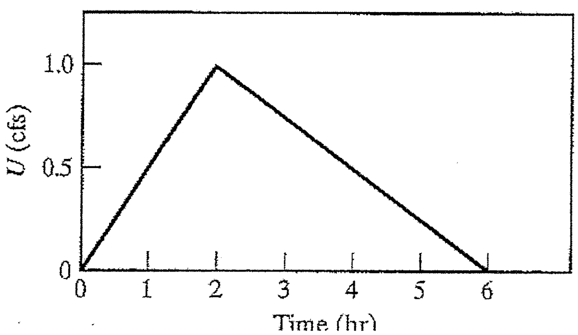




Fig. P2-8a

Fig. P2-8b

**ANSWER:**

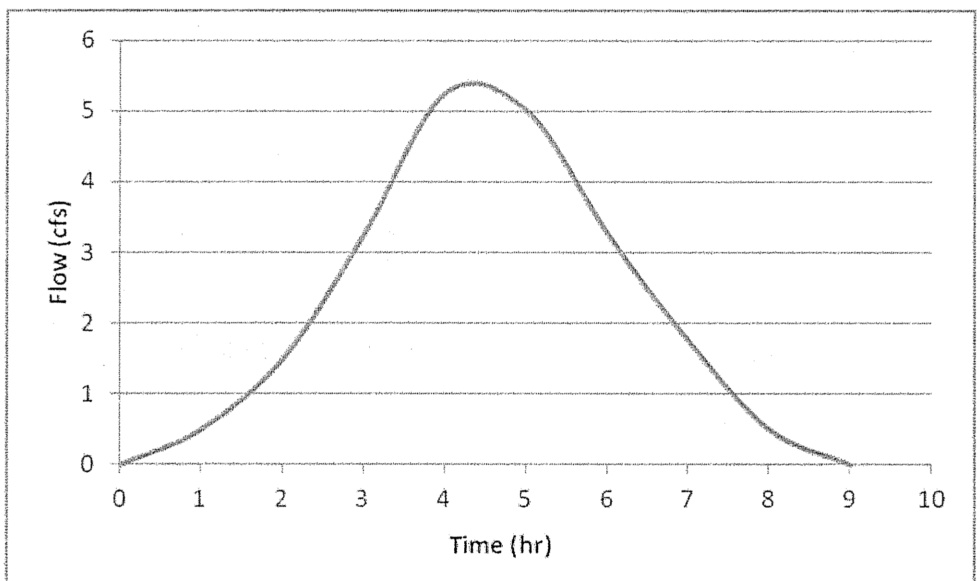
Since the rainfall is given in net rainfall, we do not need to subtract any losses. The rainfall for each time period is multiplied by the unit hydrograph ordinates to obtain the storm hydrograph. This computational procedure is in the table below:

In order to obtain $R_1U$ through $R_4U$. You take the UH units and you multiply it by the intensity for that given hour. Once you proceed to the next hour the values are lagged one hour. To obtain Q the values are then added across the table.

2.8 cont'

| Time (hrs) | UH | $R_1U$ | $R_2U$ | $R_3U$ | $R_4U$ | Q |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | | | | 0 |
| 1 | 0.5 | 0.5 | 0 | | | 0.5 |
| 2 | 1 | 1 | 0.5 | 0 | | 1.5 |
| 3 | 0.75 | 0.75 | 1 | 1.5 | 0 | 3.25 |
| 4 | 0.5 | 0.5 | 0.75 | 3 | 1 | 5.25 |
| 5 | 0.25 | 0.25 | 0.5 | 2.25 | 2 | 5 |
| 6 | 0 | | 0.25 | 1.5 | 1.5 | 3.25 |
| 7 | | | 0 | 0.75 | 1 | 1.75 |
| 8 | | | | 0 | 0.5 | 0.5 |
| 9 | | | | | 0 | 0 |

The hydrograph can then be plotted:



**2.9** (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,

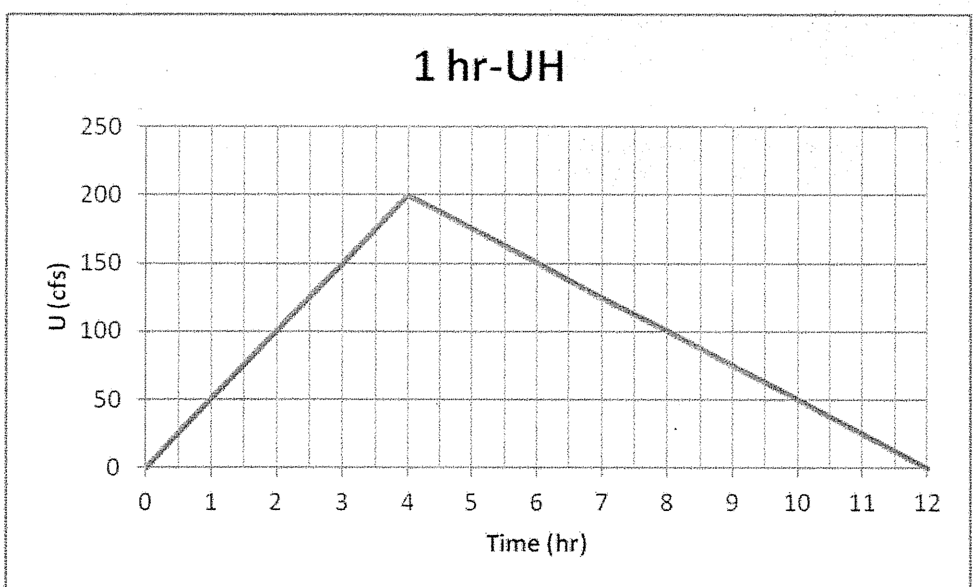
$Q_P =$ peak flow,

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 $P = [0.2,\ 1.0,\ 2.4]$.

**ANSWER:**

The UH ordinates are derived using the triangular 1-hr UH graph in 1 hour intervals:



2.9 cont'

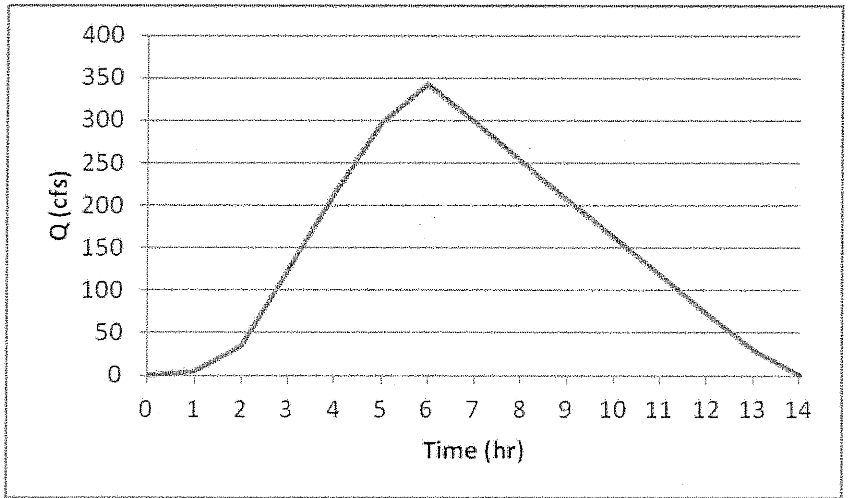
| Time (hr) | U (cfs) |
|---|---|
| 0 | 0 |
| 1 | 50 |
| 2 | 100 |
| 3 | 150 |
| 4 | 200 |
| 5 | 175 |
| 6 | 150 |
| 7 | 125 |
| 8 | 100 |
| 9 | 75 |
| 10 | 50 |
| 11 | 25 |
| 12 | 0 |

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

a.

| Time (hr) | 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 |

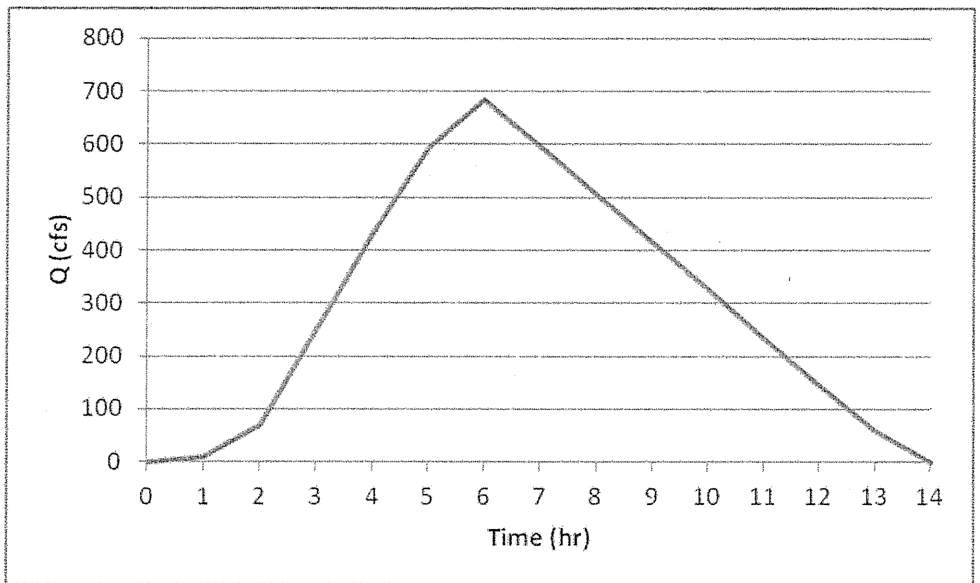
2.9 cont'




b.

| Time (hr) | U (cfs) | P1*U | P2*U | P3*U | Q |
|---|---|---|---|---|---|
| 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 |

2.9 cont'



800
700
600
500
400
300
200
100
0
Q (cfs)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Time (hr)

**2.10** A sketch of the Buffalo Creek Watershed is shown in Fig. P2–10. 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.

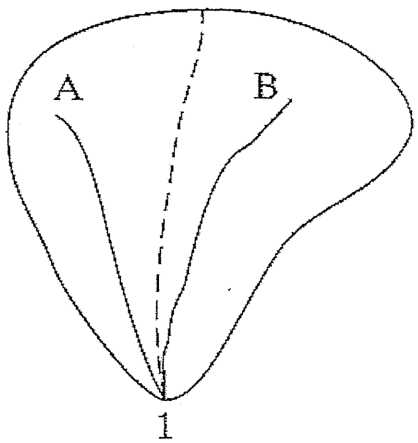



Fig P2-10

(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** | **9** | **10** | **11** | **12** | **13** | **14** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| UH (nat) | 0 | 12 | 32 | 62 | 108 | 180 | 208 | 182 | 126 | 80 | 53 | 32 | 18 | 6 | 0 |

2.10 cont'

**ANSWER:**

a. Assuming uniform loss, there is a loss rate of:

1 in. for two hours = $\frac{1\ in}{2\ hrs} = 0.5\frac{in}{hr}$

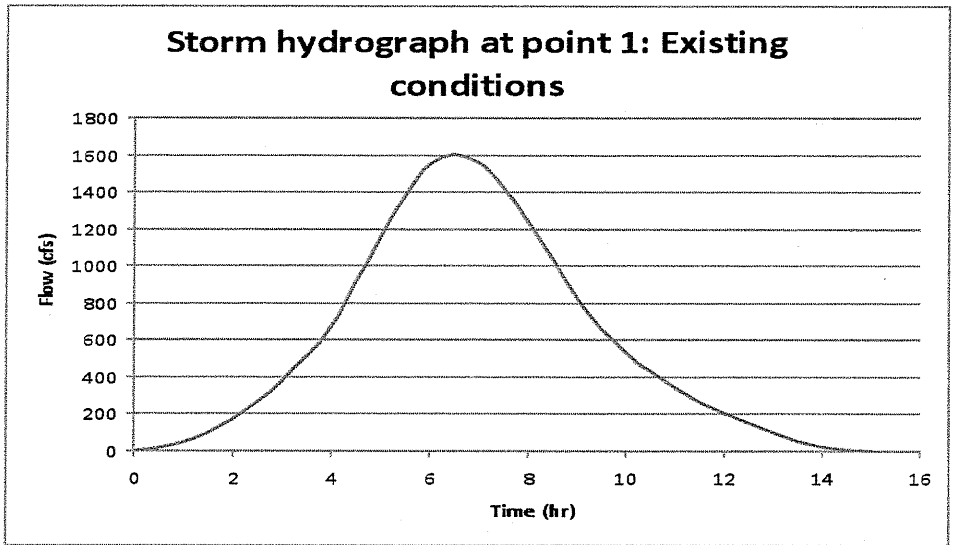
Net rainfall intensity = 2.5 – 0.5 = 2 in/hr for two hours

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) | $U_{nat}$ (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 |

2.10 cont'




$Q_p = 1560$ cfs at t = 7hr.

b. In this case we have to determine the storm hydrograph at point 1 for a 1-hr duration rainfall. i = 2in/hr for 1 hr

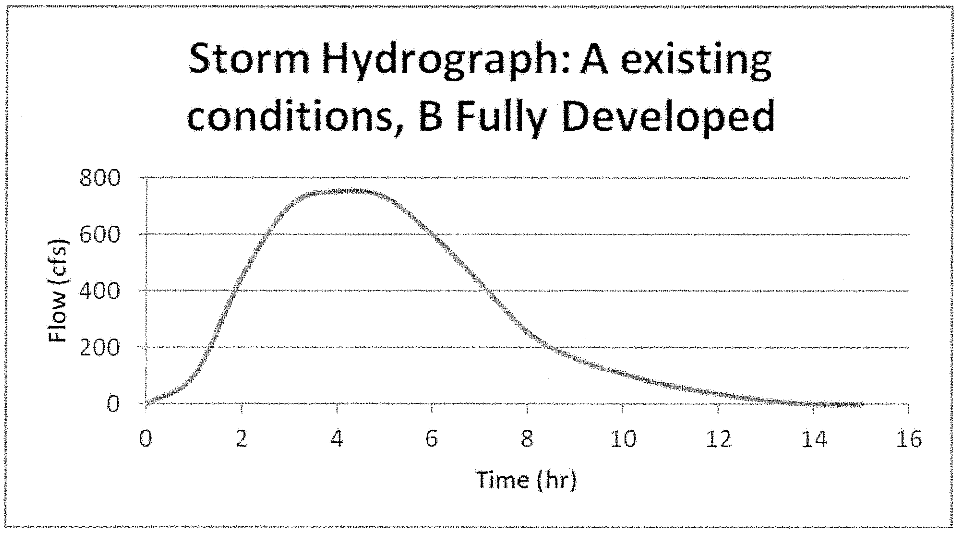
$Q_A$ = natural conditions

$Q_B$ = Fully developped

| Time (hr) | Unat (cfs) | Udevel | Qa (cfs) | Qb (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 |
| 15 | 0 | | 0 | | 0 |

2.10 cont'

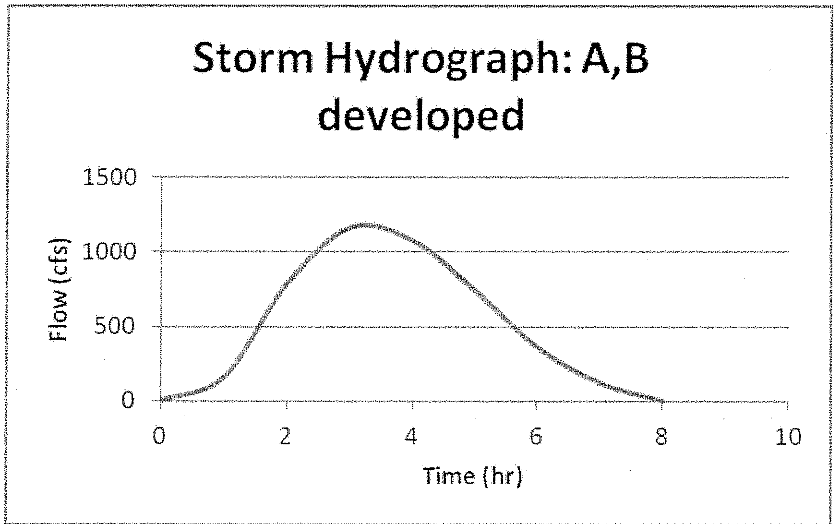



$Q_p = 752$ cfs at t = 4hr.

c. Areas A and B are fully developed. i = 2in/hr for 1 hr

| Time (hr) | Udevel | Qa (cfs) | Qb (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 |

2.10 cont'




$Q_p = 1160$ cfs at $t = 3$hr.

