HYDROLOGIC ANALYSIS

Hydrology and
Floodplain Analysis,
Chapter 2

CEVE 412
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Overview

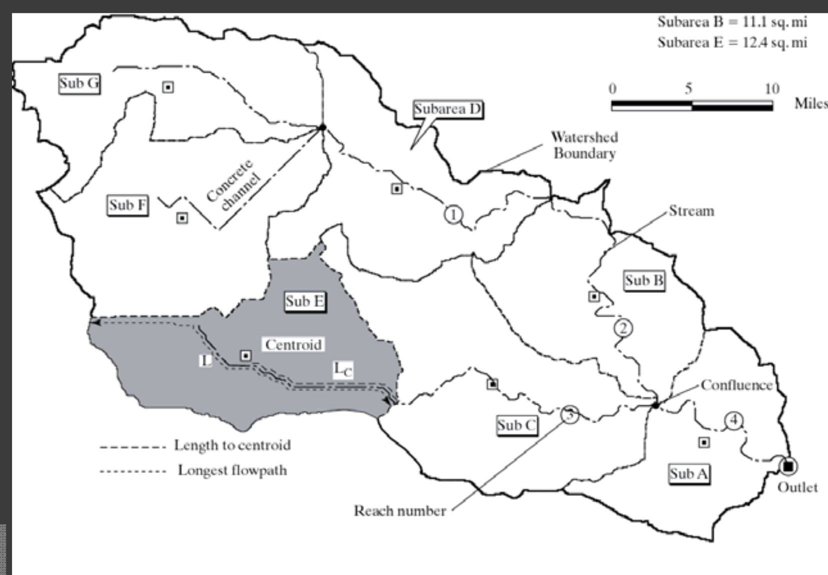
- Watershed Concepts
- Unit Hydrographs
- Synthetic Hydrographs
- Hydrologic Loss

Hydrology and Floodplain Analysis, Chapter 2.1

Watershed Concepts

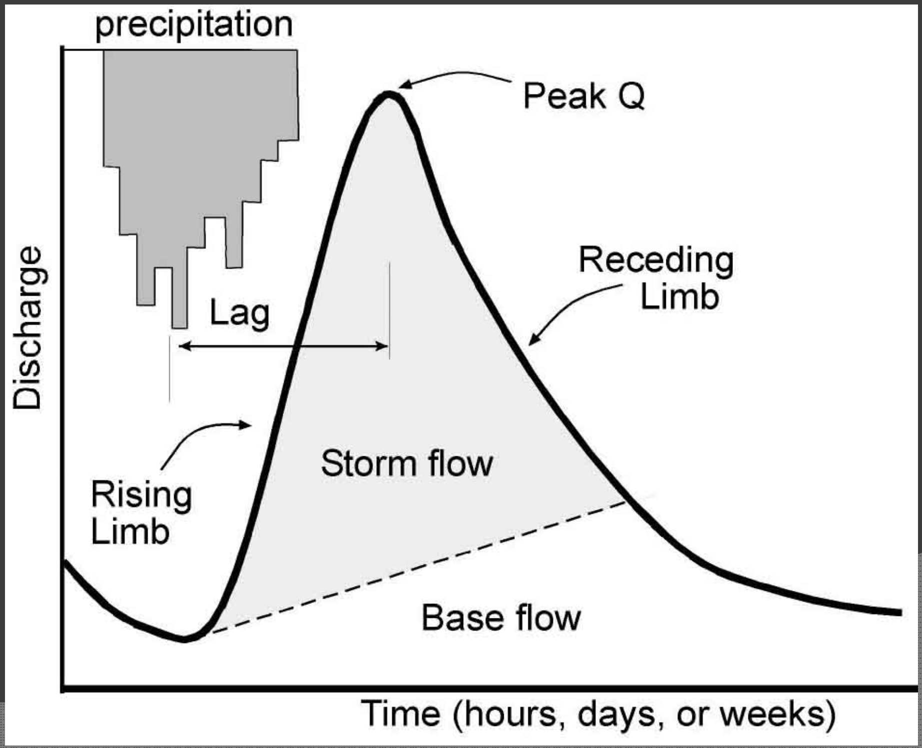
Watershed Basics Revisited

- **Watershed:** Basic unit used in most hydrologic analysis relating to water balances or runoff
  - Often characterized by one main channel and tributaries with subareas of drainage



Watershed Basics

- **Hydrograph:** plot of flow rate vs. time for given location
  - Main hydrologic response function for a watershed

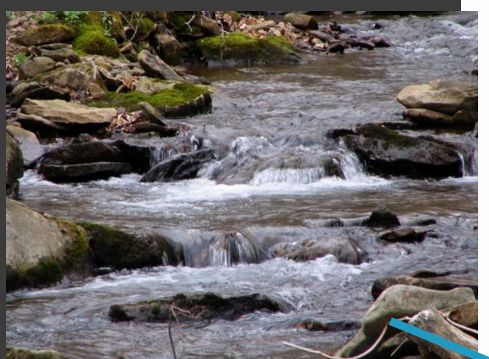


Important Parameters

- **Drainage Area (*A*)**: Area of watershed that contributes to an outlet
  - Reflects volume of water generated by rainfall
- **Channel/Watershed Slope (S/S_0)**
  - Influences flow and flow rate
- **Soil Types**
  - Determine infiltration rates

Important Parameters

- **Land Use and Land Cover**
  - Affect rates of runoff during rainfall



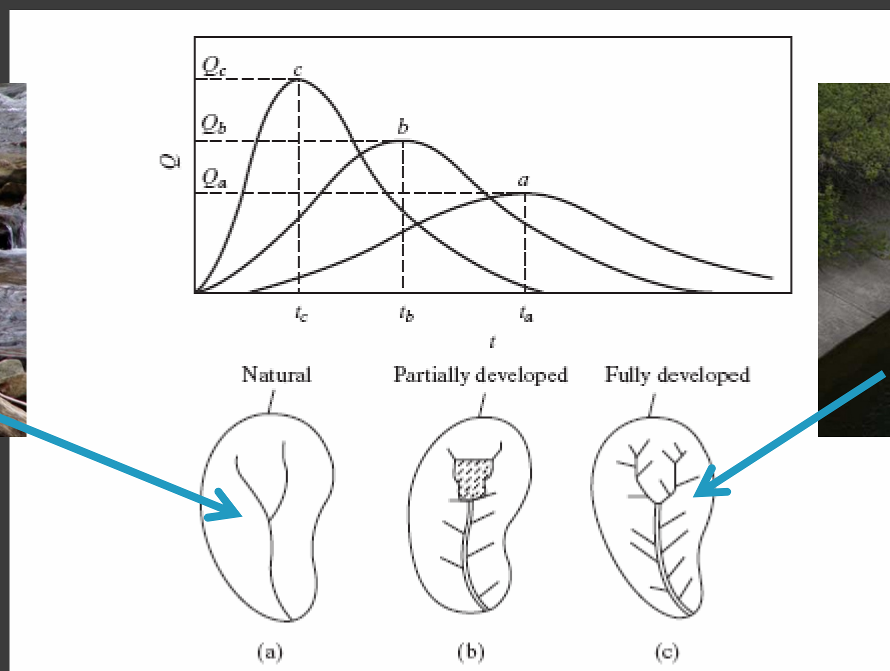
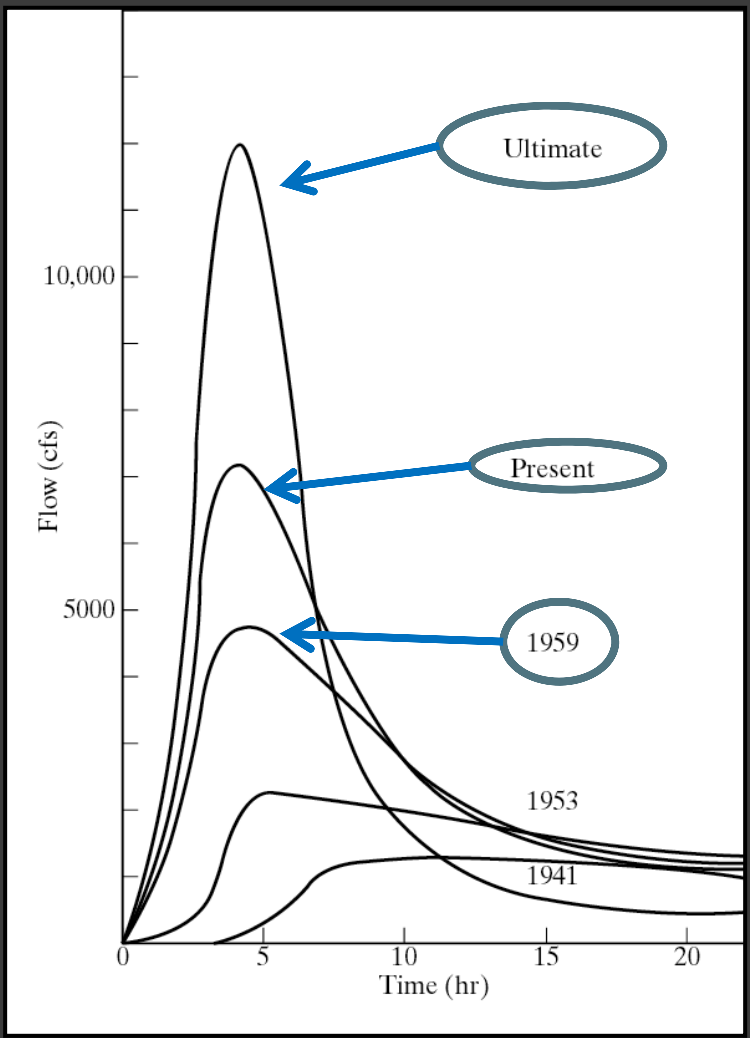


