Geology 4182: Physical Hydrogeology
Spring 2009
TTH 9:00-10:30 AM
E207 Howe-Russell

- **Instructor**: Jeffrey A. Nunn
- **Office**:Room E339 Howe-Russell
- **Telephone**:578-3353/0081
- **e-mail**: gljeff@lsu.edu
- **Office hours**: 2:30 to 4:30 M or by appointment

Resources

- **Class web page** http://www.geol.lsu.edu/jnunn/gl4182/
  - Course outline, exam schedule
  - Outlines of each lecture
  - Post grades
- **Text: C. W. Fetter, Applied Hydrogeology, 4th Edition**

Classroom Conduct

- Turn off cell phones and other electronic devices
- Put away newspapers, magazines etc.
- Arrive on time
- If you MUST leave early, let me know and leave quietly

Evaluation

- Four Problem Sets (140 points)
- Four Individual Projects (200 points)
- Group Project (100 points)
- Blog participation (60 points)
- Three Exams (300 points)

CxC Certified: Written & Technological Communication

This course is certified as a "Communication-Intensive Course" and meets all of the requirements explained on the CxC Web site: http://cxc.lsu.edu., including the following: Emphases on formal and informal assignments in written communication and technological communication, class time spent on communication, 40% of the final grade based on communication projects, revisions after faculty feedback on 2 formal projects (one for each emphasis), and a student/faculty ratio of 35:1. Because it meets these requirements, students may count it toward "Distinguished Communicator" certification on LSU transcripts.

Technological Communication

Individual Projects

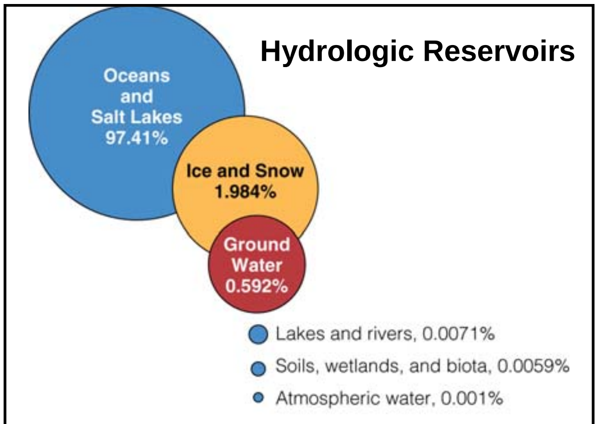
- **Excel Program of Laplace's Method**
- **Well Test Software**
- **Basin 2 simulations of driving forces**
- **Louisiana Groundwater Usage (with graphs using google application)**

Group Project

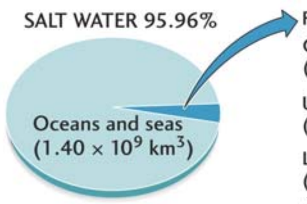
- **Environmental Consulting Firm Video**

> *There were dry years too . . . The water came in a thirty-year cycle. There would be five or six wet and wonderful years when there might be nineteen to twenty-five inches of rain, and the land would shout with grass. Then would come six or seven pretty good years of twelve to sixteen inches of rain. And then the dry years would come, and sometimes there would be only seven or eight inches of rain. The land dried up . . . And it never failed that during the dry years the people forgot the rich years, and during the wet years they lost all memory of the dry years. It was always that way.*
>
> *East of Eden*, John Steinbeck, 1952

Hydrologic Reservoirs



The Distribution of Water on Earth



FRESH WATER 4.04%

Glaciers and polar ice 2.97%
$(4.34 \times 10^7\ km^3)$

Underground waters 1.05%
$(1.54 \times 10^7\ km^3)$

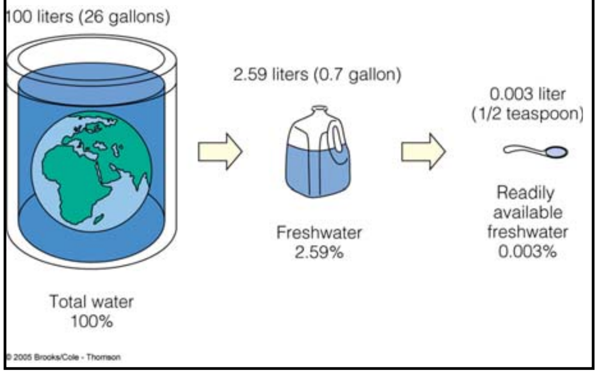
Lakes and rivers 0.009%
$(1.27 \times 10^5\ km^3)$

Atmosphere 0.001%
$(1.5 \times 10^4\ km^3)$

Biosphere 0.0001%
$(2 \times 10^3\ km^3)$

Figure 13.1

Freshwater in limited supply



© 2005 Brooks/Cole - Thomson

The Hydrologic Cycle

The continuous movement of H_2O from one reservoir to another.

The Hydrologic Cycle

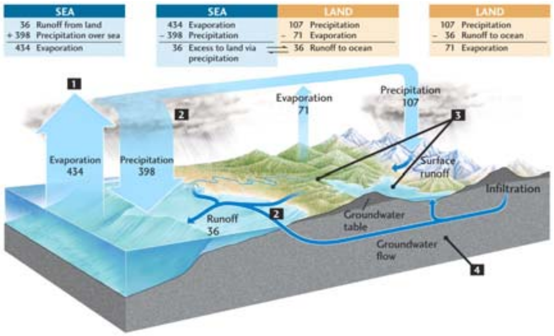


Figure 13.2

LIVE SCIENCE

Study Reveals Top 10 Wettest U.S. Cities

By Andrea Thompson, LiveScience Staff Writer
posted: 18 May 2007 01:43 pm ET

Do you think Seattle is the rainiest city in the United States? Well, think again.