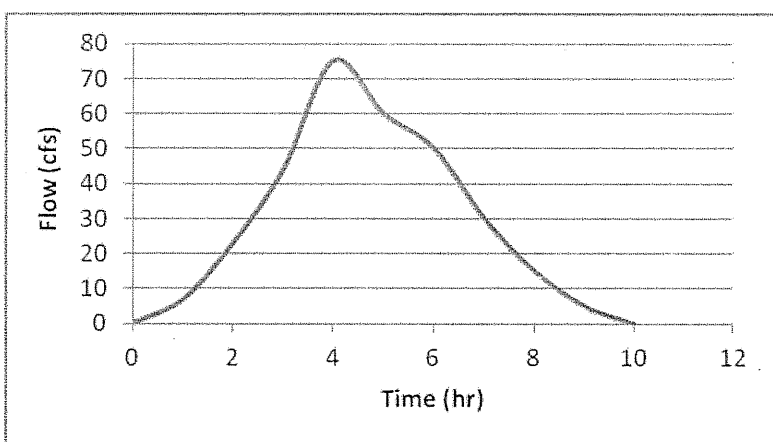
**2.11** The 1-hr UH in the accompanying table was recorded for a particular watershed. Determine the size of the watershed in acres and then convert the 1-hr UH into a 3-hr UH for the watershed.

| **Time (hr)** | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| U (cfs) | 0 | 7 | 23 | 44 | 75 | 60 | 50 | 30 | 15 | 5 | 0 |

**ANSWER:**

Create the hydrograph with the given data. With the time interval, the area of the watershed can be found by multiplying it by flow and then summing all the values, as given in the table.

| Time (hr) | Q (cfs) | Vol (cfs-hr) |
|---|---|---|
| 0 | 0 | 0 |
| 1 | 7 | 7 |
| 2 | 23 | 23 |
| 3 | 44 | 44 |
| 4 | 75 | 75 |
| 5 | 60 | 60 |
| 6 | 50 | 50 |
| 7 | 30 | 30 |
| 8 | 15 | 15 |
| 9 | 5 | 5 |
| 10 | 0 | 0 |

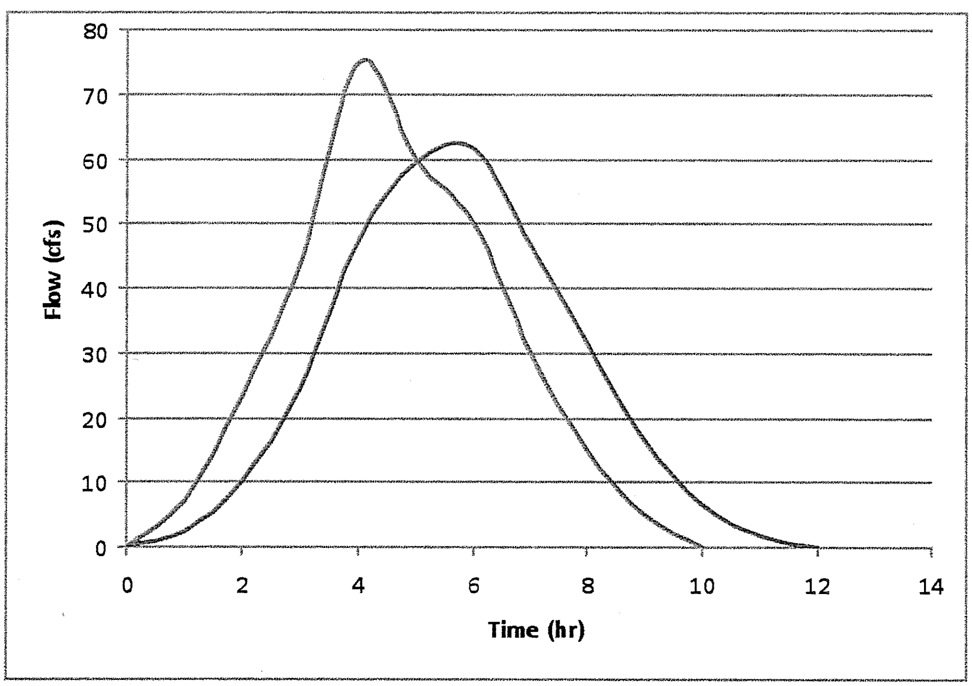


2.11 cont'

SUM =309 cfs-hr ≈309 ac-in. By the definition of a UH, the value under the UH represents the direct run off of 1 in. of rainfall excess over the watershed , so it follows that the **size of the watershed is 309 acres.**

To create a 3-hr UH, add together three incremental 1-hr UH's, lagging each by 1 hr, and divide the total by three. 3-hr UH = (U1 + U2 + U3)*(1/3)

| Time (hr) | Q (cfs) | U1 | U2 | U3 | 3 hr. UH |
|---|---|---|---|---|---|
| 0 | 0 | 0 | | | 0 |
| 1 | 7 | 7 | 0 | | 2 |
| 2 | 23 | 23 | 7 | 0 | 10 |
| 3 | 44 | 44 | 23 | 7 | 25 |
| 4 | 75 | 75 | 44 | 23 | 47 |
| 5 | 60 | 60 | 75 | 44 | 60 |
| 6 | 50 | 50 | 60 | 75 | 62 |
| 7 | 30 | 30 | 50 | 60 | 47 |
| 8 | 15 | 15 | 30 | 50 | 32 |
| 9 | 5 | 5 | 15 | 30 | 17 |
| 10 | 0 | 0 | 5 | 15 | 7 |
| 11 | | | 0 | 5 | 2 |
| 12 | | | | 0 | 0 |



**2.12** A major storm event was recorded for Little Bear Creek. The incremental rainfall and measured hydrograph data for this storm are provided in Table P2–12 in 1-hr increments. The drainage area for the basin is 3.25 $mi^2$. Assume base flow for Little Bear is zero. (See Fig. 1.26).

(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.

**Table P2–12**. Little Bear Creek Data

| **Date/Time** | | **Incremental Precipitation (in.)** | **Flow (cfs)** |
|---|---|---|---|
| 6/8/01 | 16:00 | 0 | 0.0 |
| 6/8/01 | 17:00 | 0.05 | 0.5 |
| 6/8/01 | 18:00 | 0.04 | 0.5 |
| 6/8/01 | 19:00 | 0 | 0.6 |
| 6/8/01 | 20:00 | 0.08 | 14 |
| 6/8/01 | 21:00 | 0.05 | 32 |
| 6/8/01 | 22:00 | 0.42 | 54 |
| 6/8/01 | 23:00 | 0.1 | 78 |
| 6/9/01 | 0:00 | 0.3 | 105 |
| 6/9/01 | 1:00 | 0.14 | 158 |
| 6/9/01 | 2:00 | 0.19 | 201 |
| 6/9/01 | 3:00 | 0.45 | 228 |

| | | | |
|---|---|---|---|
| 6/9/01 | 4:00 | 0.01 | 258 |
| 6/9/01 | 5:00 | 0 | 272 |
| 6/9/01 | 6:00 | | 225 |
| 6/9/01 | 7:00 | | 189 |
| 6/9/01 | 8:00 | | 142 |
| 6/9/01 | 9:00 | | 119 |
| 6/9/01 | 10:00 | | 98 |
| 6/9/01 | 11:00 | | 66 |
| 6/9/01 | 12:00 | | 42 |
| 6/9/01 | 13:00 | | 27 |
| 6/9/01 | 14:00 | | 0 |

**ANSWER:**

a. The volume can be determined be using the individual flows, timing it by the time interval and then adding them. The volume will be in cfs-hr. In this case since the time interval is 1 hr. $\sum Flow = \sum Volume =$ 2309.6 cfs-hr ~ 2309.6 ac-in

We are given the area in square miles which can be converted to acres and can be used to find runoff in inches.

$3.25\ mi^2 \cdot \frac{640\ acres}{1\ mi^2} = 2080\ acres \qquad \frac{2309.6\ ac-in}{2080\ ac} = \mathbf{1.11}\ \boldsymbol{inches}$

b. Knowing the amount of direct runoff in inches we can then subtract it from total rainfall to find what was lost to infiltration:

With the incremental precipitation we can find the total rainfall = $\sum incremental\ rainfall = 1.83\ inches$

Thus, total precipitation – direct runoff = infiltration loss

$1.83\ in - 1.11\ in = \mathbf{0.72}\ \boldsymbol{inches}$

2.12 cont'

c. Time to peak is found knowing the center of mass of rainfall excess and the time to the peak of the hydrograph. The peak of the hydrograph happens 13 hrs after the storm starts (at 5 o'clock). The center of mass of rainfall can be calculated by finding the weighted average of the rain (multiplying rainfall by the time) and then dividing it by the total rainfall.

See Excel table below.

$$\sum_{i=0}^{13} P_i t_i / \sum_{i=0}^{13} P_i = \text{Time to Center of Mass of Rainfall}$$

$$\frac{14.55 in.\cdot hr}{1.83 in.} = 7.95 \text{ hr}$$

Time to Peak Flow – Time to CM of Rainfall = 13 – 7.95 = **5 hr = Time to Peak**

*Note*: "Time to Peak" is NOT equal to "Time to Peak Flow"

| Date/Time | | Time Increment, t (hr) | Precipitation, P (in.) | P*t | Flow (cfs) |
|---|---|---|---|---|---|
| 6/8/2001 | 16:00 | 0 | 0 | 0 | 0 |
| 6/8/2001 | 17:00 | 1 | 0.05 | 0.05 | 0.5 |
| 6/8/2001 | 18:00 | 2 | 0.04 | 0.08 | 0.5 |
| 6/8/2001 | 19:00 | 3 | 0 | 0 | 0.6 |
| 6/8/2001 | 20:00 | 4 | 0.08 | 0.32 | 14 |
| 6/8/2001 | 21:00 | 5 | 0.05 | 0.25 | 32 |
| 6/8/2001 | 22:00 | 6 | 0.42 | 2.52 | 54 |
| 6/8/2001 | 23:00 | 7 | 0.1 | 0.7 | 78 |
| 6/9/2001 | 0:00 | 8 | 0.3 | 2.4 | 105 |
| 6/9/2001 | 1:00 | 9 | 0.14 | 1.26 | 158 |
| 6/9/2001 | 2:00 | 10 | 0.19 | 1.9 | 201 |
| 6/9/2001 | 3:00 | 11 | 0.45 | 4.95 | 228 |
| 6/9/2001 | 4:00 | 12 | 0.01 | 0.12 | 258 |
| 6/9/2001 | 5:00 | 13 | 0 | 0 | 272 |
| 6/9/2001 | 6:00 | | | | 225 |
| 6/9/2001 | 7:00 | | | | 189 |
| 6/9/2001 | 8:00 | | | | 142 |
| 6/9/2001 | 9:00 | | | | 119 |
| 6/9/2001 | 10:00 | | | | 98 |
| 6/9/2001 | 11:00 | | | | 66 |
| 6/9/2001 | 12:00 | | | | 42 |
| 6/9/2001 | 13:00 | | | | 27 |
| 6/9/2001 | 14:00 | | | | 0 |
| | | **SUM** | **1.83** | **14.55** | **2309.6** |

**2.13** Plot the hydrograph for the storm data given in Problem 1.22 (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).

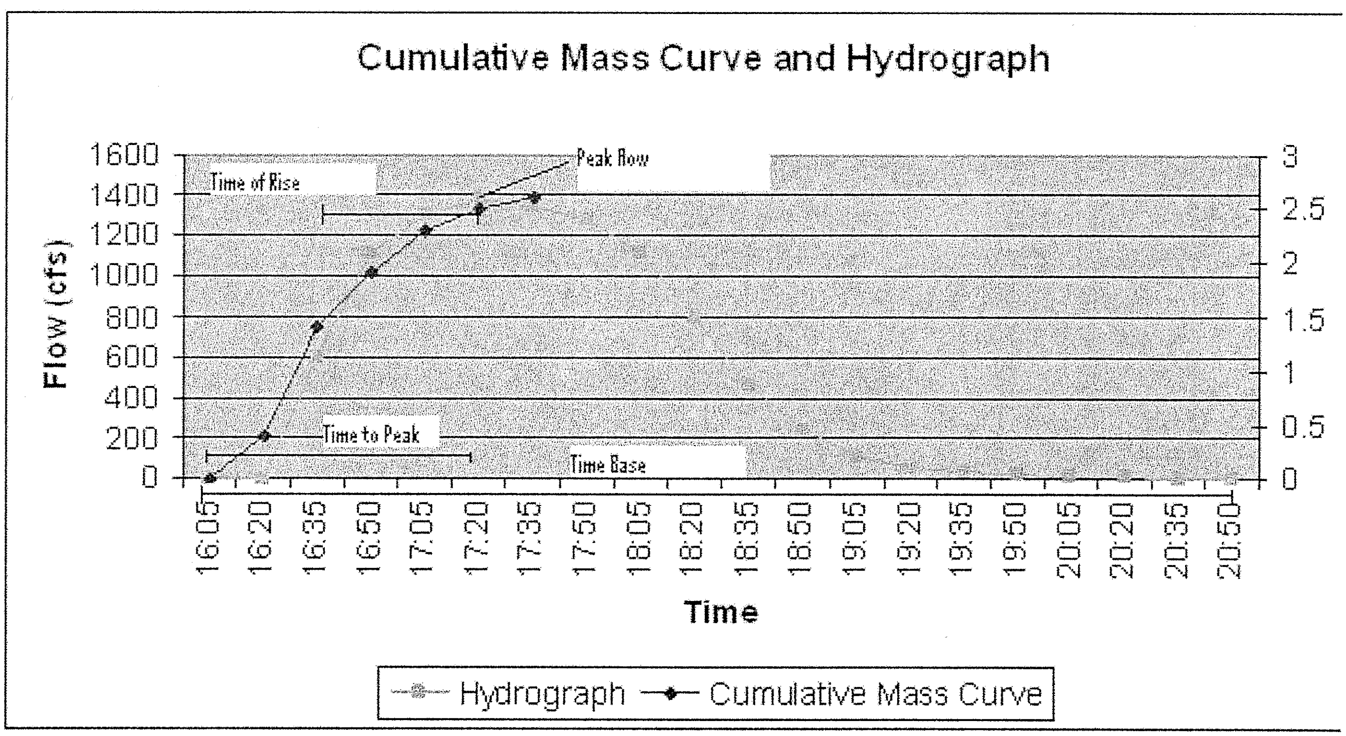
**ANSWER:**

(a) peak flow $Q_p$ =**1380 cfs**

(b) time to peak $t_p$ = **1hr**

(c) time of rise $T_R$ = **1.25hrs**

(d) time base $T_B$ = **2.75 hrs**



**2.14** 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.

| **Time (hr)** | **0** | **0.5** | **1.0** | **1.5** | **2.0** | **2.5** | **3.0** | **3.5** | **4.0** | **4.5** | **5.0** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $i$ (cm/hr) | 0 | 1.0 | 1.25 | 2.5 | 1.0 | | | | | | |
| $f$ (cm/hr) | 0 | 0.75 | 0.5 | 0.4 | 0.3 | | | | | | |
| U ($m^3$/s) | 0 | 33 | 66 | 80 | 75 | 55 | 35 | 20 | 10 | 4 | 0 |