Figure 2–5
Modifying factors on unit hydrographs. (a) Natural watershed development, represented by curve *a* in the bottom part of the figure. (b) Partial development, represented by curve *b*. (c) Fully developed watershed, represented by curve *c*.

Land Use Effects



- Actual Unit Hydrographs for Brays Bayou in Houston, Texas
- Faster response and higher peak flow with development
- Requires providing downstream capacity

Important Parameters

- **Main Channel/Tributary Characteristics**
  - Affect streamflow response in numerous ways
    - Slope
    - Cross-Sectional Area
    - Manning's Roughness Coefficient
    - Obstructions
    - Meander Pattern

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Unit Hydrograph Theory

Unit Hydrograph

- Defined as 1-in of precipitation spread uniformly over a watershed in a given duration
  - 0.5 hr UH
  - 1 hr UH
  - 3 hr UH
- Used to easily represent the effect of rainfall on a particular basin
  - Hypothetical unit response of watershed to a unit of rainfall

UH Example

- 2-Hr UH
  - Note that 0.5 in/hr fall for the 2 hours

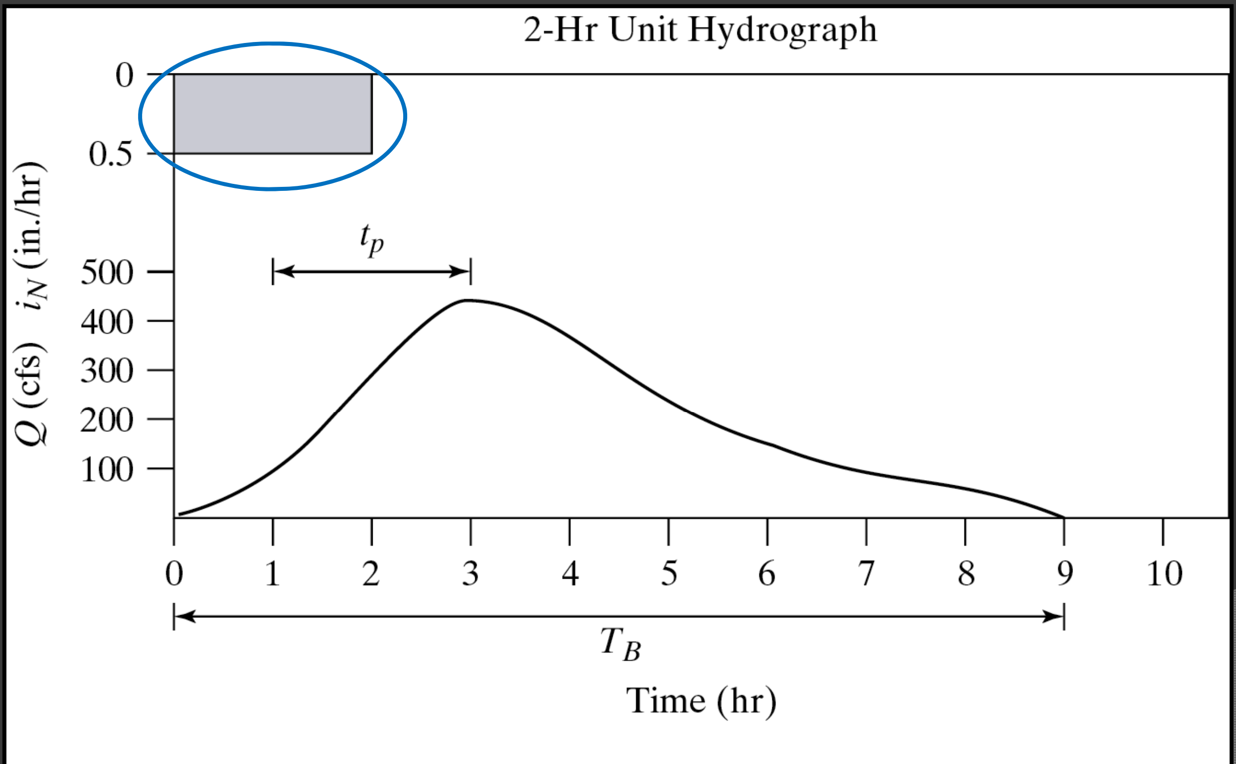


Figure E2.3(c)

UH Applications

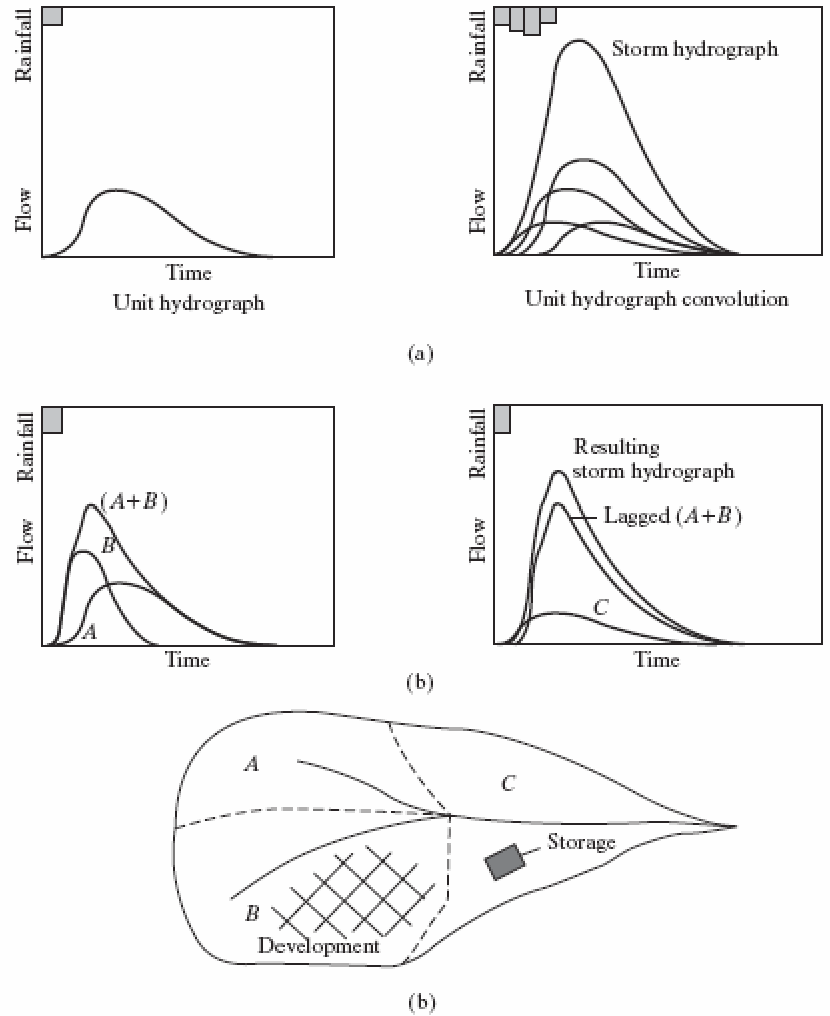


Figure 2–9
Unit hydrograph applications.
(a) Development of a design storm hydrograph.
(b) Development of a watershed hydrograph.