Mobile, Alabama, actually topped a new list of soggiest cities in the 48 contiguous states, with more than 5 feet of rainfall annually, according to a study conducted by San Francisco-based WeatherBill, Inc.

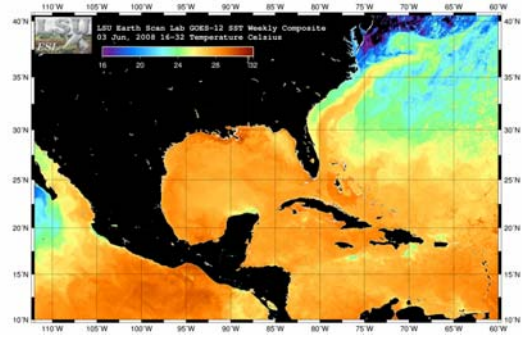
The Southeast dominated the most rainy list, while the Pacific Northwest never enters the list until Olympia, Washington pops up at number 24.

The 10 rainiest cities in the U.S. by amount of annual rainfall include:

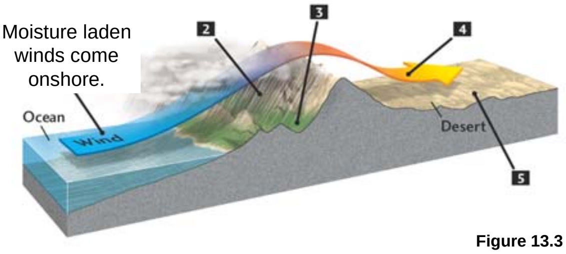
Mobile, Alabama--67 inches average annual rainfall; 59 average annual rainy days
Pensacola, Florida--65 inches average annual rainfall; 56 average annual rainy days
New Orleans, Louisiana--64 inches average annual rainfall; 59 average annual rainy days
West Palm Beach, Florida--63 inches average annual rainfall; 58 average annual rainy days
Lafayette, Louisiana--62 inches average annual rainfall; 55 average annual rainy days
Baton Rouge, Louisiana--62 inches average annual rainfall; 56 average annual rainy days ←
Miami, Florida--62 inches average annual rainfall; 57 average annual rainy days
Port Arthur, Texas--61 inches average annual rainfall; 51 average annual rainy days
Tallahassee, Florida--61 inches average annual rainfall; 56 average annual rainy days
Lake Charles, Louisiana--58 inches average annual rainfall; 50 average annual rainy days

Southeastern cities are so prevalent on the list because the warm waters of the Gulf of Mexico fuel storms that frequently soak the region, particularly between June and November.

GOM – Sea Surface Temperatures

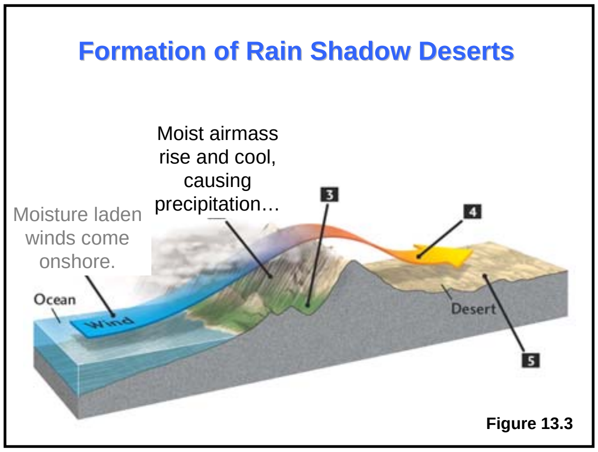


Formation of Rain Shadow Deserts



Moisture laden winds come onshore.

Figure 13.3

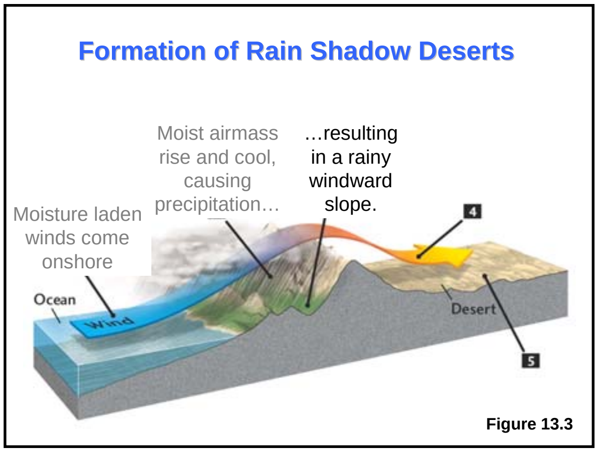


Formation of Rain Shadow Deserts

Moisture laden winds come onshore.

Moist airmass rise and cool, causing precipitation…

Figure 13.3



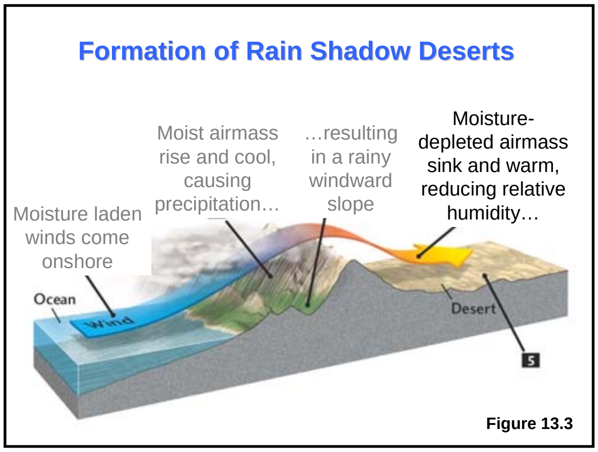
Formation of Rain Shadow Deserts

Moisture laden winds come onshore

Moist airmass rise and cool, causing precipitation…

…resulting in a rainy windward slope.