**ANSWER:**

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 |

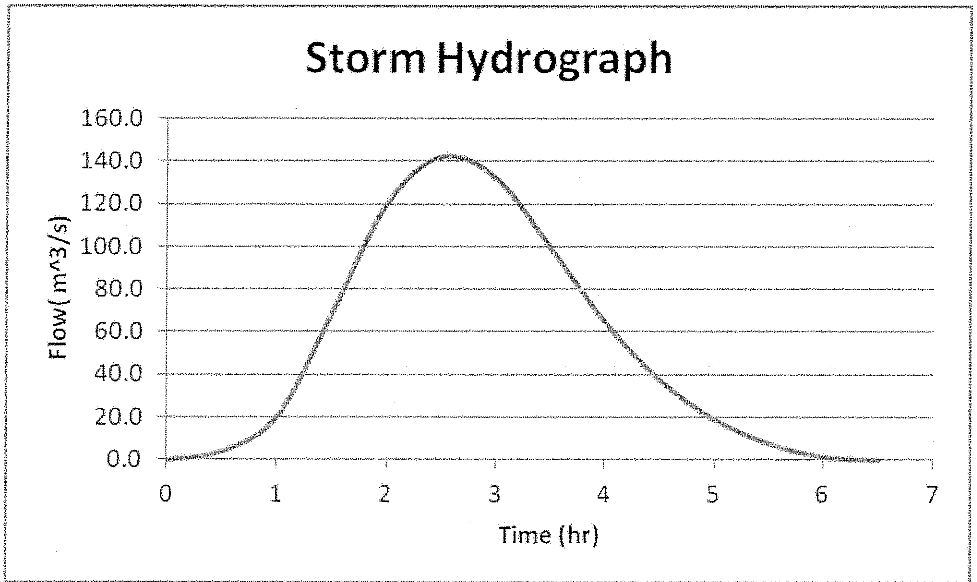
So net rainfall is found by multiplying Net Rainfall Intensity by 30 min (0.5 hr):

$P_n = \{0.125, 0.375, 1.05, 0.35\}$ cm

Then using a program such as Excel, the storm hydrograph can be developed.

| Time | U | P1*U | P2*U | P3*U | P4*U | Q |
|---|---|---|---|---|---|---|
| 0 | 0 | 0.0 | | | | 0.0 |
| 0.5 | 33 | 4.1 | 0.0 | | | 4.1 |
| 1 | 66 | 8.3 | 12.4 | 0.0 | | 20.6 |
| 1.5 | 80 | 10.0 | 24.8 | 34.7 | 0.0 | 69.4 |
| 2 | 75 | 9.4 | 30.0 | 69.3 | 11.6 | 120.2 |
| 2.5 | 55 | 6.9 | 28.1 | 84.0 | 23.1 | 142.1 |
| 3 | 35 | 4.4 | 20.6 | 78.8 | 28.0 | 131.8 |
| 3.5 | 20 | 2.5 | 13.1 | 57.8 | 26.3 | 99.6 |
| 4 | 10 | 1.3 | 7.5 | 36.8 | 19.3 | 64.8 |
| 4.5 | 4 | 0.5 | 3.8 | 21.0 | 12.3 | 37.5 |
| 5 | 0 | 0.0 | 1.5 | 10.5 | 7.0 | 19.0 |
| 5.5 | | | 0.0 | 4.2 | 3.5 | 7.7 |
| 6 | | | | 0.0 | 1.4 | 1.4 |
| 6.5 | | | | | 0.0 | 0.0 |

2.14 cont'


Storm Hydrograph
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Flow( m^3/s)
0
1
2
3
4
5
6
7
Time (hr)

**2.15** Using a program such as Excel, develop the S-curve for the given 30-min UH, and then develop the 15-min UH from the 30-min UH.

| **Time (hr)** | **0** | **0.25** | **0.5** | **0.75** | **1.0** | **1.25** | **1.5** |
|---|---|---|---|---|---|---|---|
| U (cfs) | 0 | 15 | 70.9 | 118.6 | 109.4 | 81.6 | 60.9 |

| **Time (hr)** | **1.75** | **2.0** | **2.25** | **2.5** | **2.75** | **3.0** | **3.25** |
|---|---|---|---|---|---|---|---|
| U (cfs) | 45.4 | 33.9 | 25.3 | 18.9 | 14.1 | 10.5 | 7.8 |

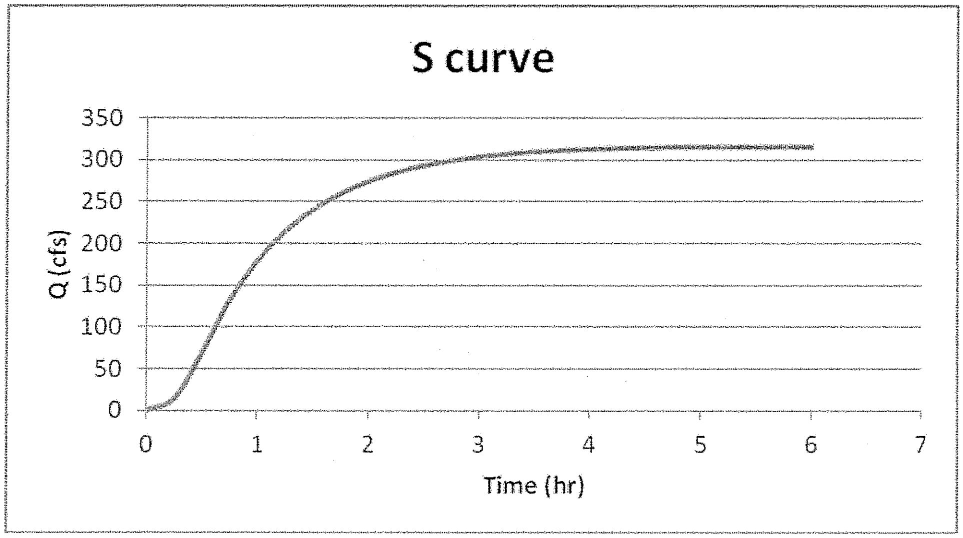
| **Time (hr)** | **3.5** | **3.75** | **4.0** | **4.25** | **4.5** | **4.75** | **5.0** | **5.25** |
|---|---|---|---|---|---|---|---|---|
| U (cfs) | 5.8 | 4.4 | 3.3 | 2.4 | 1.8 | 1.6 | 0.8 | 0 |

## ANSWER:

Create the S using the 30-min unit hydrograph. Lag by 30 min until you reach 0

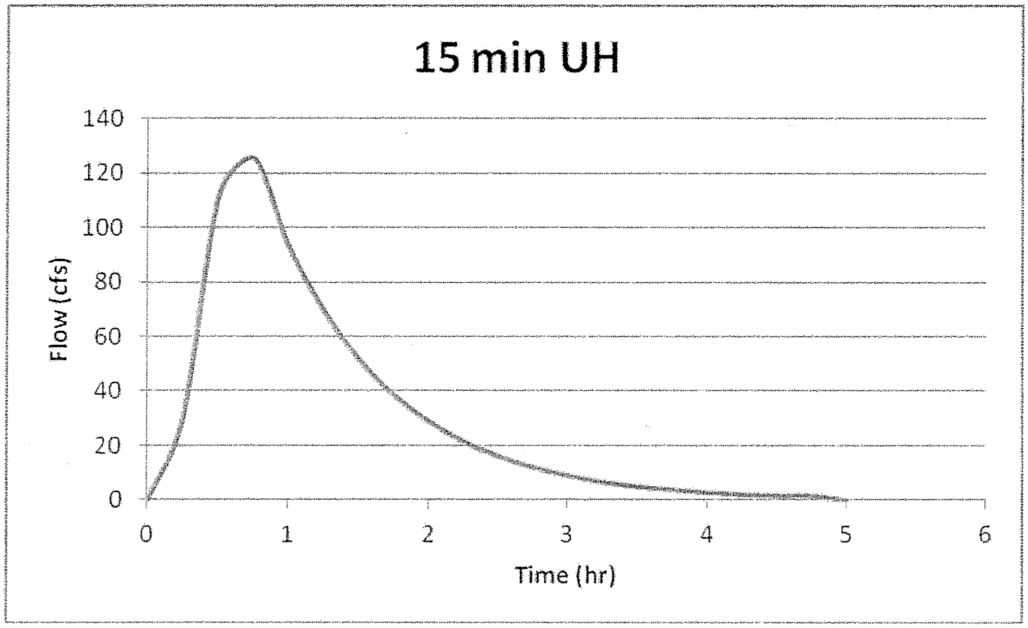
| Time | U (cfs) | 30 min lagged UH | | | | | | | | | | | | S-curve |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | | | | | | | | | | | | | 0 |
| 0.25 | 15 | | | | | | | | | | | | | 15 |
| 0.5 | 70.9 | 0 | | | | | | | | | | | | 70.9 |
| 0.75 | 118.6 | 15 | | | | | | | | | | | | 133.6 |
| 1 | 109.4 | 70.9 | 0 | | | | | | | | | | | 180.3 |
| 1.25 | 81.6 | 118.6 | 15 | | | | | | | | | | | 215.2 |
| 1.5 | 60.9 | 109.4 | 70.9 | 0 | | | | | | | | | | 241.2 |
| 1.75 | 45.4 | 81.6 | 118.6 | 15 | | | | | | | | | | 260.6 |
| 2 | 33.9 | 60.9 | 109.4 | 70.9 | 0 | | | | | | | | | 275.1 |
| 2.25 | 25.3 | 45.4 | 81.6 | 118.6 | 15 | | | | | | | | | 285.9 |
| 2.5 | 18.9 | 33.9 | 60.9 | 109.4 | 70.9 | 0 | | | | | | | | 294 |
| 2.75 | 14.1 | 25.3 | 45.4 | 81.6 | 118.6 | 15 | | | | | | | | 300 |
| 3 | 10.5 | 18.9 | 33.9 | 60.9 | 109.4 | 70.9 | 0 | | | | | | | 304.5 |
| 3.25 | 7.8 | 14.1 | 25.3 | 45.4 | 81.6 | 118.6 | 15 | | | | | | | 307.8 |
| 3.5 | 5.8 | 10.5 | 18.9 | 33.9 | 60.9 | 109.4 | 70.9 | 0 | | | | | | 310.3 |
| 3.75 | 4.4 | 7.8 | 14.1 | 25.3 | 45.4 | 81.6 | 118.6 | 15 | | | | | | 312.2 |
| 4 | 3.3 | 5.8 | 10.5 | 18.9 | 33.9 | 60.9 | 109.4 | 70.9 | 0 | | | | | 313.6 |
| 4.25 | 2.4 | 4.4 | 7.8 | 14.1 | 25.3 | 45.4 | 81.6 | 118.6 | 15 | | | | | 314.6 |
| 4.5 | 1.8 | 3.3 | 5.8 | 10.5 | 18.9 | 33.9 | 60.9 | 109.4 | 70.9 | 0 | | | | 315.4 |
| 4.75 | 1.6 | 2.4 | 4.4 | 7.8 | 14.1 | 25.3 | 45.4 | 81.6 | 118.6 | 15 | | | | 316.2 |
| 5 | 0.8 | 1.8 | 3.3 | 5.8 | 10.5 | 18.9 | 33.9 | 60.9 | 109.4 | 70.9 | 0 | | | 316.2 |
| 5.25 | 0 | 1.6 | 2.4 | 4.4 | 7.8 | 14.1 | 25.3 | 45.4 | 81.6 | 118.6 | 15 | | | 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 | | 316.2 |
| 5.75 | | 0 | 1.6 | 2.4 | 4.4 | 7.8 | 14.1 | 25.3 | 45.4 | 81.6 | 118.6 | 15 | | 316.2 |
| 6 | | | 0.8 | 1.8 | 3.3 | 5.8 | 10.5 | 18.9 | 33.9 | 60.9 | 109.4 | 70.9 | 0 | 316.2 |

2.15 cont'




| Time | S-curve | S-Curve lagged (15 min) | Difference | 15 min 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 |

2.15 cont'



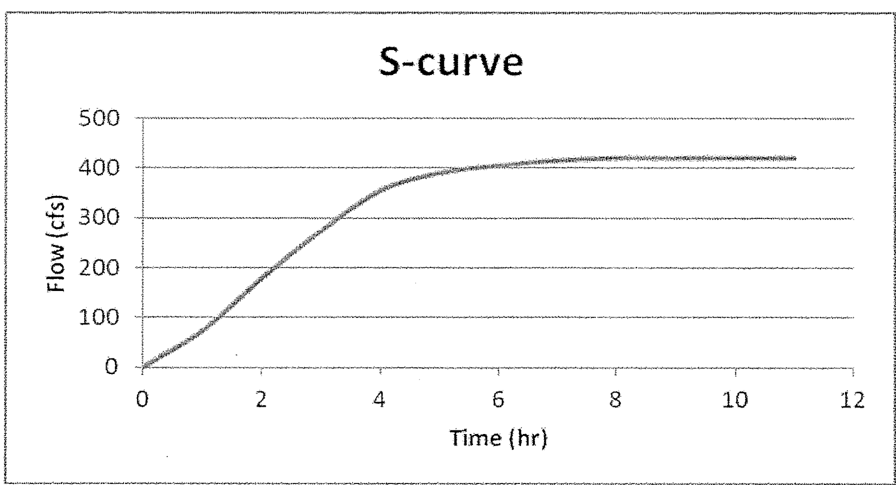
**2.16** Using Excel spreadsheet programs, develop the S-curve for the given 3-hr UH, and then develop the 2-hr UH from the 3-hr UH.

| **Time (hr)** | **0** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|---|
| U (cfs) | 0 | 75 | 180 | 275 | 280 | 210 |
| **Time (hr)** | **6** | **7** | **8** | **9** | **10** | **11** |
| U (cfs) | 130 | 60 | 30 | 15 | 5 | 0 |