Development of design storm hydrograph

Development of watershed hydrograph

Developing UHs - Gages

- Rules for using a gauged watershed
  - Storms must have simple structure and relatively uniform spatial and temporal distribution
  - Watershed is 1 – 10 mi^2
  - Direct runoff is 0.5 – 2.0 in
  - Duration of rainfall excess is 25%-30% of lag time
  - Use multiple storms of similar duration to obtain an average UH
  - Repeat #5 for storms of different durations

Developing UHs – Single Storm

- Procedure for using a single storm hydrograph
  - Analyze hydrograph
    - separate base flow
  - Calculate total volume of DRO
    - convert to inches (mm) over watershed
  - Subtract infiltration
    - Rainfall excess = DRO
    - Evaluate duration D of rainfall excess produced by DRO hydrograph
  - Divide ordinates of DRO hydrograph
    - By volume in inches
    - Check to make sure it is 1.0 in of total rainfall
  - Plot results as Unit Hydrograph

UH developed from a single storm

- Total storm hydrograph
- Hydrograph minus baseflow, rainfall minus losses
- Hydrograph adjusted to be a 2-hr UH

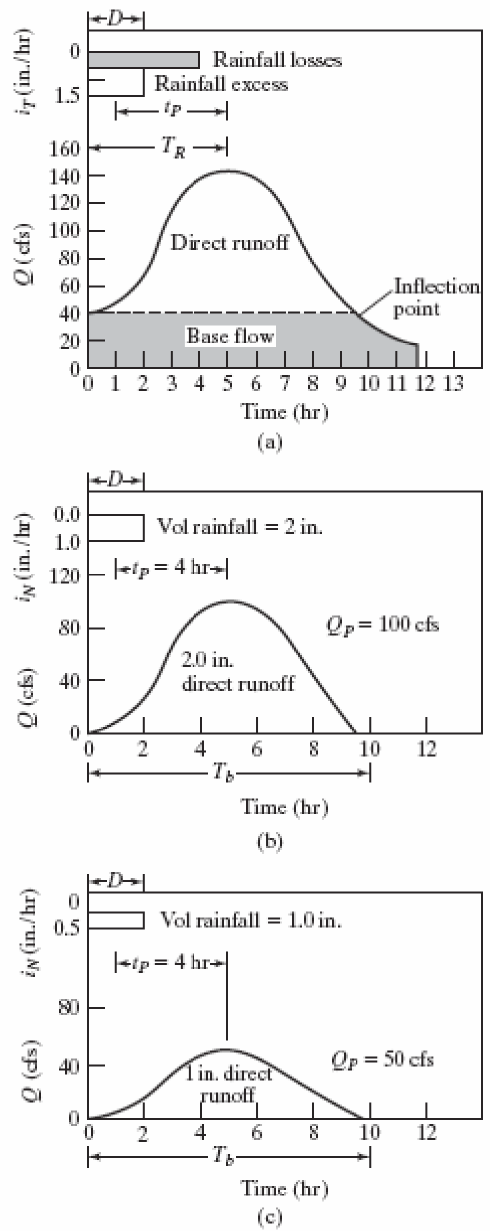


Figure 2–1
Unit hydrograph determination. (a) Total storm hydrograph. (b) Hydrograph minus baseflow, rainfall minus losses. (c) Hydrograph adjusted to be a 2-hr unit hydrograph.

Concerns with UHs

- Assumptions of linearity are inherent in UH development
- Linearity can be violated if…
  - intensity variations are large over long-duration storms
  - Storage effects in watershed are important
- Typically should not exceed areas of 5 – 10 mi^2
  - Divide the watershed into subareas if needed

S-Curve Method

- Allows for the construction of UH of any duration

- Creating the S-Curve
  - Add and lag series of UH of duration, *D*, by time period *D*
    - Gives runoff hydrograph from continuous rainfall excess intensity of 1/*D*
    - Equilibrium hydrograph or an S-Curve

S-Curve Method

- S-Curve to UH
  - Shift the curve by *D'* hr
  - Subtract ordinates between the two curves
    - Receive curve (b)
  - Multiply all ordinate by *D/D'*
  - Receive UH of duration *D'*

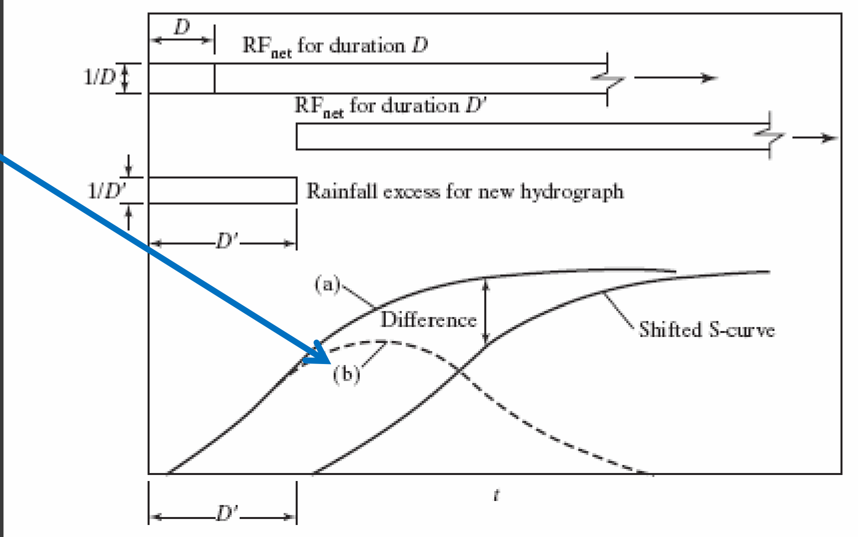


Figure 2–3
Graphical representation of the S-curve hydrograph method.

Unit Hydrograph Convolution

- Deriving hydrographs from multiperiod rainfall excess

$$Q_n = \sum_{i=1}^{n} P_i U_{n-i+1}$$

or

$$Q_n = P_n U_1 + P_{n-1} U_2 + \cdots + P_1 U_j$$

- Where
  - Q_n = storm hydrograph ordinate
  - P_i = rainfall excess
  - U_j = UH ordinate
    - where j = n - i + 1

Unit Hydrograph Convolution

- Can view this graphically
  - Note that the final hydrograph goes to time-step 10
    - UH goes from 0-7
    - 4 Rainfall periods of 1 time step

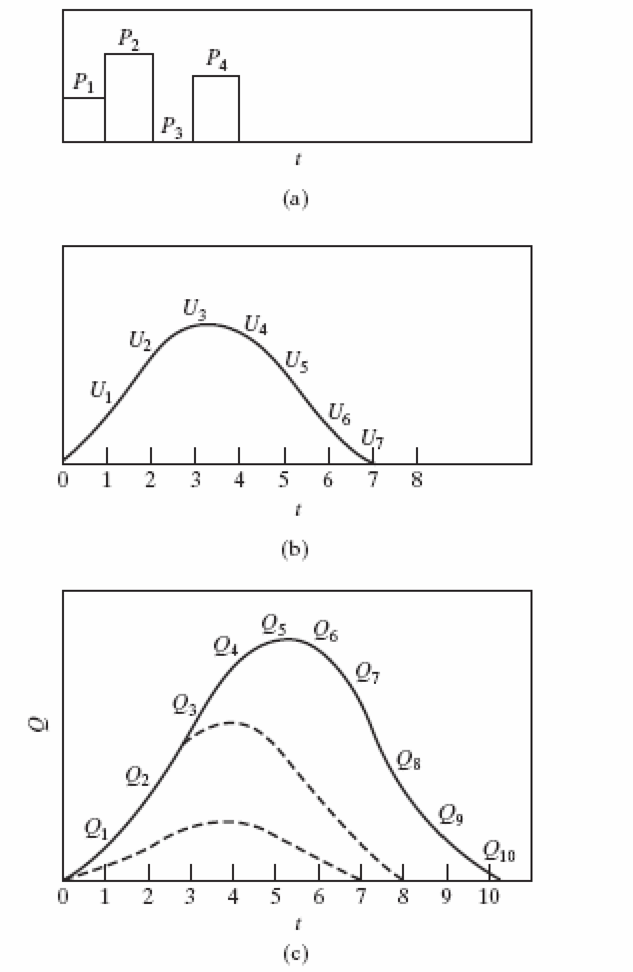
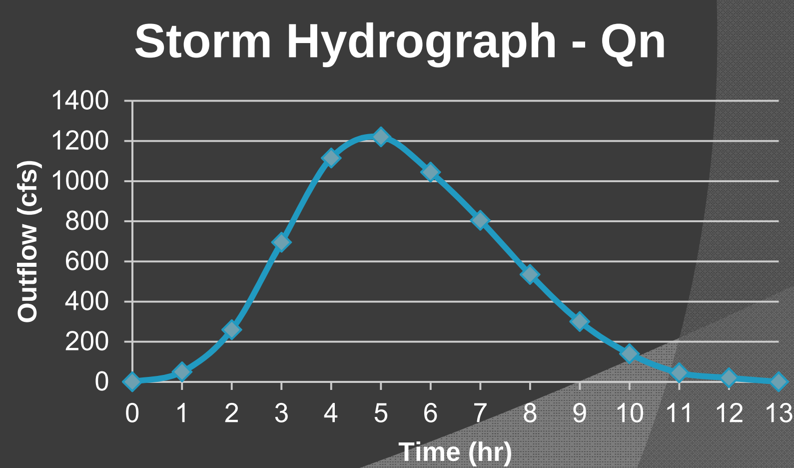