Figure 13.3



Formation of Rain Shadow Deserts

Moisture laden winds come onshore

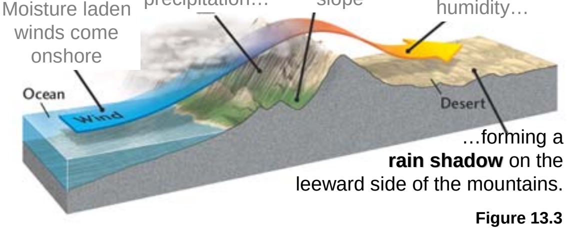
Moist airmass rise and cool, causing precipitation…

…resulting in a rainy windward slope

Moisture-depleted airmass sink and warm, reducing relative humidity…

Figure 13.3

Formation of Rain Shadow Deserts



Moisture laden winds come onshore

Moist airmass rise and cool, causing precipitation…

…resulting in a rainy windward slope

Moisture-depleted airmass sink and warm, reducing relative humidity…

…forming a **rain shadow** on the leeward side of the mountains.

Figure 13.3

Average U.S. Annual Precipitation

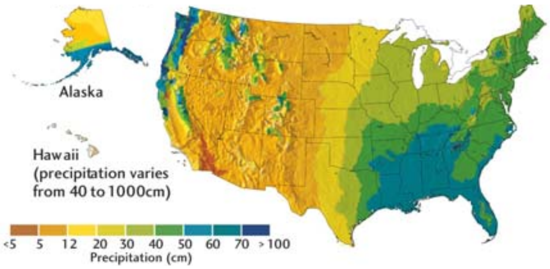


Figure 13.4.a

Average U.S. Annual Runoff

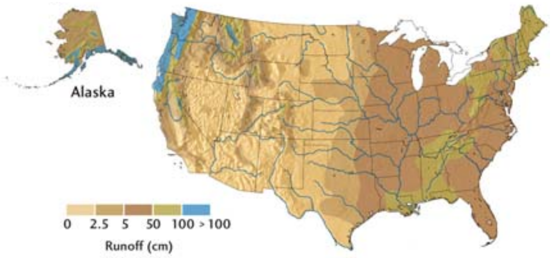
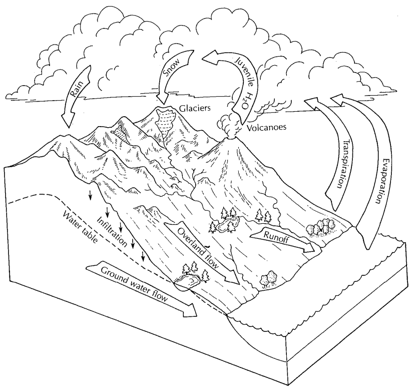


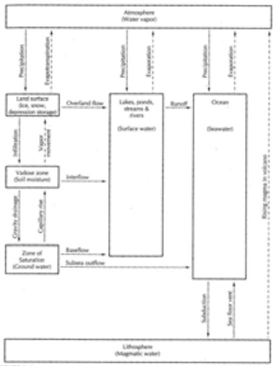
Figure 13.4.b

Table 13.1:
Average Discharges of Major Rivers of the World

River	Water Flow (m^3/s)
Amazon, South America	175,000
La Plata, South America	79,300
Congo, Africa	39,600
Yangtze, Asia	21,800
Brahmaputra, Asia	19,800
Ganges, Asia	18,700
Mississippi, North America	17,500



▲ FIGURE 1.3
The hydrologic cycle.



▲ FIGURE 1.4
Schematic drawing of the hydrologic cycle. Movement of liquid water is shown by a solid line and movement of water vapor is shown by a dashed line.

U.S. Groundwater Withdrawals: 1950-1995

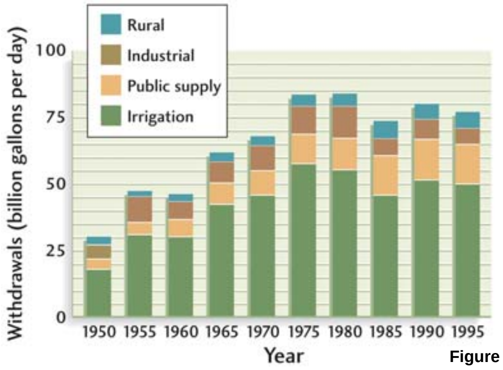
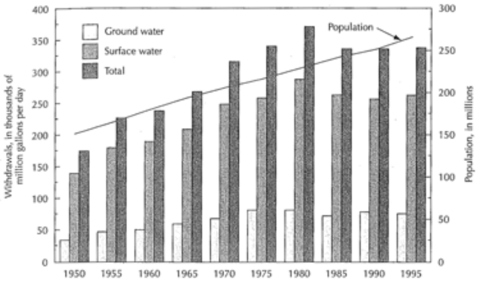
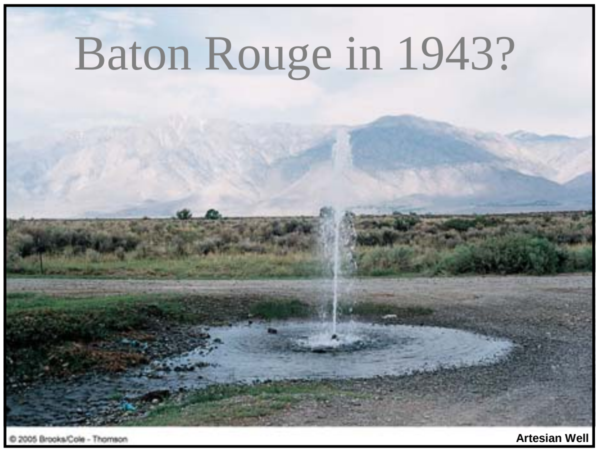


Figure 13.16



▲ FIGURE 1.1
Trends in fresh ground- and surface-water withdrawals and population in the United States.
Source: Solley, Pierce, and Perlman, 1998.