**ANSWER:**

First develop the S-curve for the 3 hr UH

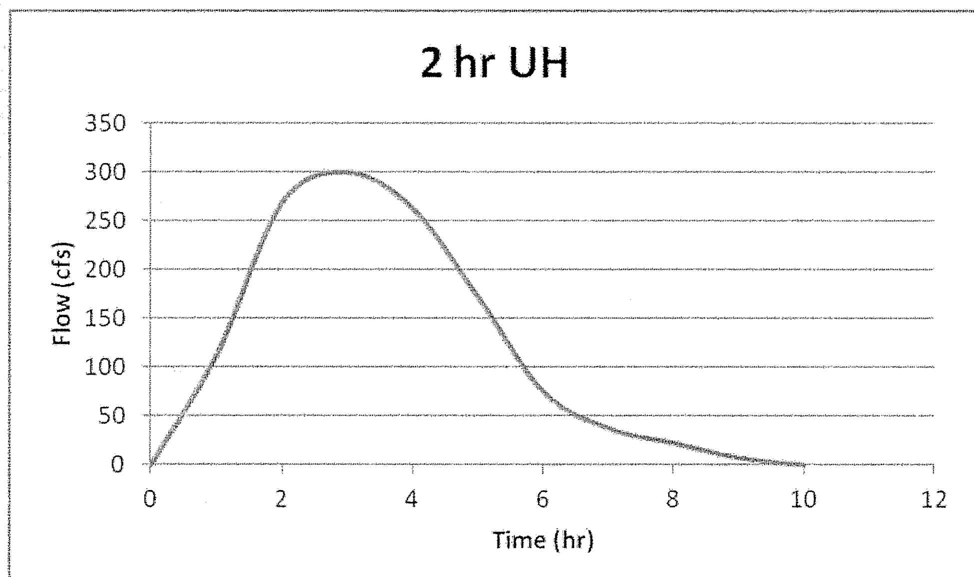
| Time (hr) | U (cfs) | 3 hr lagged UH | | | S-curve |
|---|---|---|---|---|---|
| 0 | 0 | | | | 0 |
| 1 | 75 | | | | 75 |
| 2 | 180 | | | | 180 |
| 3 | 275 | 0 | | | 275 |
| 4 | 280 | 75 | | | 355 |
| 5 | 210 | 180 | | | 390 |
| 6 | 130 | 275 | 0 | | 405 |
| 7 | 60 | 280 | 75 | | 415 |
| 8 | 30 | 210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



2.16 cont'

The next step is to lag the S-curve by two hours and subtract 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 | Difference | 2 hr UH |
|---|---|---|---|---|
| | | lagged 2 hrs | | (D/D'=3/2) |
| 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 |



**2.17** 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 | 25 | 125 | 250 | 400 | 500 | 450 |

| **Time (hr)** | **7** | **8** | **9** | **10** | **11** | **12** | **13** |
|---|---|---|---|---|---|---|---|
| Flow (cfs) | 350 | 300 | 225 | 150 | 100 | 25 | 0 |

**ANSWER**:

Procedure to obtain the 1 hr hydrograph:

~ 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 of D/D' where D is the original duration and D' is the desired duration (2/1 =2)

| Time | 2-Hr UH | | | | | | | S-curve | Lagged S-curve | Difference (cfs) | 1 Hr UH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | | | | | | | 0 | | 0 | 0 |
| 1 | 25 | | | | | | | 25 | 0 | 25 | 50 |
| 2 | 125 | 0 | | | | | | 125 | 25 | 100 | 200 |
| 3 | 250 | 25 | | | | | | 275 | 125 | 150 | 300 |
| 4 | 400 | 125 | 0 | | | | | 525 | 275 | 250 | 500 |
| 5 | 500 | 250 | 25 | | | | | 775 | 525 | 250 | 500 |
| 6 | 450 | 400 | 125 | 0 | | | | 975 | 775 | 200 | 400 |
| 7 | 350 | 500 | 250 | 25 | | | | 1125 | 975 | 150 | 300 |
| 8 | 300 | 450 | 400 | 125 | 0 | | | 1275 | 1125 | 150 | 300 |
| 9 | 225 | 350 | 500 | 250 | 25 | | | 1350 | 1275 | 75 | 150 |
| 10 | 150 | 300 | 450 | 400 | 125 | 0 | | 1425 | 1350 | 75 | 150 |
| 11 | 100 | 225 | 350 | 500 | 250 | 25 | | 1450 | 1425 | 25 | 50 |
| 12 | 25 | 150 | 300 | 450 | 400 | 125 | 0 | 1450 | 1450 | 0 | 0 |
| 13 | 0 | 100 | 225 | 350 | 500 | 250 | 25 | 1450 | 1450 | 0 | 0 |

The same procedure is done to convert to the 2 hr UH.

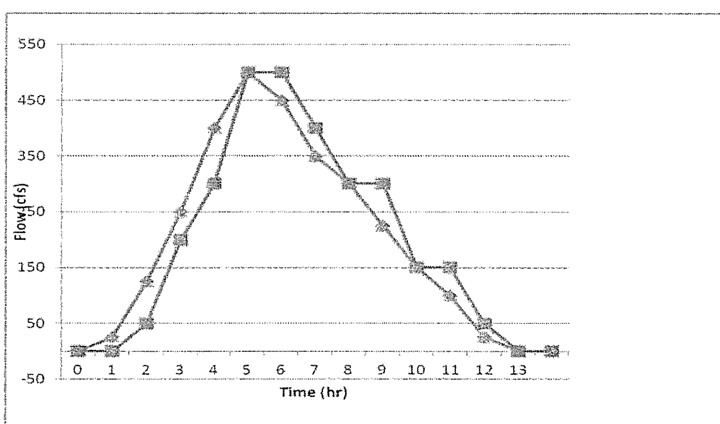
2.17 cont'

~Lag the 1-hr unit hydrograph by 1-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, 2 hr)

~Multiply the resulting ordinate values by the ratio of D/D' where D is the original duration and D' is the desired duration (1/2 =.5)

| Time | 1-Hr UH lagged | | | | | | | | | | | | | | S-curve | Lagged S-curve | Difference (cfs) | 1 Hr UH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | | | | | | | | | | | | | | 0 | | 0 | 0 |
| 1 | 50 | 0 | | | | | | | | | | | | | 50 | | 50 | 25 |
| 2 | 200 | 50 | 0 | | | | | | | | | | | | 250 | 0 | 250 | 125 |
| 3 | 300 | 200 | 50 | 0 | | | | | | | | | | | 550 | 50 | 500 | 250 |
| 4 | 500 | 300 | 200 | 50 | 0 | | | | | | | | | | 1050 | 250 | 800 | 400 |
| 5 | 500 | 500 | 300 | 200 | 50 | 0 | | | | | | | | | 1550 | 550 | 1000 | 500 |
| 6 | 400 | 500 | 500 | 300 | 200 | 50 | 0 | | | | | | | | 1950 | 1050 | 900 | 450 |
| 7 | 300 | 400 | 500 | 500 | 300 | 200 | 50 | 0 | | | | | | | 2250 | 1550 | 700 | 350 |
| 8 | 300 | 300 | 400 | 500 | 500 | 300 | 200 | 50 | 0 | | | | | | 2550 | 1950 | 600 | 300 |
| 9 | 150 | 300 | 300 | 400 | 500 | 500 | 300 | 200 | 50 | 0 | | | | | 2700 | 2250 | 450 | 225 |
| 10 | 150 | 150 | 300 | 300 | 400 | 500 | 500 | 300 | 200 | 50 | 0 | | | | 2850 | 2550 | 300 | 150 |
| 11 | 50 | 150 | 150 | 300 | 300 | 400 | 500 | 500 | 300 | 200 | 50 | 0 | | | 2900 | 2700 | 200 | 100 |
| 12 | 0 | 50 | 150 | 150 | 300 | 300 | 400 | 500 | 500 | 300 | 200 | 50 | 0 | | 2900 | 2850 | 50 | 25 |
| 13 | 0 | 0 | 50 | 150 | 150 | 300 | 300 | 400 | 500 | 500 | 300 | 200 | 50 | 0 | 2900 | 2900 | 0 | 0 |




Blue = 1-hr UH, Red = 2-hr UH.

**2.18** Develop storm hydrographs from UHs of subareas 1 and 2 shown in figure P2-18 for the given rainfall and infiltration.

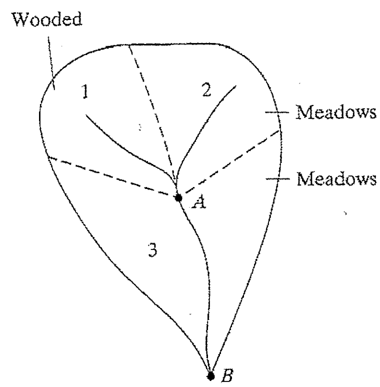



Fig P2-18

| *t* (hr) | *i* (in./hr) | *f* (in./hr) |
|---|---|---|
| 1 | 0.5 | 0.4 |
| 2 | 1.1 | 0.2 |
| 3 | 3 | 0.2 |
| 4 | 0.9 | 0.2 |

| Time (hr) | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| $UH_1$ (cfs) | 0 | 200 | 450 | 650 | 450 | 300 | 150 | 0 | | |
| $UH_2$ (cfs) | 0 | 150 | 300 | 500 | 350 | 250 | 125 | 100 | 50 | 0 |

**ANSWER:**

| Time (hr) | *i* (in./hr) | *f* (in./hr) | Net Rainfall Intensity (in/hr) |
|---|---|---|---|
| 1 | 0.5 | 0.4 | 0.1 |
| 2 | 1.1 | 0.2 | 0.9 |
| 3 | 3 | 0.2 | 2.8 |
| 4 | 0.9 | 0.2 | 0.7 |

2.18 cont'

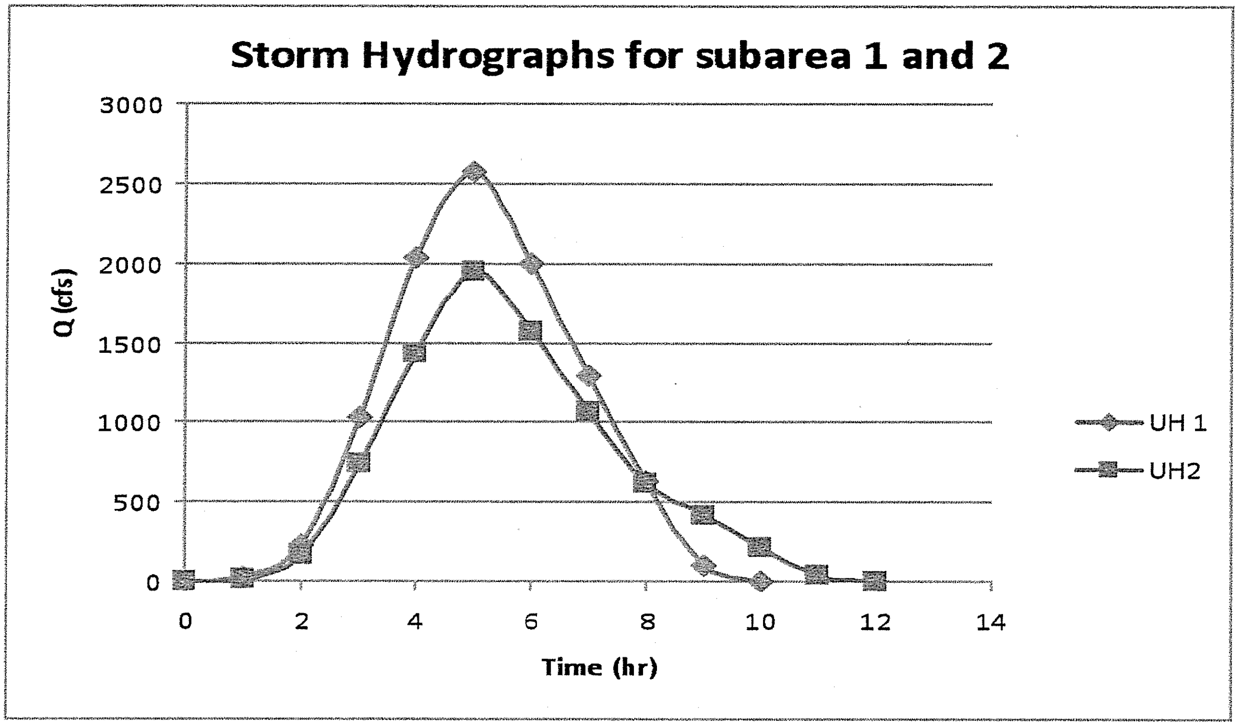
Subarea 1

| 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 | 450 | 45 | 180 | 0 | | 225 |
| 3 | 650 | 65 | 405 | 560 | 0 | 1030 |
| 4 | 450 | 45 | 585 | 1260 | 140 | 2030 |
| 5 | 300 | 30 | 405 | 1820 | 315 | 2570 |
| 6 | 150 | 15 | 270 | 1260 | 455 | 2000 |
| 7 | 0 | 0 | 135 | 840 | 315 | 1290 |
| 8 | | | 0 | 420 | 210 | 630 |
| 9 | | | | 0 | 105 | 105 |
| 10 | | | | | 0 | 0 |

Subarea 2

| Time (hr) | UH2 | P1*UH2 (cfs) | P2*UH2 (cfs) | P3*UH2 (cfs) | P4*UH2 (cfs) | Q2 (cfs) |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | | | | 0 |
| 1 | 150 | 15 | 0 | | | 15 |
| 2 | 300 | 30 | 135 | 0 | | 165 |
| 3 | 500 | 50 | 270 | 420 | 0 | 740 |
| 4 | 350 | 35 | 450 | 840 | 105 | 1430 |
| 5 | 250 | 25 | 315 | 1400 | 210 | 1950 |
| 6 | 125 | 12.5 | 225 | 980 | 350 | 1567.5 |
| 7 | 100 | 10 | 112.5 | 700 | 245 | 1067.5 |
| 8 | 50 | 5 | 90 | 350 | 175 | 620 |
| 9 | 0 | 0 | | 280 | 87.5 | 367.5 |
| 10 | | | | | 70 | 70 |
| 11 | | | | | 35 | 35 |
| 12 | | | | | 0 | 0 |

2.18 cont'



Storm Hydrographs for subarea 1 and 2
3000
2500
2000
1500
1000
500
0
Q (cfs)
0
2
4
6
8
10
12
14
Time (hr)
UH 1
UH2

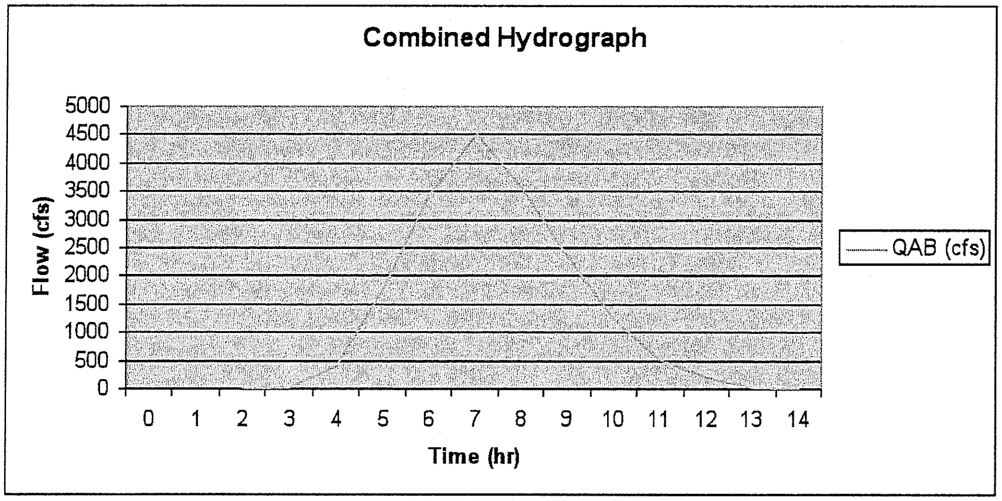
**2.19** Develop a combined storm hydrograph at point *A* in the watershed (Fig. P2–18) and lag route (shift in time only) assuming that travel time from point *A* to *B* is exactly 2 hours.