Figure 2–4 Graphical representation of a unit hydrograph for a multiperiod storm

UH Convolution Example

- P_n= [0.5, 1.0, 1.5, 0.0, 0.5] in
- U_n= [0, 100, 320, 450, 370, 250, 160, 90, 40, 0] cfs

Time (hr)	P_1U_n	P_2U_n	P_3U_n	P_4U_n	P_5U_n	Q_n
0	0					**0**
1	50	0				**50**
2	160	100	0			**260**
3	225	320	150	0		**695**
4	185	450	480	0	0	**1115**
5	125	370	675	0	50	**1220**
6	80	250	555	0	160	**1045**
7	45	160	375	0	225	**805**
8	20	90	240	0	185	**535**
9	0	40	135	0	125	**300**
10		0	60	0	80	**140**
11			0	0	45	**45**
12				0	20	**20**
13					0	**0**



Unit Hydrograph Convolution

- Can reverse procedure
  - Multiperiod rainfall excess hydrograph → UH

- Uses matrix methods
  - $[Q] = [P][U]$ →
    $[P^TP][U] = [P^T][Q]$ →
    $\mathbf{[U] = [P^TP]^{-1}[P^T][Q]}$

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Synthetic Hydrograph Development

Synthetic Unit Hydrographs

- UHs developed for ungaged basins
  - Based on data for similarly gauged basins
- Revolutionized ability to predict hydro response
  - Produce storm hydrographs from rainfall data
- Can be updated to reflect changes in watershed geography/land cover
- Variety of approaches but most based on t_p (lag time) and Q_p (peak flow)

Synthetic Methods

- Snyder's Method (1938)
- Clark Method (1945)
- Nash IUH (1958)
- SCS (1957, 1964)
- Kinematic Wave (1970s)

Snyder's Method (1938)

- First to develop a synthetic UH
  - Studied watersheds in Appalachian Highlands
- Simple and popular method

- **$t_p = C_t*(L*L_c)^{0.3}$**

  T_p = lag time (hr)

  C_t = coeff. (1.8-2.2)

  L = length of main stream (mi)

  L_c = length to centroid (mi)

- **$Q_p = 640*C_p\ A/t_p$**

  Q_p = peak flow (cfs)

  C_p = coefficient (0.4-0.8)

  A = area (sq mi)

- **$T_b = 3 + t_p/8$**

  T_b = time base of hydrograph (days)

Snyder's Method (1938)

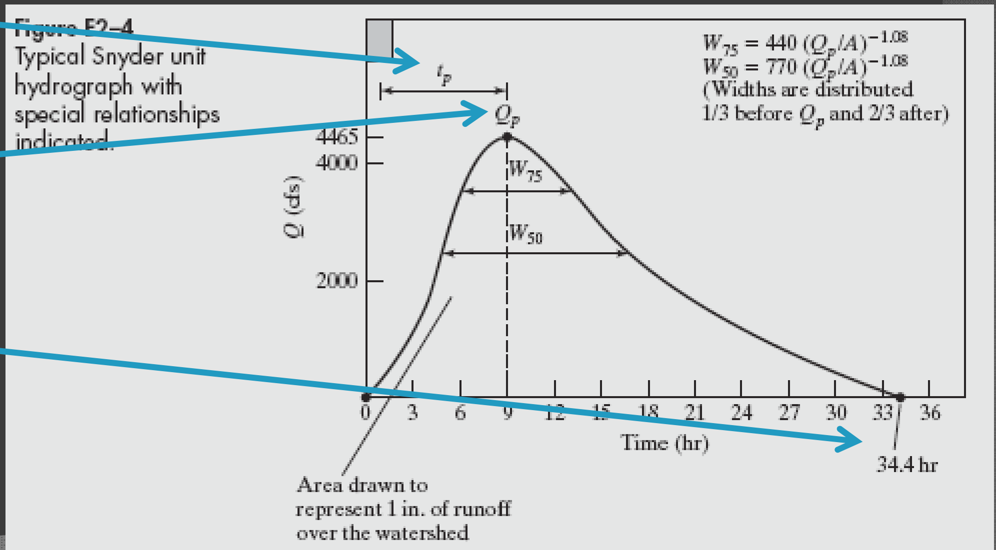
- Example
  - Skecth the approximate shape of hydrograph for an area of 100 mi^2
  - Given: **C_t = 1.8** **L = 18 mi**
    C_p = 0.6 **L_c = 10 mi**

$t_p = C_t*(L*L_c)^{0.3}$
$= 8.6$ hr

$Q_p = 640*C_p A/t_p$
$= 4465$ cfs

$T_b \sim 4t_p$
$= 34.4$ hr

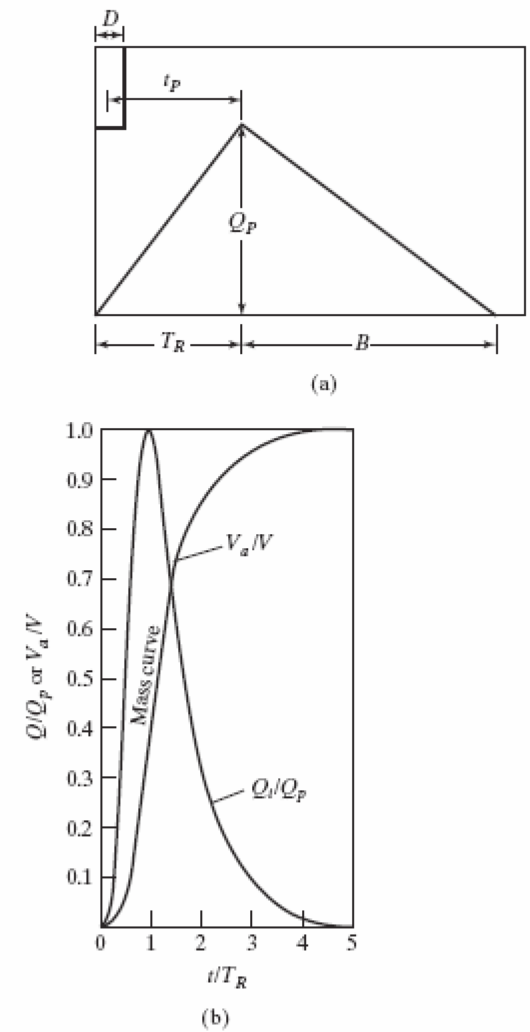
Duration = $t_p/5.5$ hr
= 1.6 hr



SCS Method (1957, 1964)

- Developed by Soil Conservation Service
- Dimensionless hydrograph
  - Developed from a large number of UHs from gauged watersheds ranging in size/location