Baton Rouge in 1943?



© 2005 Brooks/Cole - Thomson

Artesian Well

Formation of a Cone of Depression

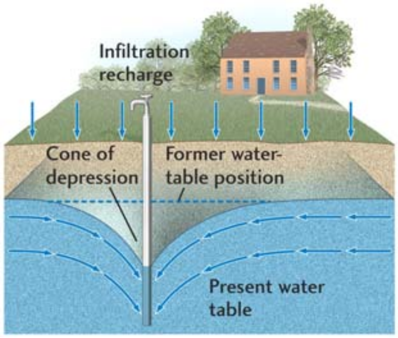
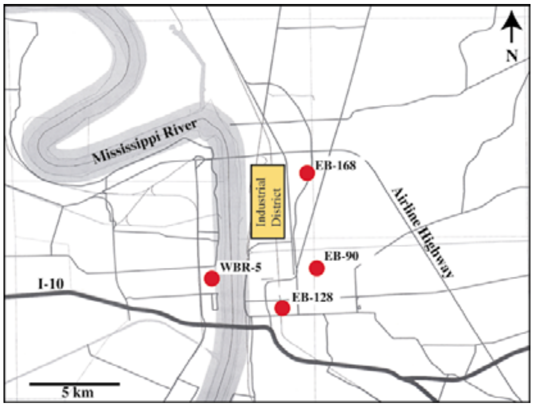
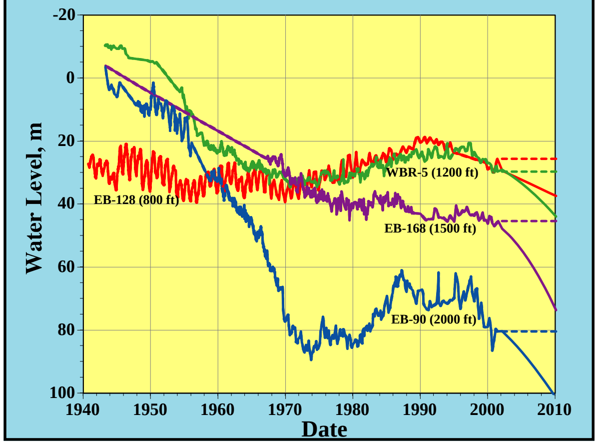


Figure 13.12





Average U.S. Annual Precipitation

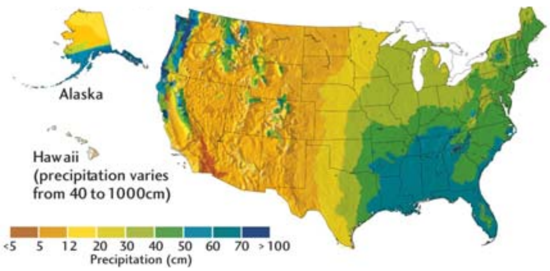
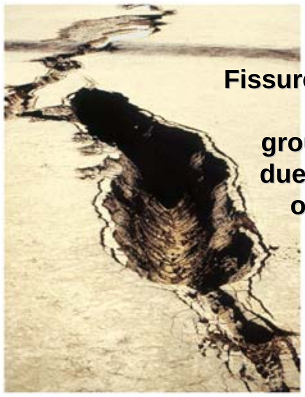


Figure 13.4.a



Fissures and depressions caused by ground subsidence due to overpumping of groundwater

Figure 13.13

The thickness of the fresh groundwater floating on top of the salty groundwater is affected by the balance between groundwater recharge and discharge

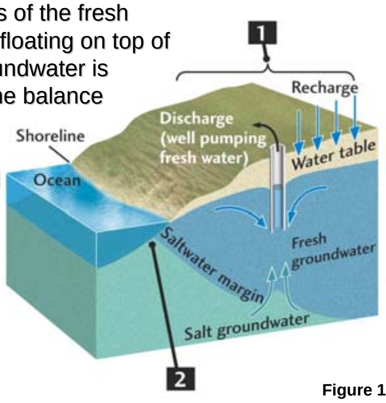
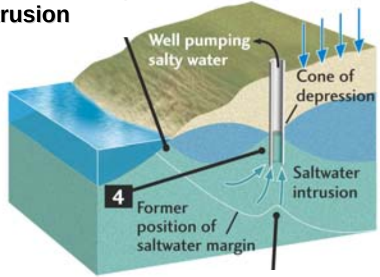


Figure 13.14

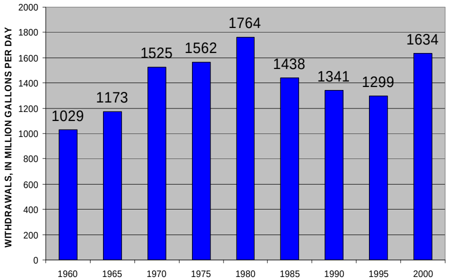
If the rate of discharge increases too much (by overpumping), the saltwater will rise, causing **saltwater intrusion** in the well