**ANSWER:**

We add the ordinates $Q_1$ and $Q_2$ from the previous problem to develop the combined storm hydrograph at point A.

We then account for a 2-hr lag between points A and B to create a combined hydrograph for A and B.

| Time (hr) | $Q_1$ (cfs) | $Q_2$ (cfs) | $Q_A$ (cfs) | $Q_{AB}$ (cfs) |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | |
| 1 | 20 | 15 | 35 | |
| 2 | 225 | 165 | 390 | 0 |
| 3 | 1030 | 740 | 1770 | 35 |
| 4 | 2030 | 1430 | 3460 | 390 |
| 5 | 2570 | 1950 | 4520 | 1770 |
| 6 | 2000 | 1568 | 3568 | 3460 |
| 7 | 1290 | 1068 | 2358 | 4520 |
| 8 | 630 | 620 | 1250 | 3568 |
| 9 | 105 | 412.5 | 517.5 | 2358 |
| 10 | 0 | 210 | 210 | 1250 |
| 11 | | 35 | 35 | 517.5 |
| 12 | | 0 | 0 | 210 |
| 13 | | | | 35 |
| 14 | | | | 0 |


Combined Hydrograph
Flow (cfs)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Time (hr)
QAB (cfs)

**2.20** Develop a storm hydrograph for subarea 3 from the given UH, add to the combined hydrograph from Problem 2.19, and produce a final storm hydrograph at the outlet of the watershed, *B*.

| Time (hr) | $UH_3$ (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 | | | |

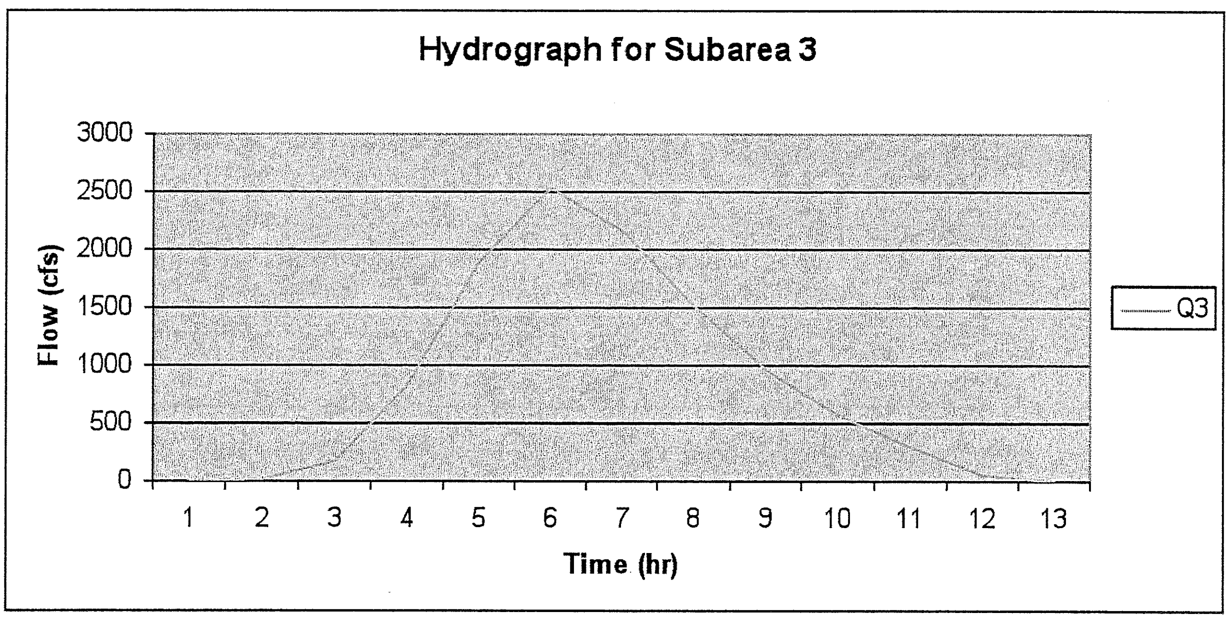
**ANSWER:**

The net rainfall intensity was obtained in problem 2.18

| Time (hr) | *i* (in./hr) | *f* (in./hr) | **Net Rainfall Intensity (in/hr)** |
|---|---|---|---|
| 1 | 0.5 | 0.4 | 0.1 |
| 2 | 1.1 | 0.2 | 0.9 |
| 3 | 3 | 0.2 | 2.8 |
| 4 | 0.9 | 0.2 | 0.7 |

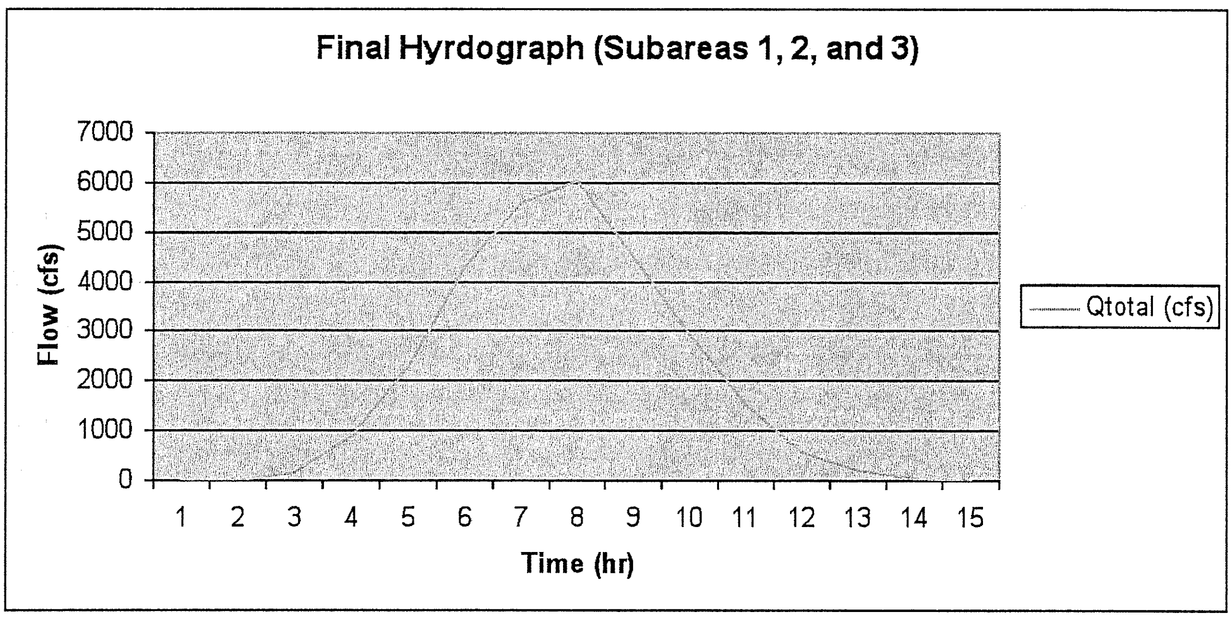
2.20 cont'

| Time (hr) | UH3 | P1*UH3 | P2*UH3 | P3*UH3 | P4*UH3 | Q3 |
|---|---|---|---|---|---|---|
| 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 |



2.20 cont'

| Time (hr) | $Q_{AB}$ (cfs) | $Q_3$ (cfs) | $Q_{total}$ (cfs) |
|---|---|---|---|
| 0 | | 0 | 0 |
| 1 | | 14 | 14 |
| 2 | 0 | 168 | 168 |
| 3 | 35 | 833 | 868 |
| 4 | 390 | 1890 | 2280 |
| 5 | 1770 | 2534 | 4304 |
| 6 | 3460 | 2149 | 5609 |
| 7 | 4520 | 1525 | 6045 |
| 8 | 3568 | 957 | 4525 |
| 9 | 2358 | 574 | 2932 |
| 10 | 1250 | 287 | 1537 |
| 11 | 517.5 | 49 | 566.5 |
| 12 | 210 | 0 | 210 |
| 13 | 35 | | 35 |
| 14 | 0 | | 0 |



**2.21** Redo Example 2–6 if the watershed is soil type B in good cover forest land. How does the forested area compare to the meadow UH?

**ANSWER:**

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

$$S = (1000 / CN) - 10 = (1000 / 55) - 10 = 8.18 \text{ in.}$$

Convert miles into feet.

$$L = (5 \text{ mi})(5280 \text{ ft/mi}) = 26{,}400 \text{ ft.}$$

The slope is 100 ft/mi, so

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

Thus, time to peak is

$$t_p = \left[\frac{(L)^{0.8}(S+1)^{0.7}}{1900\sqrt{y}}\right] = \left[\frac{(26{,}400)^{0.8}(8.18+1)^{0.7}}{1900\sqrt{1.9}}\right] = 6.21 \text{ hr}$$

With rainfall duration D = 2 hr, the time to rise is

$$T_R = D/2 + t_p = 2/2 + 6.21 = 7.21 \text{ hr}$$

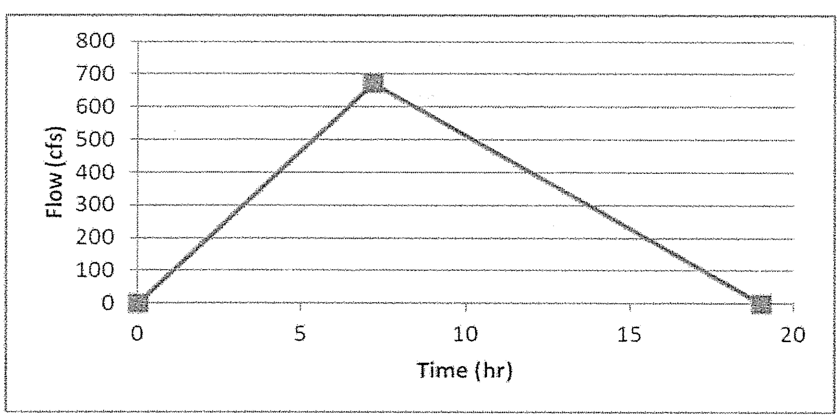
Peak flow is

$$Q_p = (484A / T_R) = (484*10 / 6.21) = 779.4 \text{ cfs}$$

where A is the area of 10 $mi^2$

To complete the graph it is necessary to know the time of fall B.

$B = 1.67T_R = 12.04$



2.21 cont'

| | Forested Area (Group B) | Meadow (Group D) |
|---|---|---|
| $T_R$ | 7.2 hr | 4.36 hr |
| B | 11.84 hr | 7.17 hr |
| $Q_p$ | 672.2 cfs | 1110 cfs |
| S | 8.18 | 2.82 in. |

**2.22** 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.

**ANSWER:**

| | Soil Group | % | CN |
|---|---|---|---|
| Good Meadow Conditions | A | 0.6*0.3 = 0.18 | 30 |
| | C | 0.6*0.7 = 0.42 | 71 |
| Good cover forest land | A | 0.4*0.3 = .12 | 25 |
| | C | 0.4*0.7 = .28 | 70 |

The weighted CN is:

$$(0.18)(30) + (0.42)(71) + (0.12)(25) + (0.28)(70) = \mathbf{58}$$

l = length to divide

$$l = 18 \text{ mi.} = (18 \text{ mi.})(5280 \text{ ft/mi.}) = \mathbf{95{,}040\ ft}$$

D = rainfall duration (hr)

$$D = \mathbf{3\ hr}$$

y = average watershed slope (in percent)

$$y = (100 \text{ ft/mi.})(1 \text{ mi./}5280 \text{ ft})(100\%) = \mathbf{1.9\%}$$

S = (1000/CN) – 10 (in.)

$$S = (1000/58) - 10 = \mathbf{7.24\ in.}$$

$t_p$ = lag time (hr)

$$t_p = \frac{L^{0.8}(S+1)^{0.7}}{1900\sqrt{y}} = \frac{(95{,}040)^{0.8}(7.24+1)^{0.7}}{1900\sqrt{1.9}} = \mathbf{16.05\ hr}$$

$T_R$ = time of rise (hr)

$$T_R = D/2 + t_p = (3/2) + 16.05 = \mathbf{17.55\ hr}$$

$Q_P$ = peak flow (cfs) and A = area of watershed (mi.$^2$)

$$Q_P = \frac{484A}{T_R} = \frac{(484)(100)}{17.55} = \mathbf{2{,}758\ cfs}$$

2.22 cont'

B = time of fall

$$B = 1.67T_R = (1.67)(17.55) = \mathbf{29.31\ hr}$$

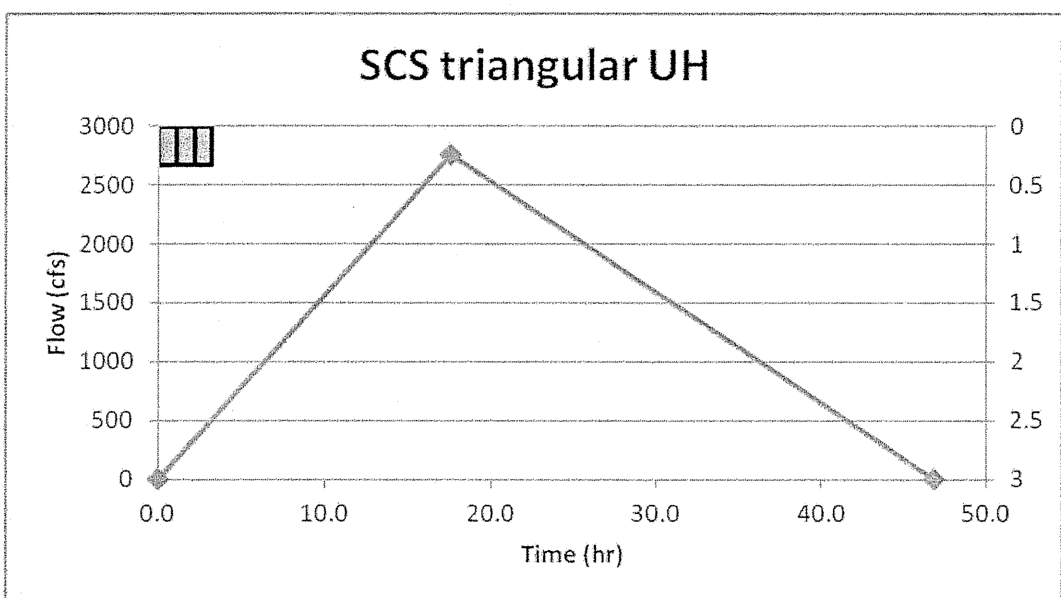
Alternatively, since the volume is known to be 1 in. of direct runoff over the watershed,

$$\text{Vol} = (10mi.^2)\left(\frac{5280ft}{mi.}\right)^2\left(\frac{ac}{43{,}560ft^2}\right)(1in.) = 64{,}000 \text{ ac-in} \approx 64{,}000 \text{ cfs-hr}$$

$$\text{Vol} = \frac{Q_P T_R}{2} + \frac{Q_P B}{2} = 64{,}000 \text{ cfs-hr}$$

$$64{,}000 \text{ cfs-hr} = \frac{(2758cfs)(17.55hr)}{2} + \frac{(2758cfs)(Bhr)}{2}$$