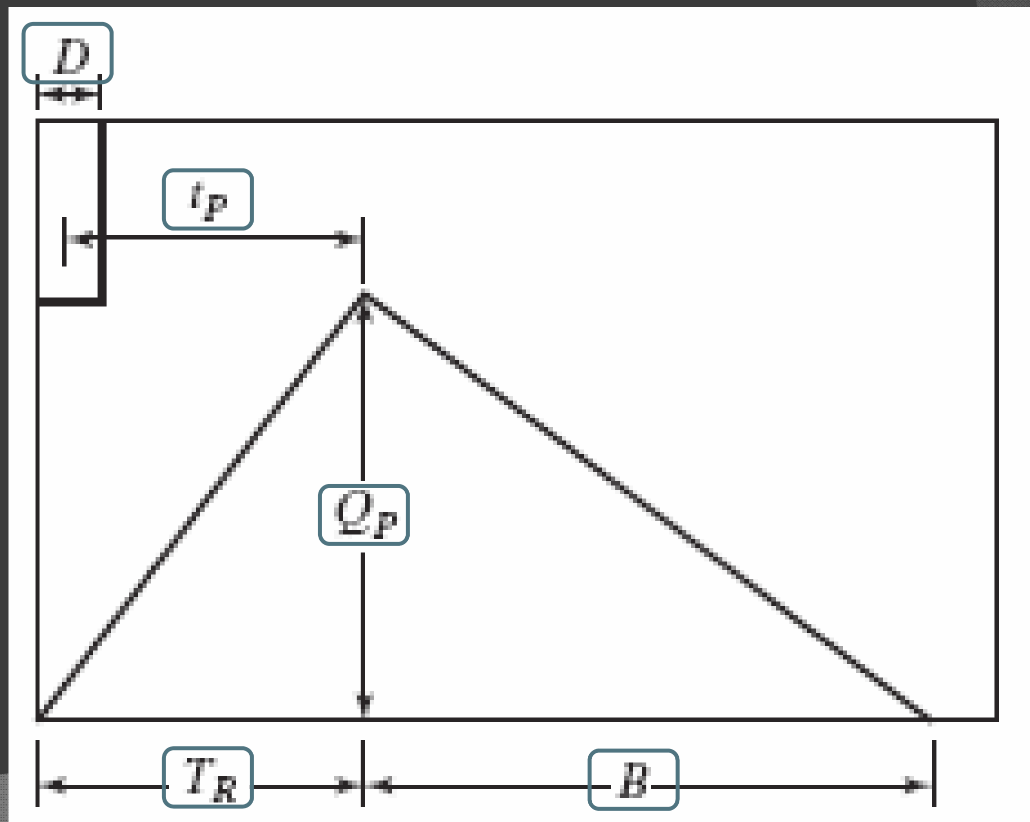
Figure 2–7
(a) SCS triangular unit hydrograph.
(b) SCS dimensionless unit hydrograph (SCS 1964).



SCS Method - Triangle

- Early method assumed a simple triangle hydrograph with certain parameters

D – rain duration (hr)
T_R – time of rise (hr)
B – time of fall (hr)
Q_P – peak flow (cfs)
t_P – lag time from centroid of rainfall to Q_P



SCS Method - Triangle

- Volume of direct runoff from hydrograph

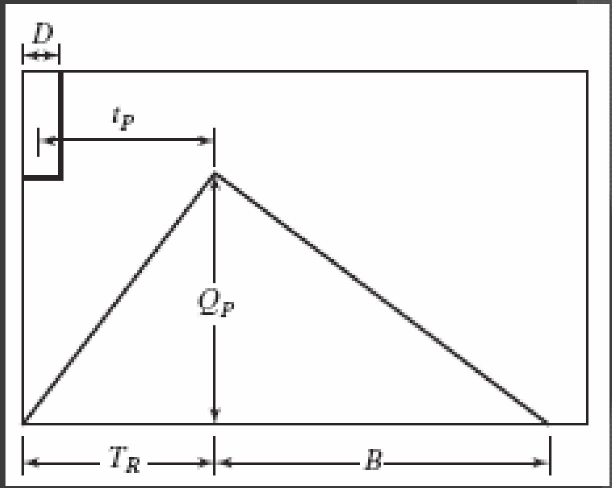
$$Vol = \frac{Q_p T_R}{2} + \frac{B Q_p}{2}$$

  - Where

$$B = 1.67 T_R$$

$$Q_p = \frac{2Vol}{T_R + B} \longrightarrow Q_p = \frac{0.75\,Vol}{T_R}$$

$$T_R = \frac{D}{2} + t_p$$



SCS Method - Triangle Lag Time

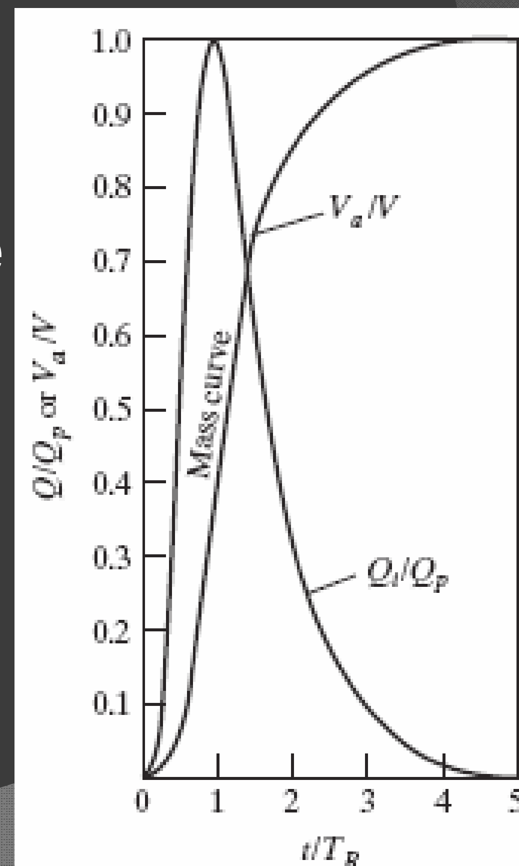
- Lag time (t_P) is most often estimated using formula below
  - Make sure units match

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

  - L = length to divide (ft)
  - y = average watershed slope (%)
  - S = 1000/CN – 10”
    - CN = curve number from soil/land use table

SCS Method → Curved Hyd.

- SCS dimensionless UH can be used to develop a curved hydrograph
  - Use same t_P and Q_p
  - Shaped curves in the figure are used to develop the entire UH



Clark UH Method (1945)

- Based on the use of a watershed
- Modeled as a linear channel in series with a linear reservoir
  - Accounts for translation and attenuation

- Creates instantaneous UH (IUH) from the outflow (O_i) from the linear reservoir
  - Inflow ($\bar{I}_i$) to the linear reservoir is the outflow from the linear channel

Clark UH – Broken Down

- Linear Channel
  - Uses time-area relationship
  - Estimates time distribution of runoff from basin
  - **Time of Concentration (T_C)** – time of runoff from most remote part of basin to outlet

Clark UH – Broken Down

- Linear Reservoir
  - Represents storage and resistance effects from basin
  - $S_i = RO_i$
    - S_i = storage at the end of period *I*
    - O_i = outflow during period *I*
    - *R* = storage coefficient

Clark UH – Broken Down

- Allows for a modification of the continuity equation…

$$\bar{I}_i - \frac{O_{i-1} + O_i}{2} = \frac{S_i - S_{i-1}}{\Delta t} \longrightarrow \bar{I}_i - \frac{O_{i-1} + O_i}{2} = \frac{RO_i - RO_{i-1}}{\Delta t}$$

- $\bar{I}_i$ = average inflow in period *i*, determined from area-time method
- O_i = outflow during period *i*
- S_i = storage at the end of period *i*
- *R* = storage coefficient
  - Slope of the storage-outflow curve for the linear reservoir

Clark UH – Broken Down

- T_c and R are the two major parameters of this method
  - Obtained from observed hydrographs on gaged basins
  - Inflection point at time, T_c, from end of rainfall burst, is where inflow to the linear reservoir = 0
    - Can express continuity equation as:

$$-\frac{O_{i-1}+O_i}{2}=\frac{S_i-S_{i-1}}{\Delta t}$$

  - Estimate R by dividing DRO discharge at inflection point by slope of hydrograph at that point

$$R=\frac{(O_{i-1}+O_i)/2}{-(O_i-O_{i-1})/\Delta t}$$

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Applications of Unit Hydrographs

Applications

- For complex watersheds:
  1. Design storm hydrographs (10-yr, 25-yr,100-yr)
  2. Evaluate effects of land use changes, storage additions, and other variables
  3. Simulate storm hydrographs (Ch. 4)
  4. Analysis of flood control options (Ch. 4)