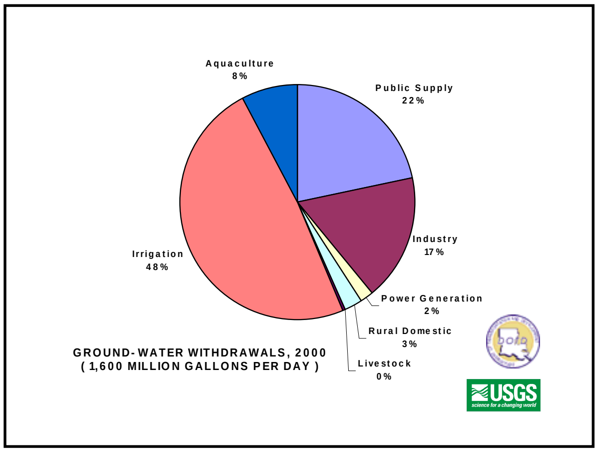
Inverted
Cone of depression

Figure 13.14

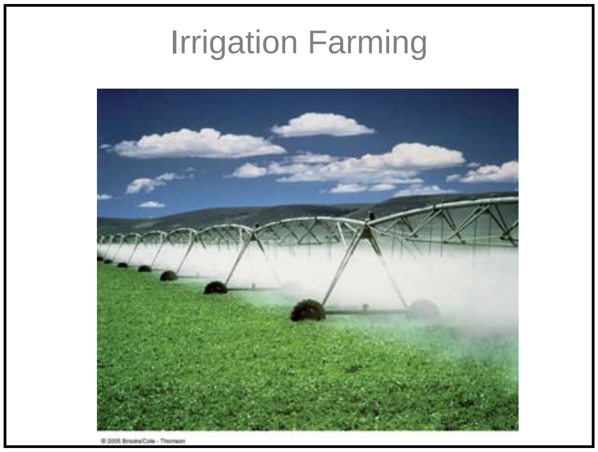
GROUND-WATER WITHDRAWALS IN LOUISIANA, 1960-2000



USGS
science for a changing world

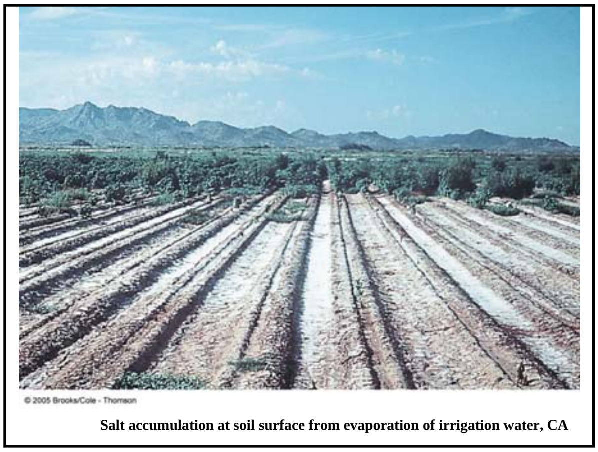


GROUND-WATER WITHDRAWALS, 2000
(1,600 MILLION GALLONS PER DAY)



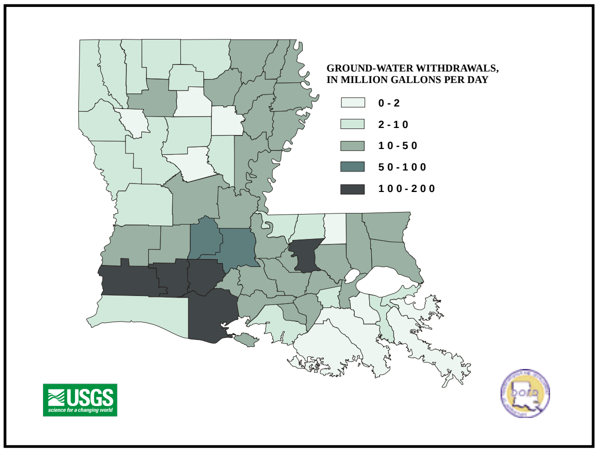
Irrigation Farming

© 2005 Brooks/Cole - Thomson



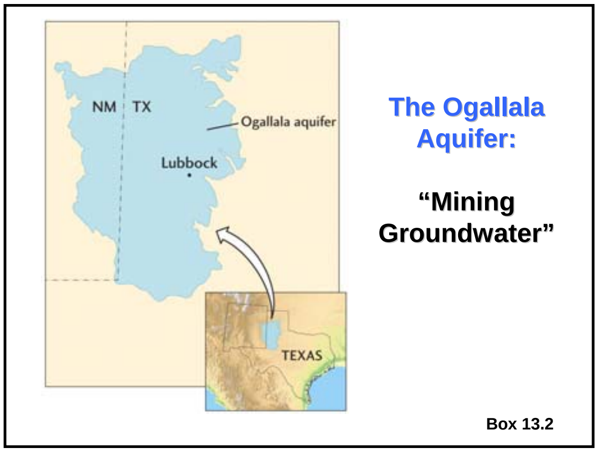
© 2005 Brooks/Cole - Thomson

Salt accumulation at soil surface from evaporation of irrigation water, CA



GROUND-WATER WITHDRAWALS,
IN MILLION GALLONS PER DAY

- 0-2
- 2-10
- 10-50
- 50-100
- 100-200



The Ogallala Aquifer:

“Mining Groundwater”