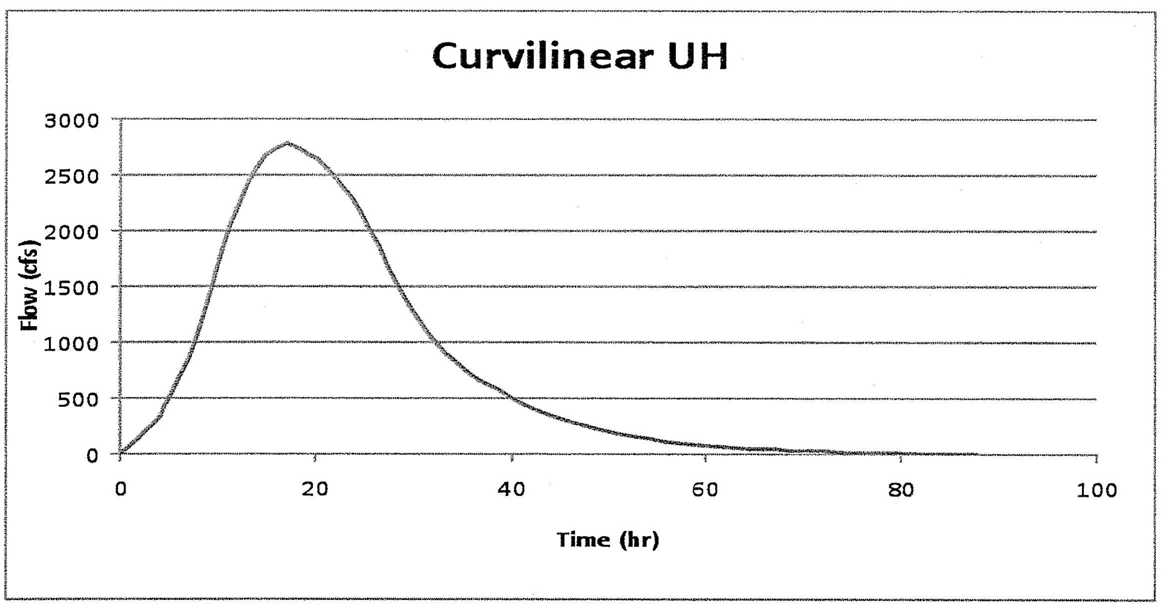
$$B = \mathbf{28.86\ hr}$$




Use the Table from example 2.9 to obtain $t/T_R$ and $Q_i/Q_P$. Multiply $t/T_R$ by $T_R$ to get t for hydrograph and multiply $Q_i/Q_P$ by $Q_P$ to get Q for hydrograph.

2.22 cont'

| $t/T_R$ | t | $Q_i/Q_p$ | $Q_i$ |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 0.2 | 3.51 | 0.1 | 276 |
| 0.3 | 5.265 | 0.19 | 524 |
| 0.4 | 7.02 | 0.31 | 855 |
| 0.5 | 8.775 | 0.47 | 1296 |
| 0.6 | 10.53 | 0.66 | 1820 |
| 0.7 | 12.285 | 0.82 | 2262 |
| 0.8 | 14.04 | 0.93 | 2565 |
| 0.9 | 15.795 | 0.99 | 2730 |
| 1 | 17.55 | 1 | 2758 |
| 1.2 | 21.06 | 0.93 | 2565 |
| 1.4 | 24.57 | 0.78 | 2151 |
| 1.6 | 28.08 | 0.56 | 1544 |
| 1.8 | 31.59 | 0.39 | 1076 |
| 2 | 35.1 | 0.28 | 772 |
| 2.2 | 38.61 | 0.207 | 571 |
| 2.4 | 42.12 | 0.147 | 405 |
| 2.6 | 45.63 | 0.107 | 295 |
| 2.8 | 49.14 | 0.077 | 212 |
| 3 | 52.65 | 0.055 | 152 |
| 3.4 | 59.67 | 0.029 | 80 |
| 4 | 70.2 | 0.011 | 30 |
| 5 | 87.75 | 0 | 0 |



**2.23** 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.

$A = 150 \text{ mi.}^2$; $C_t = 1.70$; $L = 27 \text{ mi.}$; $L_c = 15 \text{ mi.}$; $C_p = 0.7$

**ANSWER:**

$t_p = C_t(LL_c)^{0.3} = (1.70)(27*15 \text{ mi.}^2)^{0.3} = \mathbf{10.3\ hr}$

$$Q_p = \frac{640(C_p)(A)}{t_p} = \frac{640(0.7)(150)}{10.3} = \mathbf{6524\ cfs}$$

Since this is a small watershed, $T_b \approx 4t_p = \mathbf{41.2\ hr}$

**2.24** For a 55 $mi^2$ 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.

**ANSWER**:

$t_p = C_t(LL_c)^{0.3} = 2.2(15*7)^{0.3} =$ **8.9 hr**

$$Q_p = \frac{640(C_p)(A)}{t_p} = \frac{640(0.5)(55)}{8.9} = \mathbf{1978\ cfs}$$

Since this is a small watershed, $T_b \approx 4t_p =$ **35.6 hr**

$D = t_p/5.5 =$ **1.6 hr**

$T_R = t_p + D/2 = 8.9 + 1.6/2 =$ **9.7 hr**

$W_{75} = 440(Q_p/A)^{-1.08} = 440(1978/55)^{-1.08} =$ **9.2 hr**

$W_{50} = 770(Q_p/A)^{-1.08} = 770(1978/55)^{-1.08} =$ **16.1 hr**

It is necessary to obtain more flow points in order to be able to draw the hydrograph. We are aware the widths are distributed 1/3 before $Q_p$ and 2/3 after $Q_p$ so,

| | $W_{75}$ | $W_{50}$ |
|---|---|---|
| *(1/3) | 3.1 | 5.4 |
| *(2/3) | 6.1 | 10.7 |

For $W_{75}$, $Q_{75} = 0.75Q_p =$ **1484 cfs**

$t_{75,1} = 9.7 - W_{75}(1/3) =$ **6.6 hr**

$t_{75,2} = 9.7 + W_{75}(2/3) =$ **15.8 hr**

For $W_{50}$, $Q_{50} = 0.50Q_p =$ **989 cfs**

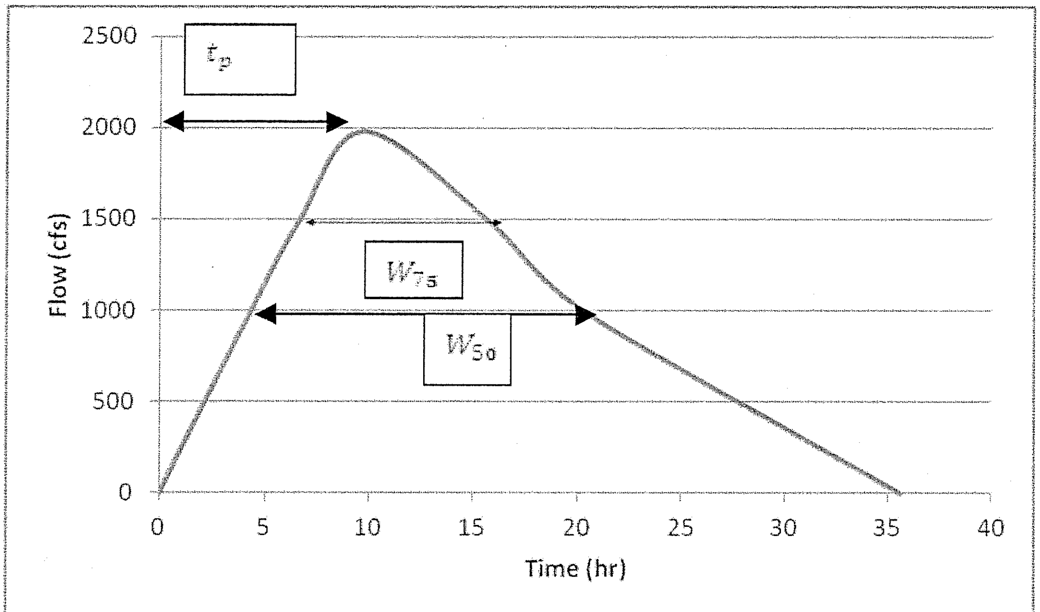
$t_{50,1} = 9.7 - W_{50}(1/3) =$ **4.3 hr**

$t_{50,2} = 9.7 + W_{50}(2/3) =$ **20.4 hr**

Therefore, the following points should be plotted:

| Time (hr) | Flow (cfs) |
|---|---|
| 0 | 0 |
| 4.3 | 989 |
| 6.6 | 1484 |
| 9.7 | 1978 |
| 15.8 | 1484 |
| 20.4 | 989 |
| 35.6 | 0 |

2.24 cont'



$t_p$
$W_{75}$
$W_{50}$
Flow (cfs)
Time (hr)
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
35
40

**2.25** Watershed data is provided on Fig. 1-22 for a small forested watershed that contains seven subareas as shown. Compute an SCS UH (dimensionless) for subarea B, based on lengths and areas from the watershed. Assume a watershed slope of 0.5% and a CN = 70.

**ANSWER:**

S = 1000/CN – 10 = 1000/70 – 10 = 4.3 in.

L = 14.2 mi. = (14.2 mi.)(5280 ft/mi.) = 74,976 ft

y = 0.5%

$t_p$ = lag time (hr)

$$t_p = \frac{L^{0.8}(S+1)^{0.7}}{1900\sqrt{y}} = \frac{(74{,}976)^{0.8}(4.3+1)^{0.7}}{1900\sqrt{0.5}} = \mathbf{19\ hr}$$

D = $t_p$/5.5 hr = **3.5 hr**

$T_R$ = D/2 + $t_p$ = (3.5/2) + 19 = **20.8 hr**

$$Q_P = \frac{484A}{T_R} = \frac{(484)(111)}{20.8} = \mathbf{2{,}583\ cfs}$$

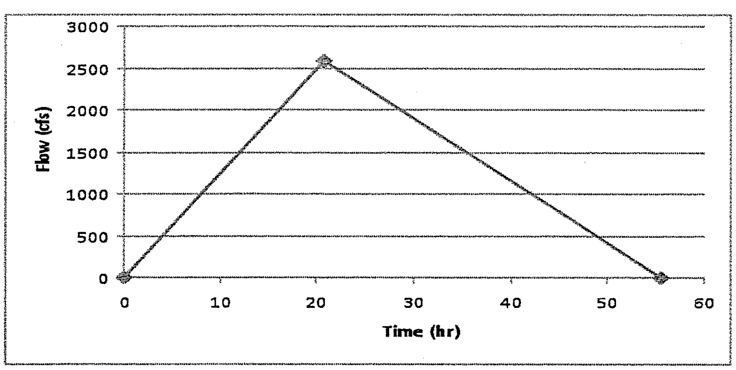
B = 1.67$T_R$ = (1.67)(20.8) = **34.7 hr**

Alternatively, since the volume is known to be 1 in. of direct runoff over the watershed,

$$\text{Vol} = (111 mi.^2)\left(\frac{5280 ft}{mi.}\right)^2\left(\frac{ac}{43{,}560 ft^2}\right)(1 in.) = 71{,}040 \text{ ac-in} \approx \mathbf{71{,}040\ cfs\text{-}hr}$$

$$71{,}040 \text{ cfs-hr} = \frac{Q_P T_R}{2} + \frac{Q_P B}{2} = \frac{(2{,}583 cfs)(20.8 hr)}{2} + \frac{(2{,}583 cfs)(B hr)}{2}$$

B = **34.2 hr**



**2.26** Assume the watershed in Example 2–5 has gone through extensive commercial and industrial growth on the wooded area. Now 50% of the formerly wooded areas have become urbanized, so of that portion, 40% is commercial and business and 60% is fair condition lawn space. Assume the soil is 50% group B and 50% group C for all areas. Using Figure 2–8, determine the runoff volume for a rainfall of 6 in.

**ANSWER:**

Originally, the watershed was 40% wooded. The new watershed is now 20% wooded since 50% of the wooded area got developed. The other 20% is divided in the following way:

Commercial and Business: 0.4*0.2 = 0.08

Fair Condition Lawn Space: 0.6*0.2 = 0.12

| Land Use | Soil Group | Fraction of Area | CN |
|---|---|---|---|
| Wooded | B | 0.2*0.5 = 0.1 | 55 |
| | C | 0.2*0.5 = 0.1 | 70 |
| Commercial and Business | B | 0.08*0.5 = 0.04 | 92 |
| | C | 0.08*0.5 = 0.04 | 94 |
| Fair Condition Lawn Space | B | 0.12*0.5 = 0.06 | 69 |
| | C | 0.12*0.5 = 0.06 | 79 |
| Residential | B | 0.6*0.5 = 0.3 | 75 |
| | C | 0.6*0.5 = 0.3 | 83 |

Weighted CN:

$$CN = 55(0.1) + 70(0.1) + 92(0.04) + 94(0.04) + 69(0.06) + 79(0.06) + 75(0.3) + 83(0.3) = 76$$

From Fig. 2-8 we get **3.4 in**. direct runoff from 6 in. of rainfall.

**2.27** Make sure the unit hydrograph for Subbasin C is a unit hydrograph (Subbasin C area = 770 ac). The unit hydrograph for Subbasin C is graphed in figure P2-27.

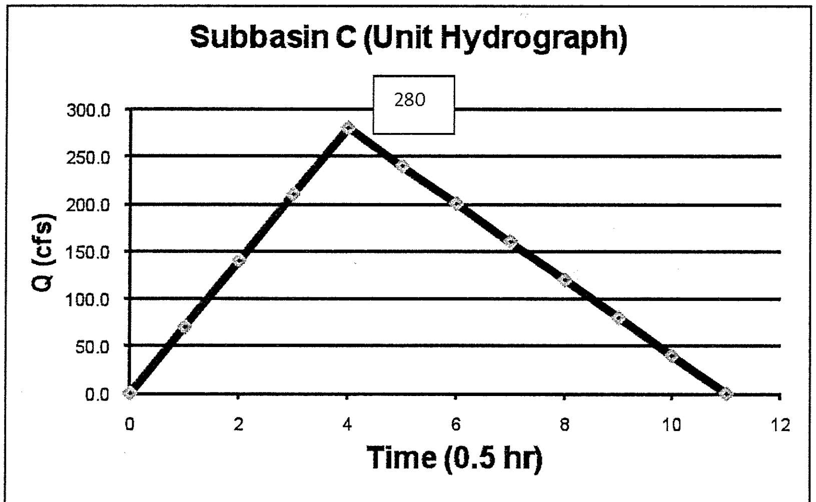



Fig 2-27

**ANSWER:**

Area of Subbasin C = 770 ac

$Q_p$ = 280 cfs

DRO = Area under the hydrograph

DRO = (280 cfs)(5.5 hr)(1/2) = 770 cfs-hr = **770 ac-in.**

770 ac-in./770 ac = **1 in.**

**This is a unit hydrograph.**

**2.28** Using Fig 2-14, find the daily evaporation from a shallow lake with the following characteristics:

Mean daily temperature = 25.6°C,

Daily solar radiation = 550 cal/cm$^2$,

Mean daily dew point = 4.4°C,

Wind movement (6 in. above pan) = 5.5 ft/s.