UH Applications

1. Design storm hydrographs (10-yr, 25-yr,100-yr)

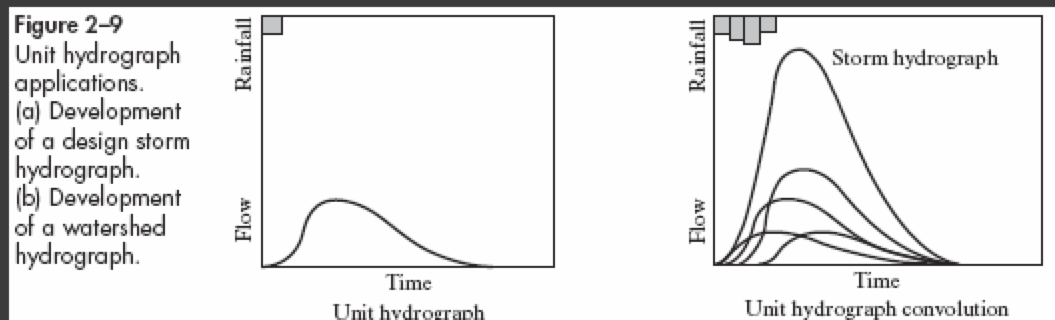
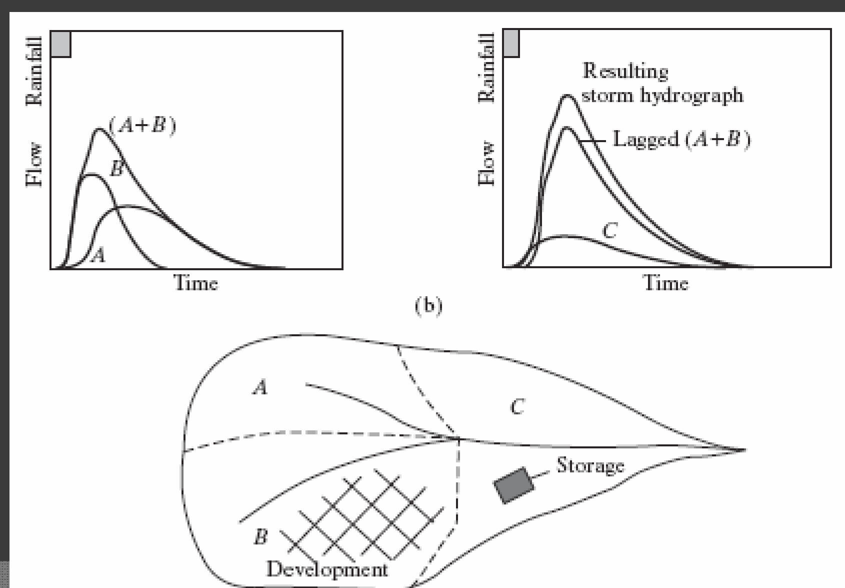


Figure 2–9
Unit hydrograph applications.
(a) Development of a design storm hydrograph.
(b) Development of a watershed hydrograph.

2. Evaluate effects of land use changes, storage additions, and other variables



UH Applications

3. Simulate storm hydrographs for each subbasin by **adding, lagging and routing** flows produced by UH.

4. Evaluate effects of changes in scenario R
   - Changes in: rainfall patterns, land use distributions (i.e. devloped/undeveloped), reservoirs or detention basins, and other variables

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Linear and Kinematic Wave Models

Instantaneous UH

- A mathematical extension of UHs rainfall excess D approaches zero while the quantity remains constant
- Runoff produced by the "instantaneous rainfall" is what is called instantaneous hydrograph
- Useful because there is a unique function for a watershed independent of time or antecedent conditions.

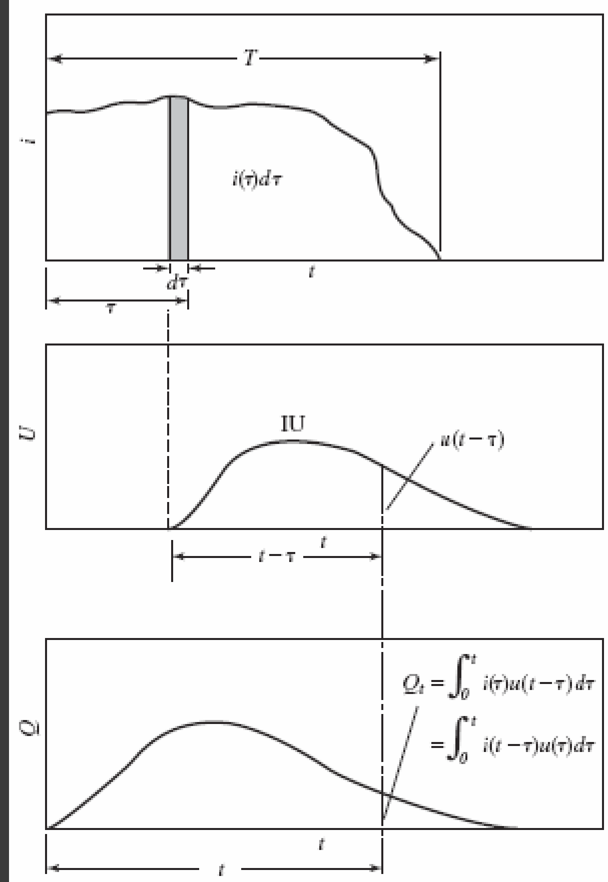

Figure 2–10 Graphical representation of how to use an IUH to generate a hydrograph.

Kinematic Wave

- Used to develop stream hydrograph and measure overland flow
- The Kinematic Wave is used because it assumes that the weight or gravity force of flowing water is simply balanced by the resistive force of bed friction
- Has been intergrated into HEC-HMS and can be used for Storm Water Management Models

Kinematic Wave

- Kinematic (kw) wave routing used to derive overland flow hydrographs
- Can be added to produce collector or channel hydrographs
- Then can be flood routed as channel or stream hydrographs.

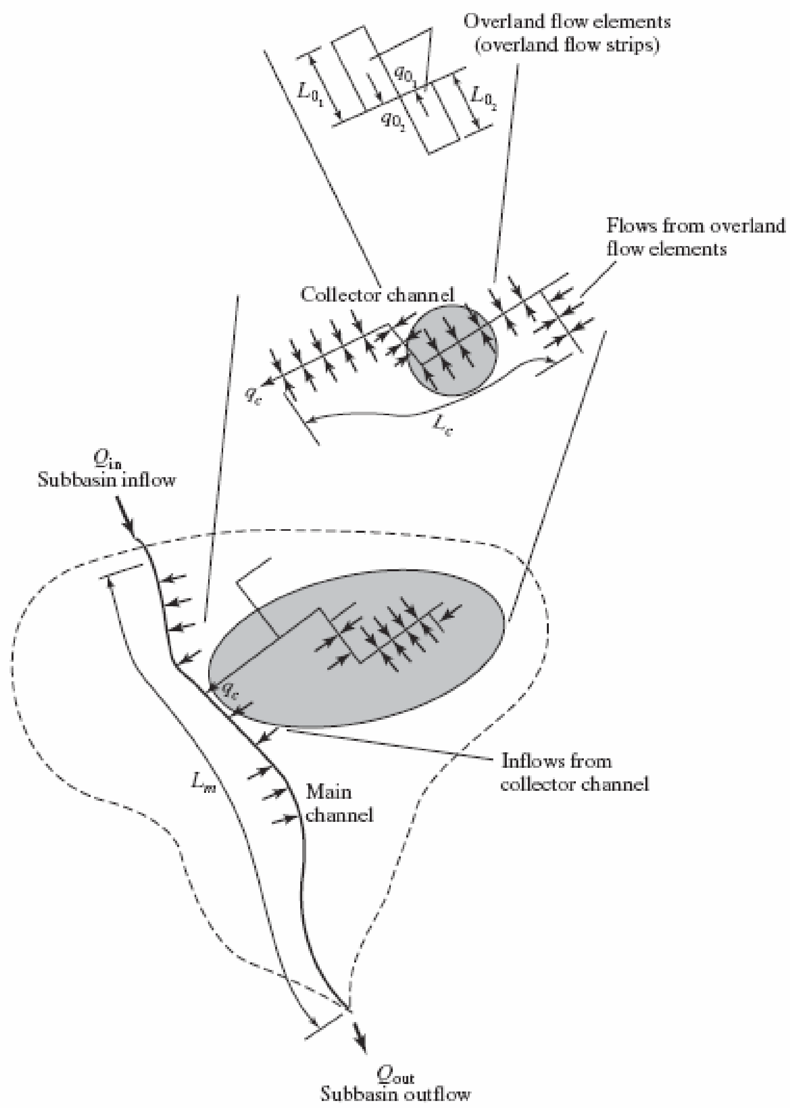

Figure 2–12 Conceptual model of the kinematic wave.

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Hydrologic Loss – Evaporation and Evapotranspiration

What's the difference?