Box 13.2

The Winter Park Sinkhole, Florida

Figure 13.18

Some Human Activities that Can Contaminate Groundwater

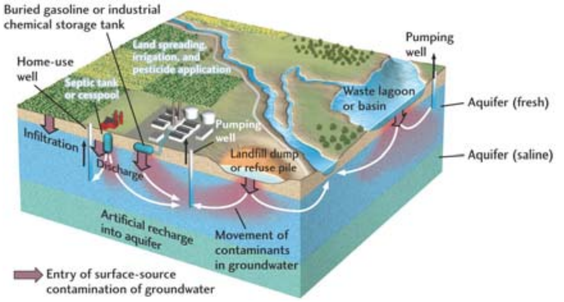
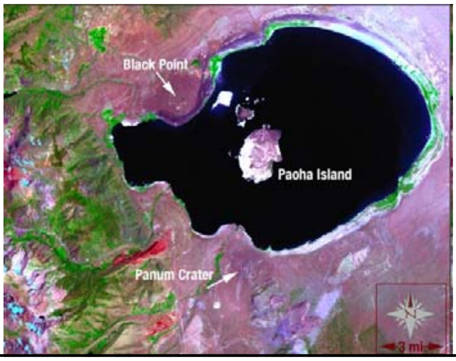


Figure 13.20

Mono Lake

▲ FIGURE 1.6
Changes in the surface elevation of Lake Mono from the year 1850 to 2000. *Source:* Mono Lake Committee (*http://www.monolake.org*). *Used with permission.*

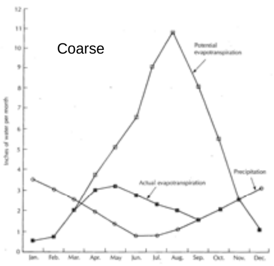
Mono Lake



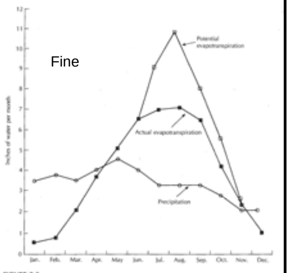
Vadose zone (zone of aeration) Water table	Vadose water	Soil water	Belt of soil water
		Intermediate vadose water	Intermediate belt
		Capillary water	Capillary fringe
Zone of saturation (phreatic zone)	Ground water		

▲ FIGURE 1.5
Classification of water beneath the land surface.

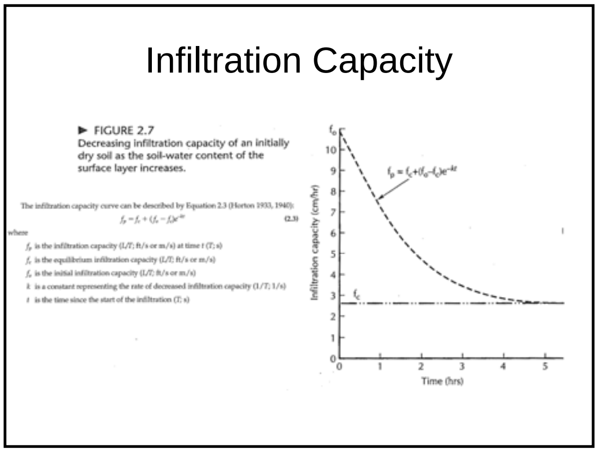
Evapotranspiration



▲ FIGURE 2.2
Diagram of potential and actual evapotranspiration in an area that has coarse soil with limited soil-moisture storage; warm, dry summers; and cool, moist winters.



▲ FIGURE 2.3
Diagram of potential and actual evapotranspiration in an area with fine soils with ample soil-moisture storage, warm summers, cool winters, and little seasonal change in precipitation.



Infiltration Capacity

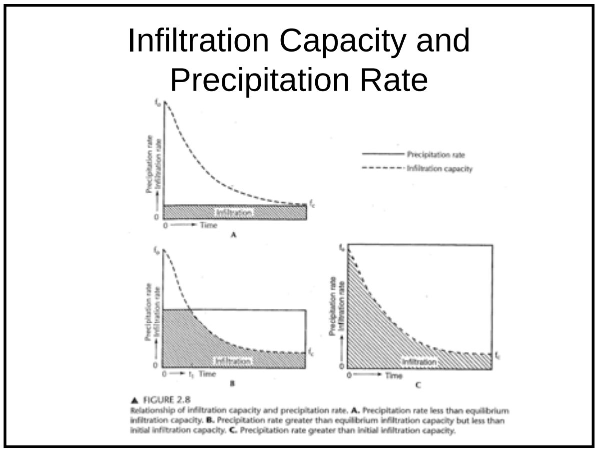
▶ FIGURE 2.7
Decreasing infiltration capacity of an initially dry soil as the soil-water content of the surface layer increases.

The infiltration capacity curve can be described by Equation 2.3 (Horton 1933, 1940):

$$f_p = f_c + (f_o - f_c)e^{-kt} \qquad (2.3)$$

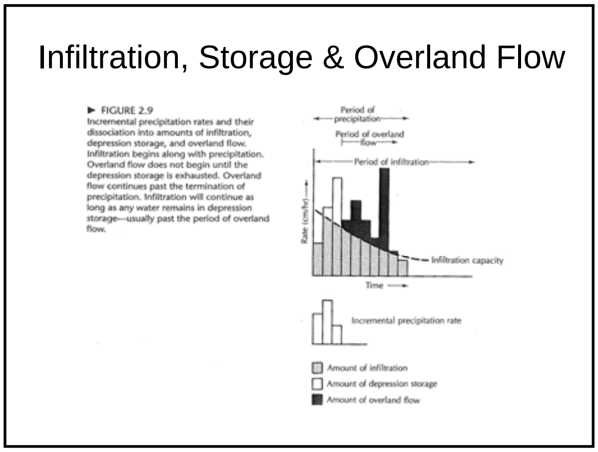
where

f_p is the infiltration capacity (L/T; ft/s or m/s) at time t (T; s)
f_c is the equilibrium infiltration capacity (L/T; ft/s or m/s)
f_o is the initial infiltration capacity (L/T; ft/s or m/s)
k is a constant representing the rate of decreased infiltration capacity (1/T; 1/s)
t is the time since the start of the infiltration (T; s)