**ANSWER:**

The chart in Fig. 2-14 is with different units of °F, cal/cm$^2$, mi/day, and in. The given measurements given need to be converted to the proper units

25.6°C = (25.6)(1.8) + 32 = 78°F

4.4°C = (4.4)(1.8) + 32 = 40°F

$$5.5\frac{ft}{s} = 5.5\frac{ft}{s}\cdot\frac{3600s}{hr}\cdot\frac{24hr}{day}\cdot\frac{1mi.}{5280ft} = 90\ \frac{mi.}{day}$$

Draw a bullet point at the intersection of T = 78°F and radiation = 550 cal/cm$^2$ (upper left quadrant). Project a horizontal line to $T_d$ = 40°F (upper right quadrant) and draw a second point. Next project a vertical line to v = 90 mi./day (bottom right quadrant) and draw a third point. Then, project a vertical line down from the first point and a horizontal line to the left from the third point. The intersection of these two lines will be the point of daily evaporation.

E = **0.25 in**.

**2.29** A class A pan is maintained near a small lake to determine daily evaporation (see table). The level in the pan is observed at the end of everyday. Water is added if the level falls *near* 7 in. For each day the difference in height level is calculated between the current and previous day, and the precipitation value is from the current day. Determine the daily lake evaporation if the pan coefficient is 0.70.

| Day | Rainfall (in.) | Water Level (in.) |
|---|---|---|
| 1 | 0 | 8.00 |
| 2 | 0.23 | 7.92 |
| 3 | 0.56 | 7.87 |
| 4 | 0.05 | 7.85 |
| 5 | 0.01 | 7.76 |
| 6 | 0 | 7.58 |
| 7 | 0.02 | 7.43 |
| 8 | 0.01 | 7.32 |
| 9 | 0 | 7.25 |
| 10 | 0 | 7.19 |
| 11 | 0 | 7.08* |
| 12 | 0.01 | 7.91 |
| 13 | 0 | 7.86 |
| 14 | 0.02 | 7.8 |

*Refilled at this point to 8 inches

**ANSWER:**

Pan evaporation = Change in water level in the pan + Amount of Rainfall

Lake Evaporation = (Pan evaporation)(coefficient)

2.29 cont'

| Day | Rainfall (in) | Water Level (in.) | Pan Evaporation (in) | Lake Evaporation (in) |
|---|---|---|---|---|
| 1 | 0 | 8 | 0 | 0 |
| 2 | 0.23 | 7.92 | 0.31 | 0.217 |
| 3 | 0.56 | 7.87 | 0.61 | 0.427 |
| 4 | 0.05 | 7.85 | 0.07 | 0.049 |
| 5 | 0.01 | 7.76 | 0.1 | 0.070 |
| 6 | 0 | 7.58 | 0.18 | 0.126 |
| 7 | 0.02 | 7.43 | 0.17 | 0.119 |
| 8 | 0.01 | 7.32 | 0.12 | 0.084 |
| 9 | 0 | 7.25 | 0.07 | 0.049 |
| 10 | 0 | 7.19 | 0.06 | 0.042 |
| 11 | 0 | 7.08* | 0.11 | 0.077 |
| 12 | 0.01 | 7.91 | 0.10* | 0.070 |
| 13 | 0 | 7.86 | 0.05 | 0.035 |
| 14 | 0.02 | 7.8 | 0.08 | 0.056 |

* On Day 11, the pan is refilled. Thus, the pan evaporation that occurs on Day 12 (before the measurement is taken) starts from 8 in, not 7.08 in.

So, 8.00 – 7.91 = 0.09 in. = Δ water level

Pan evaporation = Δ water level + amount of rainfall = 0.09 in. + 0.01 in. = **0.10 in.**

**2.30** Given an initial rate of infiltration equal to 1.5 in./hr and a final capacity of 0.5 in./hr, use Horton's equation [Eq. (2–42)] to find the infiltration capacity at the following times: $t = 10$ min, 15 min, 30 min, 1 hr, 2 hr, 4 hr, and 6 hr. You may assume a time constant $k = 0.25$/hr.

**ANSWER:**

Horton's equation: $f = f_c + (f_o - f_c)e^{-kt}$

$f = 0.5$ in./hr + (1.5 - 0.5 in./hr) $e^{-0.25t}$

$f = 0.5 + 1\,e^{-0.25t}$ plugging in given times (have to be in hours)

| t (hr) | f(in/hr) |
|---|---|
| ⅙ | 1.46 |
| ¼ | 1.44 |
| ½ | 1.38 |
| 1 | 1.28 |
| 2 | 1.11 |
| 4 | 0.87 |
| 6 | 0.72 |

**2.31** Determine a Horton equation to fit the following times and infiltration capacities.

| **Time (hr)** | ***f* (in./hr)** |
|---|---|
| 1 | 6.34 |
| 2 | 5.20 |
| 6.5 | 2.50 |
| ∞ | 1.20 |

**ANSWER:**

Horton's Equation: $f = f_c + (f_o - f_c)e^{-kt}$

At $t = \infty$,

$$f = 1.20 = f_c + 0$$

$$f_c = 1.20 \text{ (in./hr)}$$

At $t = 1$ hr,

$$f = 6.34 = 1.20 + (f_o - 1.20)e^{-k}$$

At $t = 2$ hr,

$$f = 5.20 = 1.20 + (f_o - 1.20)e^{-2k}$$

Solve for $f_0$ from $t = 1$ hr equation:

$$f_o = \frac{6.34 - 1.20}{e^{-k}} + 1.20$$

Substitute into the $t = 2$ hr equation

$$f = 5.20 = 1.20 + ((\frac{5.14}{e^{-k}} + 1.20) - 1.20)e^{-2k}$$

$$5.20 = 1.20 + \frac{5.14}{e^{-k}} \cdot e^{-2k}$$

$$5.20 = 1.20 + 5.14e^{-k}$$

$$4.00 = 5.14e^{-k}$$

2.31 cont'

$$e^{-k} = 0.78$$

k = 0.25

Solve for $f_0$

$$f = 6.34 = 1.20 + (f_o - 1.20)e^{-0.25}$$

$$5.14 = (f_o - 1.20)e^{-0.25}$$

$$f_o = 7.8 \text{ in./hr}$$

Plug known values into original equation:

$$\mathbf{f = 6.34 = 1.20 + (7.8 - 1.20)e^{-0.25t}}$$

**2.32** A 5-hr storm over a 15-ac basin produces a 5-in. rainfall: 1.2 in./hr for the first hour, 2.1 in./hr for the second hour, 0.9 in./hr for the third hour, and 0.4 in./hr for the last two hours. Determine the infiltration that would result from the Horton model with k = 1.1/hr, $f_c$ = 0.2 in./hr, and $f_o$ = 0.9 in./hr. Plot the overland flow for this condition in in./hr vs. t.

**ANSWER:**

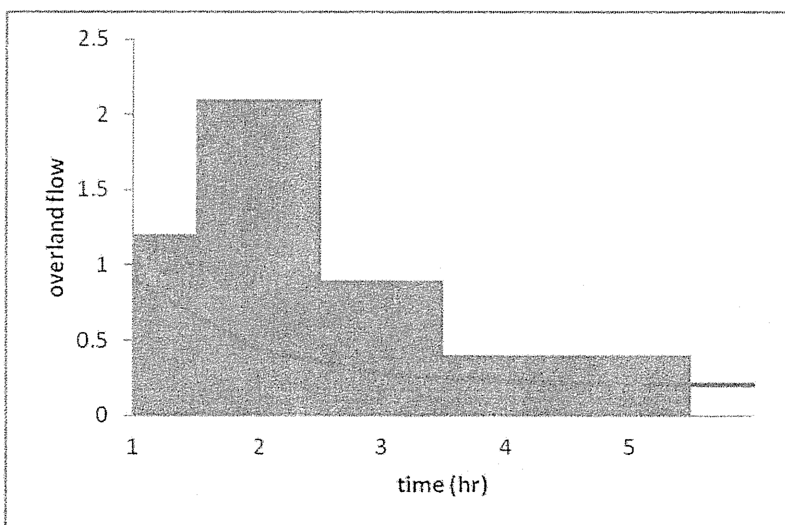
Horton's Equation: $f = f_c + (f_0 - f_c)e^{-kt}$

$$f = 0.2 + (0.9 - 0.2)e^{-1.1t}$$

$$f = 0.2 + 0.7e^{-1.1t}$$

Plug in the values of t to solve for f.

| Time | Infiltration | Rainfall |
|---|---|---|
| 0 | 0.90 | |
| 1 | 0.43 | 1.2 |
| 2 | 0.28 | 2.1 |
| 3 | 0.23 | 0.9 |
| 4 | 0.21 | 0.4 |
| 5 | 0.20 | 0.4 |




To determine the volume of infiltration, take the integral of Horton's equation:

$$\int_0^5 (0.2 + 0.7e^{-1.1t})dt = 0.2[t]_0^5 + \frac{0.7}{-1.1}[e^{-1.1t}]_0^5$$

$$= 1 + (-0.636) \cdot (0.004 - 1)$$

**=1.633 in. over the watershed**

**2.33** A plot of the infiltration curve obtained using Horton's equation is shown in Fig.

P2–33. Prove that $k = \frac{(f_o - f_c)}{F'}$ if F′ is the area between the curve and the $f_c$ line.

Find the area by integration over time, as time approaches infinity.

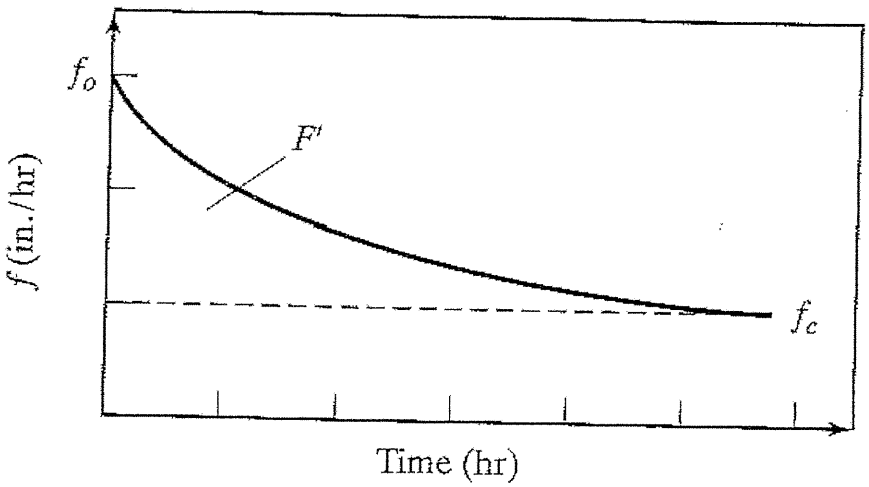



Fig 2.33

**ANSWER:**

A point is chosen on the curve such that at $t = t_1$, $f \approx f_c$. The area F′ is equal to the area under the curve above the line $f_c$ from t = 0 to $t = t_o$ . This area may be found by the integration as follows:

Let 'ta' be some arbitrary time.

$$F' = \int_0^{ta} [f_c + (f_o - f_c)e^{-kt}]dt - \int_0^{ta} f_c dt$$

$$= \int_0^{ta} (f_o - f_c)e^{-kt} dt$$

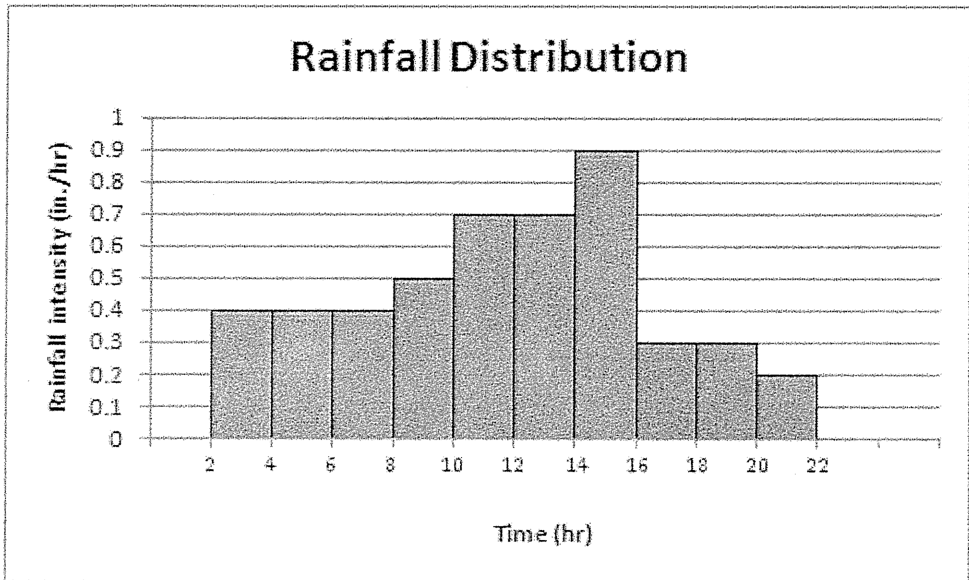
$$= (f_o - f_c)(-1/k)(e^{-kta}) - (f_o - f_c)(-1/k)$$

2.33 cont'

As ta $\rightarrow \infty$, $e^{-kta} \rightarrow 0$. Therefore,

$$F' = (1/k)(f_o - f_c)$$
$$k = (f_o - f_c)/F'$$

**2.34** Determine the $\phi$ index of Figure P2–34 if the runoff depth was a)5.6 in. of rainfall over the watershed area and b) 6.5 in.




**ANSWER:**

a. This is trial and error problem. From looking at the graph it is possible to set up the equation:

$$(0.4 - \varphi)6 + (0.5 - \varphi)2 + (0.7 - \varphi)4 + (0.9 - \varphi)2 + (0.3 - \varphi)4 + (0.2 - \varphi)2 = 5.6$$

Assume $\varphi = 0.2$ in./hr,

$$(0.4 - 0.2)6 + (0.5 - 0.2)2 + (0.7 - 0.2)4 + (0.9 - 0.2)2 + (0.3 - 0.2)4 + (0.2 - 0.2)2 = 5.6$$

Both sides of the equation agree, so

**So $\varphi$ index = 0.2 in./hr.**

b. Again, this is trial and error problem. From looking at the graph it is possible to set up the equation:

$$(0.4 - \varphi)6 + (0.5 - \varphi)2 + (0.7 - \varphi)4 + (0.9 - \varphi)2 + (0.3 - \varphi)4 + (0.2 - \varphi)2 = 6.5$$

With $\varphi$ index = 0.1 in./hr = 7.1 so the index needs to be between 0.2 and 0.1

Trying $\varphi$ index =.15 the answer is 6.6

with index = .155 the answer is 6.5 so the $\varphi$ index for a rainfall of 6.5 in. **is .155 in./hr.**

**2.35** A sandy loam has an initial moisture content of 0.18, hydraulic conductivity of 7.8 mm/hr, and average capillary suction of 100 mm. Rain falls at 2.9 cm/hr, and the final moisture content is measured to be 0.45. When does surface saturation occur? Plot the infiltration rate vs. the infiltration volume, using the Green and Ampt method of infiltration.