- Evaporation: water in its liquid or solid state transformed into water vapor and mixes with the atmosphere

- Evapotranspiration (ET): combined loss of water vapor from surface of plants (transpiration) and evaporation of moisture from soil

- Approximately 70% of the mean annual rainfall in the United States is returned to the atmosphere as ET

Evaporation Calculation Methods

- Water Budget
  - For a lake is based on the continuity equation where you can solve for evaporation knowing:

$$E = -\Delta S + I + P - O - GW \quad (2\text{–}33)$$

ΔS = Change in Storage

I = Inflow

P = Precipitation

O = Outflow

GW = Groundwater flow (infiltration)

Evaporation: Mass Transfer Method

- Mass Transfer
  - Based primarily on the concept of turbulent transfer of water vapor from a water surface to the atmosphere
  - In the form of a diffusive flux of water vapor

$$E = (e_s - e_a)(a + bu), \quad (2–34)$$

Where:

e_s = saturation vapor pressure at *Ts* of the water surface

e_a = vapor pressure at some fixed level above the water surface

- the product of relative humidity times saturation vapor pressure at *Ta* of the air

u = wind speed

a, b = empirical constants

Energy Budget Method

- Most accurate but complex method since it requires radiation measurements
  - Overall Lake Energy Budget:

$$Q_N - Q_h - Q_e = Q_\theta - Q_v,$$

  - Solve for Evaporation:

$$E = \frac{Q_N + Q_v - Q_\theta}{\rho L_e(1 + R)},$$

Where:

Q_N = net radiation absorbed by body of water

Q_h = sensible heat transfer

Q_v = advected energy of inflow and outflow

Q_θ = increase in energy stored in the water body

L_e = Latent heat of vaporization

Measuring Evaporation

- Pan Evaporation
  - Pan: open galvanized iron tank (4 ft in diam. & 10 in. deep).
  - Filled up to 8 in. and refilled when the depth has fallen to 7 in.
  - Water level measured daily, & evaporation computed as the difference between observed levels. Adjusted for precipitation
  - Pan Coefficient =

    0.64 – 0.81

Measuring Evaporation

- Combined Methods:
  - Mass transfer + Energy Budget Method
  - Penman Equation:

$$E_h = \frac{\Delta}{\Delta + \gamma} Q_N + \frac{\gamma}{\Delta + \gamma} E_a, \qquad (2\text{–}39)$$

where

E_h = flux of latent heat due to evaporation (energy/area-time) $= \rho L_e E$ with E in units of L/T,

L_e = latent heat of vaporization [Eq. (1–5)], customarily evaluated at the temperature of the air (energy/mass),

Δ = slope of e_s-vs.-T curve, which is shown as Δ/γ vs. T in Van Bavel (1966).

  - Advantage: water or soil surface temperature need not be known.

Penman Equation

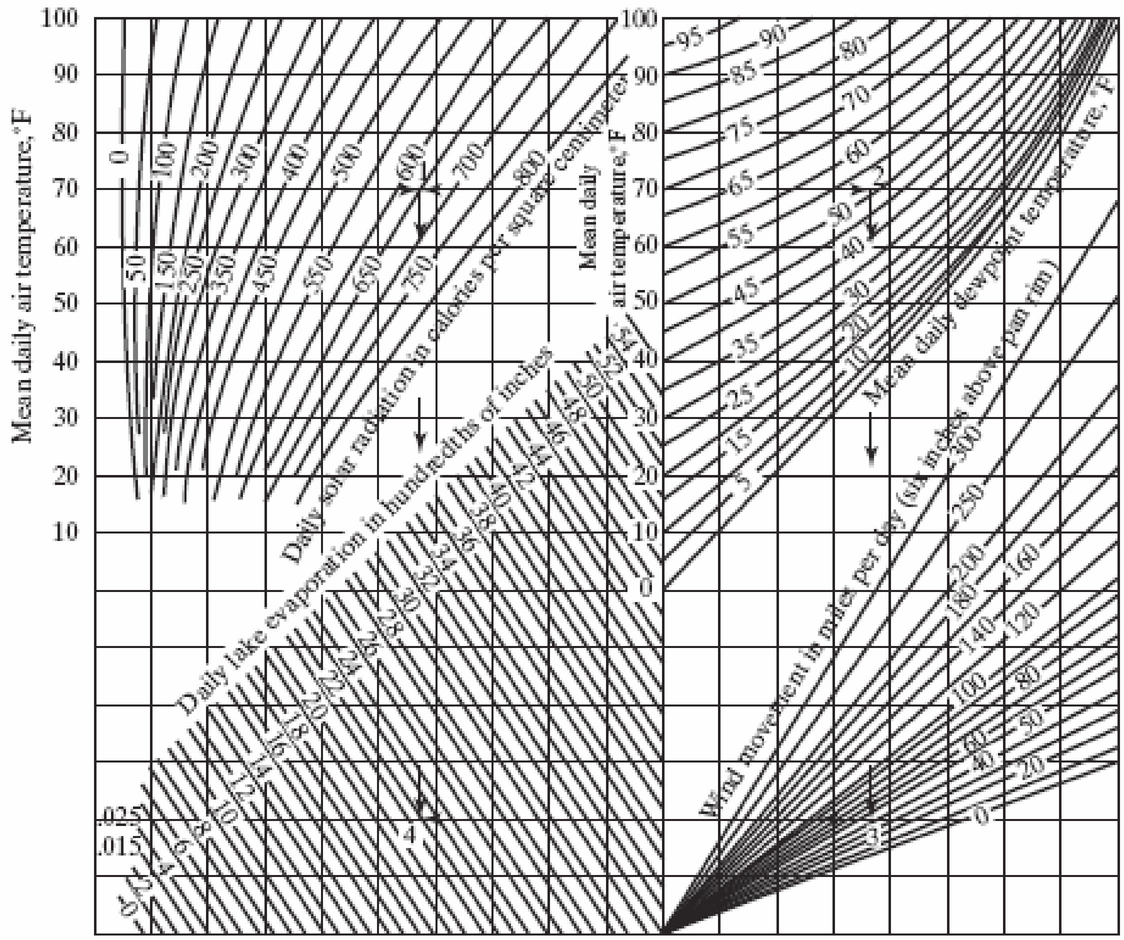
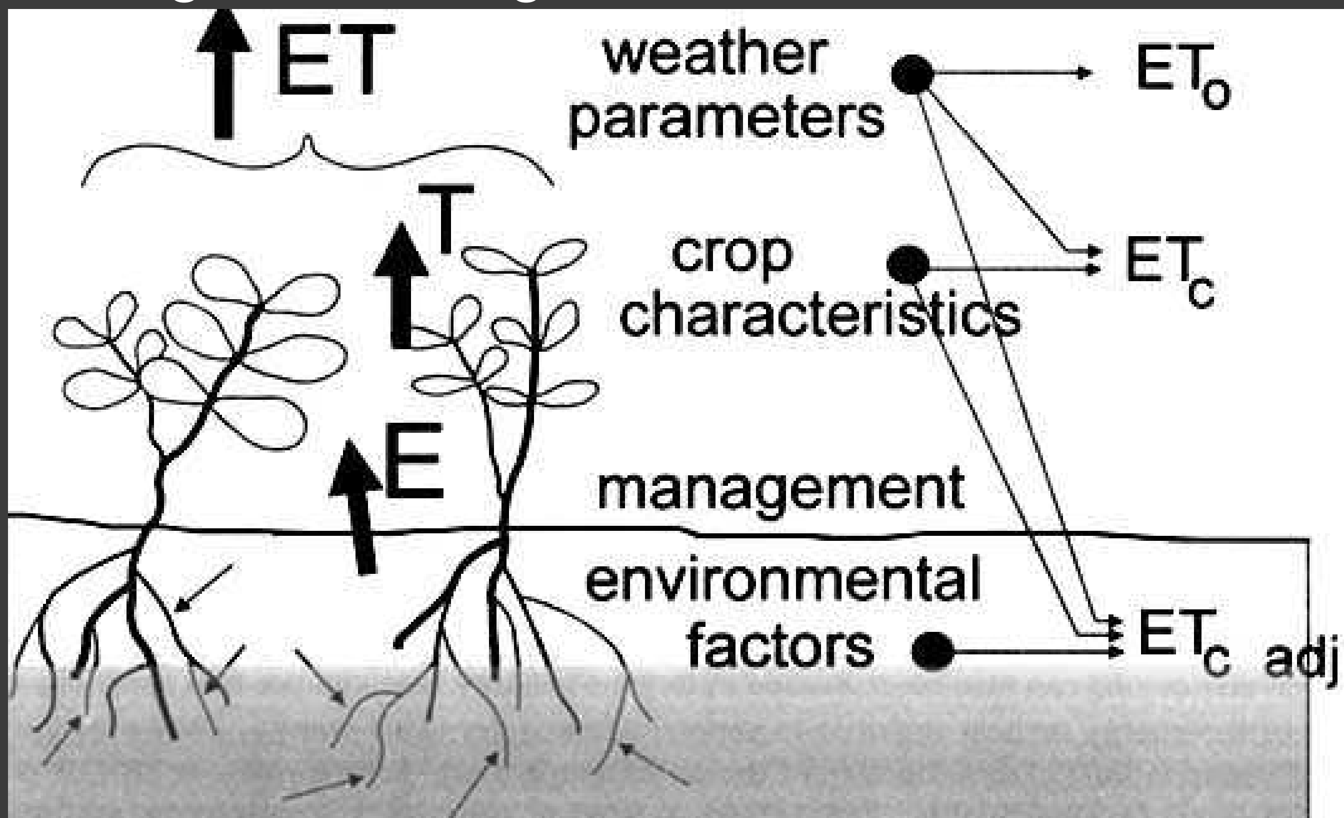


Figure 2–14
Shallow lake evaporation as a function of solar radiation, air temperature, dew point, and wind movement (Adapted from Kohler et al., 1995).