Infiltration Capacity and Precipitation Rate

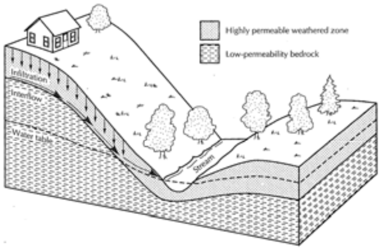
▲ FIGURE 2.8
Relationship of infiltration capacity and precipitation rate. **A.** Precipitation rate less than equilibrium infiltration capacity. **B.** Precipitation rate greater than equilibrium infiltration capacity but less than initial infiltration capacity. **C.** Precipitation rate greater than initial infiltration capacity.



Infiltration, Storage & Overland Flow

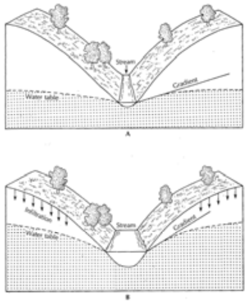
▶ FIGURE 2.9
Incremental precipitation rates and their dissociation into amounts of infiltration, depression storage, and overland flow. Infiltration begins along with precipitation. Overland flow does not begin until the depression storage is exhausted. Overland flow continues past the termination of precipitation. Infiltration will continue as long as any water remains in depression storage—usually past the period of overland flow.

Interflow



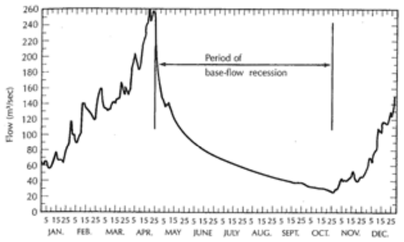
▲ FIGURE 2.10
Interflow developing where a highly permeable but thin layer of weathered rock overlies a bedrock unit of lower permeability.

Baseflow and Water-table Gradient



▲ FIGURE 2.11
Influence of the water-table gradient on baseflow. The stream in part A is being fed by ground water with a low hydraulic gradient. A gentle rain does not produce overland flow, but infiltration raises the water table. The increased hydraulic gradient of part B causes more baseflow to the stream, which is now deeper and has a greater discharge.

Base-flow Recession



▲ FIGURE 2.12
Typical annual hydrograph for a river with a long, dry summer season: Lualaba River, Central Africa. *Source: C. O. Wisler & E. F. Brater, eds.,* Hydrology, *2nd ed. (New York: John Wiley, 1959). Used with permission.*

Recession Constant

Part A: Find the recession constant for the basin of Figure 2.13.

If

$$Q = Q_0 e^{-at}$$

then

$$e^{-at} = Q/Q_0$$

$$-at = \ln Q/Q_0$$

$$a = -(1/t \ln Q/Q_0)$$

From Figure 2.13, $Q_0 = 3500\ \text{ft}^3/\text{s}$. After 100 d, $Q = 1500\ \text{ft}^3/\text{s}$.

$$a = -1/t \ln Q/Q_0$$

$$= -\frac{1}{100\text{d}} \ln \frac{1500\ \text{ft}^3/\text{s}}{3500\ \text{ft}^3/\text{s}}$$

$$= -0.01\text{d}^{-1} \ln 0.4286$$

$$= -0.01\text{d}^{-1} \times (-0.847)$$

$$= 8.47 \times 10^{-3}\ \text{d}^{-1}$$

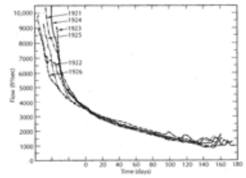
Part B: What would be the baseflow after 40 d of recession?

$$Q = Q_0 e^{-at}$$

$$= 3500\ \text{ft}^3/\text{s} \exp(-8.47 \times 10^{-3}\ \text{d}^{-1} \times 40\ \text{d})$$

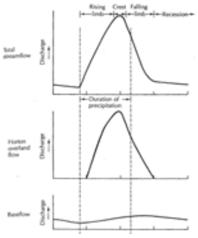
$$= 3500\ \text{ft}^3/\text{s} \times 0.713$$

$$= 2500\ \text{ft}^3/\text{s}$$



▲ FIGURE 2.13
Annual baseflow recessions for six consecutive years for the Lualaba River, Central Africa. Source: C. O
Wisler & E. F. Brater, eds., Hydrology, 2nd ed. (New York: John Wiley, 1959). Used with permission.

Overland Flow vs. Baseflow



◀ FIGURE 2.14
Hypothetical storm hydrograph for a period of evenly distributed precipitation, separated into Horton overland flow, baseflow, direct precipitation, and interflow.