**ANSWER**

$\theta_i = 0.18$

$\theta_f = 0.45$

$K_s$ = 78 mm/hr = .78 cm/hr

$\Psi$ = –100 mm = -10 cm

i = 2.9 cm/hr (for 6 hours)

$M_d = \theta_f - \theta_i = 0.45 - 0.18 = 0.27$

$$F_S = \frac{\Psi \cdot M_D}{1-\left(\frac{i}{K_S}\right)} = \frac{-100mm \cdot 0.27}{1-\left(\frac{2.9cm/hr}{0.78cm/hr}\right)} = \mathbf{9.93\ mm}$$

Until 9.93 mm has infiltrated, the rate of infiltration is equal to the rainfall rate (2.9 cm/hr). This will happen at:

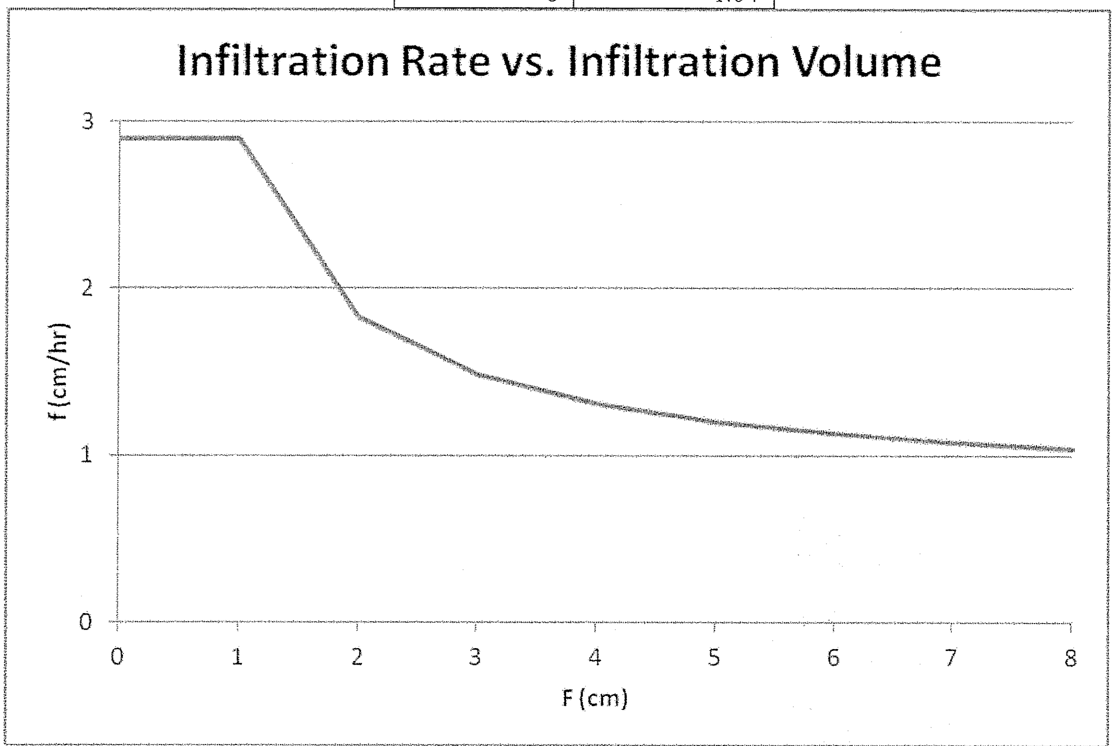
$$.993\text{ cm} \cdot \frac{1hr}{2.9cm} = \mathbf{0.34hr}$$

After surface saturation, the rate of infiltration is calculated using:

$$f = K_S\left(1-\frac{M_d \Psi}{F}\right)$$

2.35 cont'

| F (cm) | f (cm/hr) |
|---|---|
| 1 | 2.89 |
| 2 | 1.83 |
| 3 | 1.48 |
| 4 | 1.31 |
| 5 | 1.20 |
| 6 | 1.13 |
| 7 | 1.08 |
| 8 | 1.04 |



**2.36** Use the parameters given to graph the infiltration rate vs. the infiltration volume for the same storm for both types of soil. Prepare a graph using the Green–Ampt method, comparing all the curves calculated with both the lower-bound and upper-bound porosity parameters. The rainfall intensity of the storm was 1.5 cm/hr for several hours, and the initial moisture content of all the soils was 0.15.

| **Soil** | **Porosity** | **Capillary Suction (cm)** | **Hydraulic Conductivity (cm/hr)** |
|---|---|---|---|
| Silt loam | 0.42 – 0.58 | 16.75 | 0.65 |
| Sandy clay | 0.37 – 0.49 | 23.95 | 0.10 |

**ANSWER**:

$\theta_i = 0.15$

$\Psi$ = - capillary suction

i = 1.5 cm/hr

$M_d = \theta_f - \theta_i$

| | SL | SC |
|---|---|---|
| $K_s$ (cm/hr) | 0.65 | 0.10 |
| $\Psi$ (cm) | -16.75 | -23.95 |
| $\theta_f$ | 0.42 to 0.58 | 0.37 to 0.49 |

Silty Loam (SL):

$$F_S = \frac{\Psi \cdot M_D}{1-\left(\frac{i}{K_S}\right)} = \frac{-16.75cm \cdot M_d}{1-\left(\frac{1.5cm/hr}{0.65cm/hr}\right)} = 12.81 M_d$$

For low porosity:

$M_d = 0.42 - 0.15 = \mathbf{0.27}$

$F_s = \mathbf{3.46\ cm}$

Saturation time = $F_s/i$ = **2.31 h**

2.36 cont'

For high porosity:

$M_d = 0.58 - 0.15 = \mathbf{0.43}$

$F_s$ = **5.51 cm**

Saturation time = $F_s/i$ = **3.67 hr**

Sandy Clay (SC):

$$F_S = \frac{\Psi \cdot M_D}{1-\left(\frac{i}{K_S}\right)} = \frac{-23.95cm \cdot M_d}{1-\left(\frac{1.5cm/hr}{0.10cm/hr}\right)} = 1.71M_d$$

For low porosity:

$M_d = 0.37 - 0.15 = \mathbf{0.22}$

$F_s$ = **.38 cm**

Saturation time = $F_s/i$ = **0.25 hr**

For high porosity:

$M_d = 0.49 - 0.15 = \mathbf{.34}$

$F_s$ = **.58 cm**

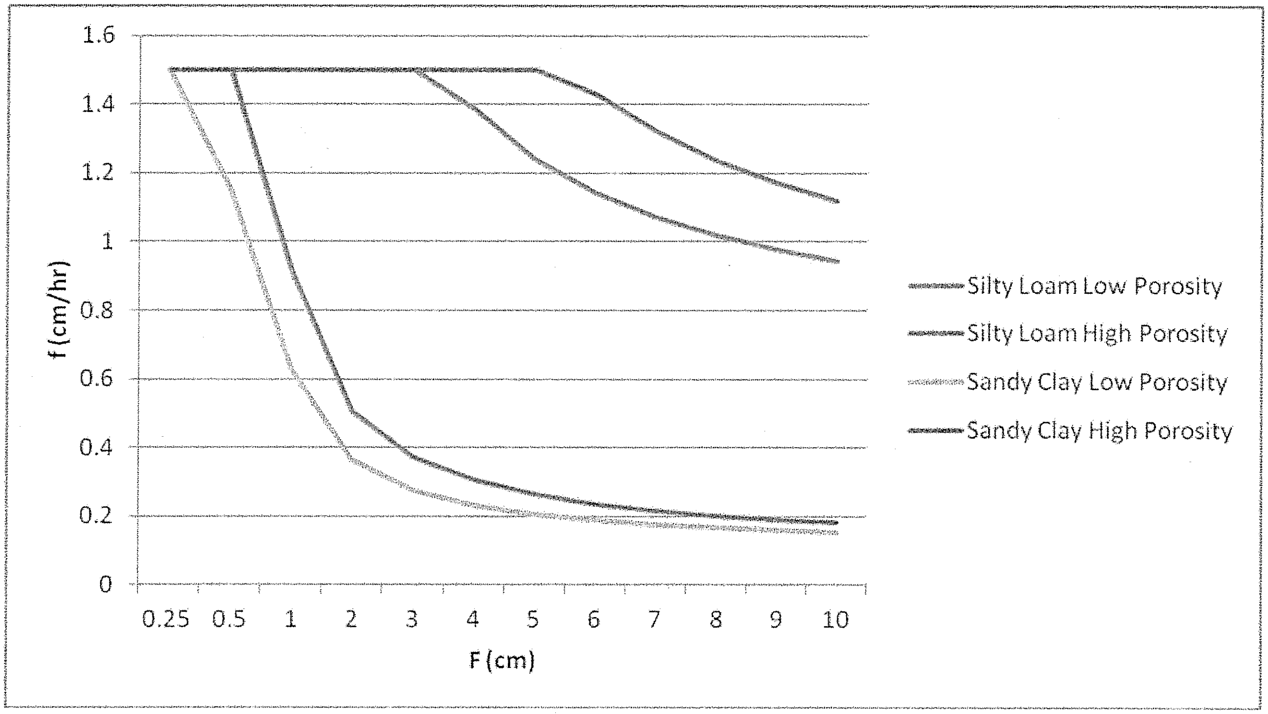
Saturation time = $F_s/i$ = **0.39 hr**

Plot the infiltration volume vs. the infiltration rate using: $f = K_S\left(1-\frac{\Psi M_d}{F}\right)$

| SL | | | | |
|---|---|---|---|---|
| F | $f_{lp}$ | $f_{hp}$ | $f_{lp}$ graph | $f_{hp}$ graph |
| 0.25 | | | 1.5 | 1.5 |
| 0.5 | | | 1.5 | 1.5 |
| 1 | 3.6 | 5.3 | 1.5 | 1.5 |
| 2 | 3.6 | 3.0 | 1.5 | 1.5 |
| 3 | 1.6 | 2.2 | 1.5 | 1.5 |
| 4 | 1.4 | 1.8 | 1.4 | 1.5 |
| 5 | 1.2 | 1.6 | 1.2 | 1.5 |
| 6 | 1.1 | 1.4 | 1.1 | 1.4 |
| 7 | 1.1 | 1.3 | 1.1 | 1.3 |
| 8 | 1.0 | 1.2 | 1.0 | 1.2 |
| 9 | 1.0 | 1.2 | 1.0 | 1.2 |
| 10 | 0.9 | 1.1 | 0.9 | 1.1 |

| SC | | | | |
|---|---|---|---|---|
| F | $f_{lp}$ | $f_{hp}$ | $f_{lp}$ graph | $f_{hp}$ graph |
| 0.25 | 2.2 | 3.4 | 1.5 | 1.5 |
| 0.5 | 1.2 | 1.7 | 1.2 | 1.5 |
| 1 | 0.6 | 0.9 | 0.6 | 0.9 |
| 2 | 0.4 | 0.5 | 0.4 | 0.5 |
| 3 | 0.3 | 0.4 | 0.3 | 0.4 |
| 4 | 0.2 | 0.3 | 0.2 | 0.3 |
| 5 | 0.2 | 0.3 | 0.2 | 0.3 |
| 6 | 0.2 | 0.2 | 0.2 | 0.2 |
| 7 | 0.2 | 0.2 | 0.2 | 0.2 |
| 8 | 0.2 | 0.2 | 0.2 | 0.2 |
| 9 | 0.2 | 0.2 | 0.2 | 0.2 |
| 10 | 0.2 | 0.2 | 0.2 | 0.2 |

2.36 cont'



1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
f (cm/hr)
0.25
0.5
1
2
3
4
5
6
7
8
9
10
F (cm)
Silty Loam Low Porosity
Silty Loam High Porosity
Sandy Clay Low Porosity
Sandy Clay High Porosity

**2.37** The Green and Ampt infiltration equation is a loss function used to compute the cumulative infiltration, $F$ (cm) for a given infiltration rate, $f$ (cm/hr). Recall that, $f=K_s \cdot (1-(M \cdot w_f)/F)$. For the given soil properties and infiltration rate, answer the following.

| | | |
|---|---|---|
| $K$ | 1 | cm/hr |
| $w_f$ | -11 | cm |
| $M$ | 0.2 | |

| t(hr) | f(cm/hr) | F(cm) |
|---|---|---|
| 0 | 0 | 0 |
| 0.01 | 15.34 | 0.15 |
| 0.25 | 3.32 | 0.95 |
| 0.50 | 2.42 | 1.55 |
| 0.75 | 2.06 | 2.07 |

a. Compute the infiltration rate, $f$ (cm/hr) for F=2.07 cm, and show your computations.

$f=K_s \cdot (1-(M \cdot w_f)/F) = 1(1-0.2*(-11)/2.07) = 2.06$ cm/hr

b. Compute the cumulative infiltration resulting from a constant rain rate of 0.5 cm/hr for 1 hr.

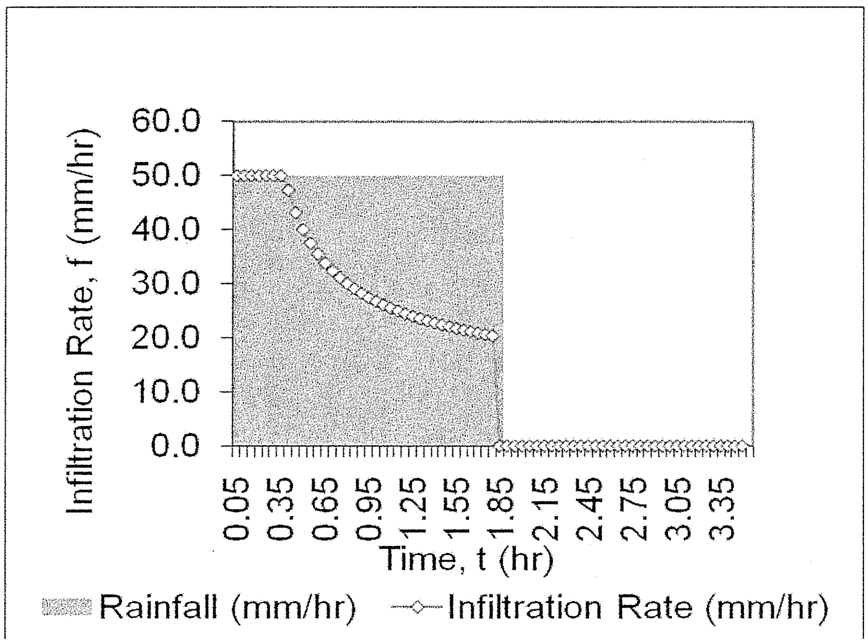
F=0.5 * 1 = 0.5 cm

c. At saturation, what is the infiltration rate in cm/hr? Justify.

At saturation, f=K=1 cm/hr

**2.38** Please refer to the Green and Ampt Infiltration and Runoff Example posted on the textbook website along with the associated Excel Spreadsheet. Complete the problem in the example, and then repeat the procedure with a constant rainfall rate of 50 mm/hr for 1.8 hrs. Determine the new cumulative runoff and runoff coefficient.

**ANSWER:**




| | | |
|---|---|---|
| $K_s$ = | 6.5 | mm/hr |
| $w_f$= | -166.8 | mm |
| $M_d$ = | 0.75 | Moisture Deficit |

| | |
|---|---|
| Cumulative Rainfall (mm) = | 92.5 |
| Cumulative Runoff (mm) = | 32.1 |
| Cumulative Infiltration (mm) = | 60.4 |
| Runoff Coefficient = | 34.7% |