Evapotranspiration (ET)

- Influencing and limiting factors:



- Potential ET : Max possible loss

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Hydrologic Loss – Infiltration

Infiltration

- Infiltration volume is subtracted from a precipitation event in order to determine the net volume of RF (= direct runoff).
- Horton's Infiltration capacity: the actual infiltration rate will follow the limiting curve:

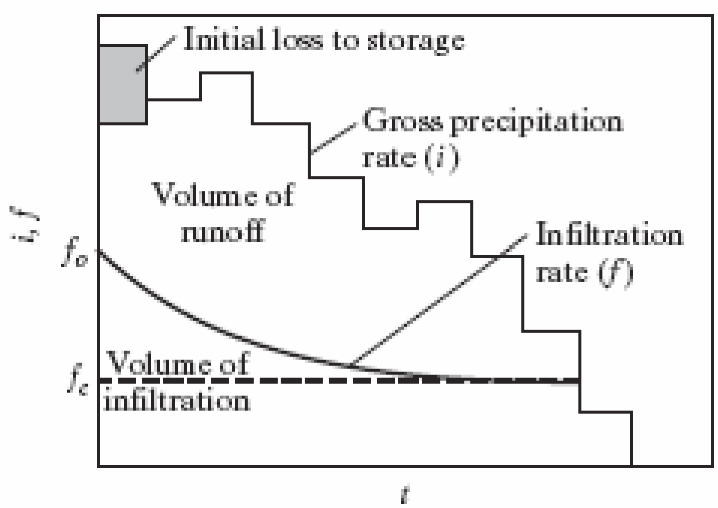


Figure 2–16
Horton's infiltration concept.

Horton Equation

- Empirical approach

$$f = f_c + (f_0 - f_c)e^{-kt},$$

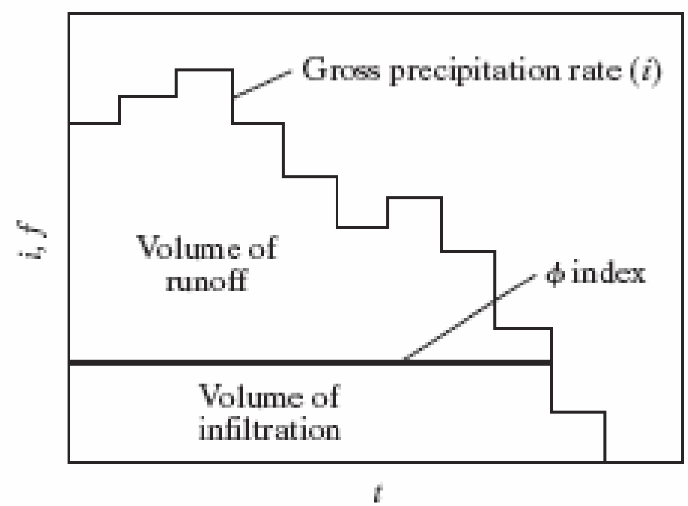
f = infiltration capacity (in./hr),
f_0 = initial infiltration capacity (in./hr),
f_c = final capacity (in./hr),
k = empirical constant (hr^{-1}).

  - Equation assumes (I > f) infiltration capacity decreases as a function of time regardless of the actual amount of water available for infiltration.
  - Without detailed measurements of actual loss rates and because urban watersheds have high imperviousness, empirical approaches usually give quite satisfactory results.

Φ Index Method

- Simplest method: Infiltrations is calculated by finding the loss difference between gross precipitation and observed surface runoff measured as a hydrograph.
- Method assumes that the loss is uniformly distributed across the rainfall pattern.

Figure 2–17
Graphical representation of the phi index method.



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Green and Ampt Infiltration Method

Green and Ampt Method

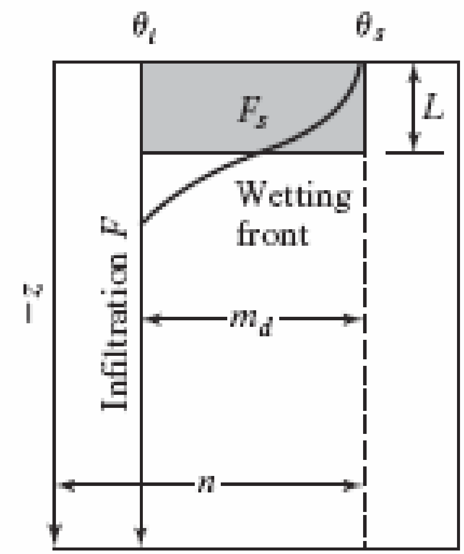
Used to predict cumulative infiltration as a function of time and readily available soil parameters (major advantage).

5 principles:

1. The soil under consideration is homogeneous and stable.
2. The supply of ponded water at the surface is not limited (subject to modification)
3. A wetting front exists and advances at the same rate as water infiltrates
4. The capillary suctions is uniform and constant
5. The soil is uniformly saturated above the wetting front, the vol. water contents remain constant and below the advancing wetting front.

Soil Properties - Terminology

- Moisture content (θ) = ratio of the volume of water to the total volume of a unit of porous media.
- Porosity (n) = ratio of interconnected void volume to total sample volume.
- Hydraulic conductivity (K) = volume of water that will flow through a unit soil column in a given time.
- Capillary suction (ψ) = measure of the combined adhesive forces that bind the water molecules to solid walls and the cohesive forces that attract water molecules to each other.



(a)

Unsaturated K

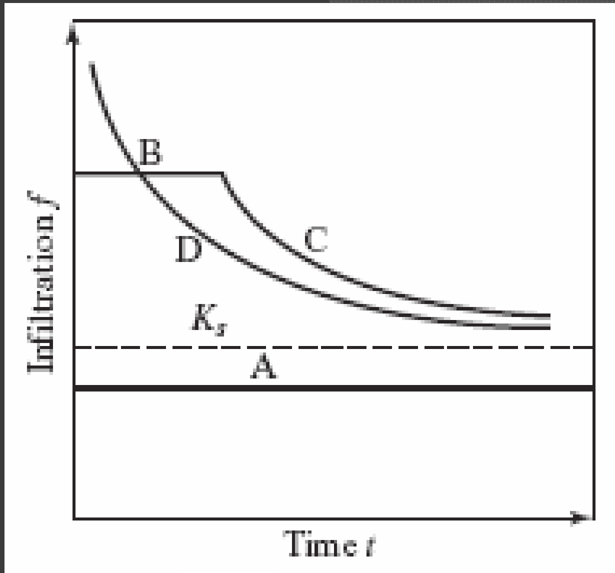
$$Q = -K(\theta)\ \partial h/\partial z$$

q = Darcy velocity

z = depth below surface

h = potential or head = z + ψ

K(θ) = unsaturated K



(c) Infiltration behavior under different rainfall. (Adapted from Main and Larson, 1973).

Equation for infiltration

$$f = K_s(1 - M_d\psi/F)$$

same restrictions as Horton's (i ≠ *f*), where:

K_s = vertically saturated K

Md = moisture deficit

F = cumulative depth of water infiltrated into the soil

Hydrology and Floodplain Analysis, Chapter 2.9

Snowfall and Snowmelt

Snow

- 13% of precipitation in the US falls as snow
- Dominant source of streamflow
- Major factors influencing timing and amount of snowmelt:
  1. Energy of snowpack
  2. Areal extent of snowcover
  3. Storage effects
- Snow water equivalent (SWE): depth of water if all the snow melted

$$SWE = .01 d_s \rho_s$$

Where: d_s = snowdepth, ρ_s = density of snow

Snowmelt calculations

- Energy balance and budget

$$\Delta H/\Delta t = Q_N + Q_g + Q_c + Q_e + Q_p$$

Q_g = conduction of heat to snowpack from underlying ground,

Q_c = convective transport of sensible heat from air to snowpack,

Q_e = release of latent heat of vaporization by condensation of water vapor onto snowpack,

Q_p = advection of heat to snowpack by rain.

Snowmelt calculations

- Melt Equations: linearization of energy budget or empirical

$$M = D_f(T_i - T_B)$$

M = daily melt as a depth of water equivalent

T_i = index air temperature

T_B = base melt temperature

D_f = degree-day melt factor