One task in analyzing a storm hydrograph is to separate the overland-flow component from the baseflow. Generally, it is first assumed that both the direct precipitation and the interflow components are inconsequential; however, the hydrogeologist should be aware of the general geology and surface slope of the drainage area before making this assumption. The overland flow is assumed to end some fixed time after the storm peak. As a rule of thumb, this can be approximated by the following formula (Linsley, Kohler, & Paulhus 1975):

$$D = A^{0.2} \qquad \textbf{(2.5)}$$

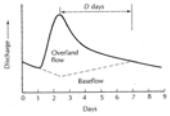
where

D is the number of days between the storm peak and the end of overland flow

A is the drainage basin area in square miles

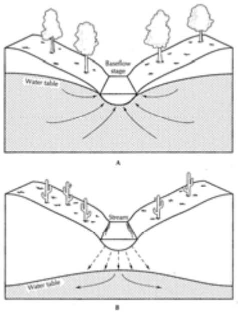
or

$$D = 0.827A^{0.2} \qquad \textbf{(2.6)}$$



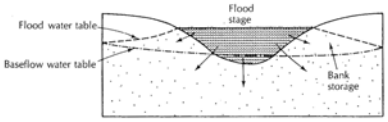
◀ FIGURE 2.15
Hydrograph separation into overland-flow component and baseflow component for a stream receiving Horton overland flow.

Gaining/Losing Streams

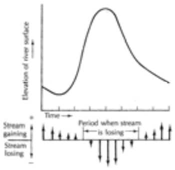


▲ FIGURE 2.16
A. Cross section of a gaining stream, which is typical of humid regions, where ground water recharges streams. **B.** Cross section of a losing stream, which is typical of arid regions, where streams can recharge ground water.

Changes during Floods

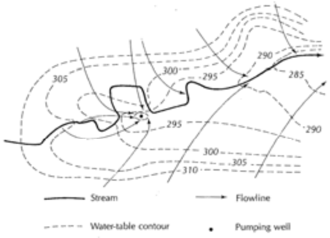


▲ FIGURE 2.17
A stream that is gaining during low-flow periods can temporarily become a losing stream during flood stage.



◄ FIGURE 2.18
Effect of flood state on the ground-water regime adjacent to the river. As the flood peak passes, the normal direction of ground-water flow into the stream is reversed.

Induced Infiltration



▲ FIGURE 2.19
Induced streambed infiltration caused by a pumping well. *Source: P. Rahn,* Ground Water *6, no. 3 (1968): 21–32. Used with permission © 1968, Ground Water Publishing Company.*

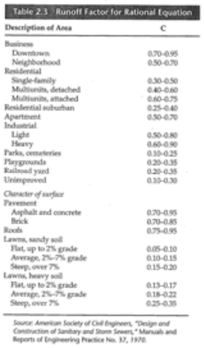
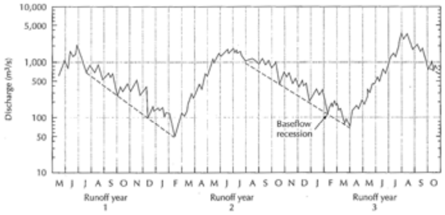


Table 2.3 Runoff Factor for Rational Equation

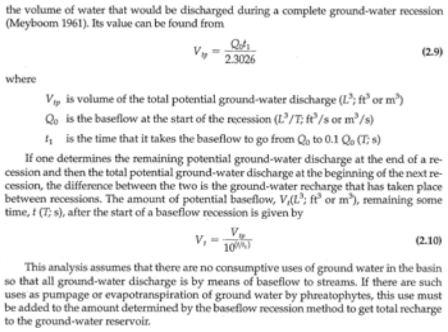
Description of Area	C
Business	
Downtown	0.70–0.95
Neighborhood	0.50–0.70
Residential	
Single-family	0.30–0.50
Multiunits, detached	0.40–0.60
Multiunits, attached	0.60–0.75
Residential suburban	0.25–0.40
Apartment	0.50–0.70
Industrial	
Light	0.50–0.80
Heavy	0.60–0.90
Parks, cemeteries	0.10–0.25
Playgrounds	0.20–0.35
Railroad yard	0.20–0.35
Unimproved	0.10–0.30
Character of surface	
Pavement	
Asphalt and concrete	0.70–0.95
Brick	0.70–0.85
Roofs	0.75–0.95
Lawns, sandy soil	
Flat, up to 2% grade	0.05–0.10
Average, 2%–7% grade	0.10–0.15
Steep, over 7%	0.15–0.20
Lawns, heavy soil	
Flat, up to 2% grade	0.13–0.17
Average, 2%–7% grade	0.18–0.22
Steep, over 7%	0.25–0.35

Source: American Society of Civil Engineers, "Design and Construction of Sanitary and Storm Sewers," Manuals and Reports of Engineering Practice No. 37, *1970.*

Baseflow Recessions



▲ FIGURE 2.21
Semilogarithmic stream hydrograph showing baseflow recessions.



the volume of water that would be discharged during a complete ground-water recession (Meyboom 1961). Its value can be found from

$$V_{tp} = \frac{Q_0 t_1}{2.3026} \qquad \textbf{(2.9)}$$

where

V_{tp} is volume of the total potential ground-water discharge (L^3; ft^3 or m^3)

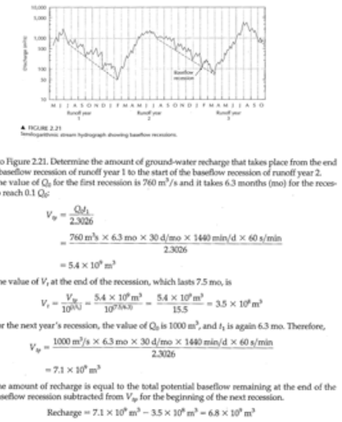
Q_0 is the baseflow at the start of the recession (L^3/T; ft^3/s or m^3/s)

t_1 is the time that it takes the baseflow to go from Q_0 to 0.1 Q_0 (T; s)

If one determines the remaining potential ground-water discharge at the end of a recession and then the total potential ground-water discharge at the beginning of the next recession, the difference between the two is the ground-water recharge that has taken place between recessions. The amount of potential baseflow, V_t(L^3; ft^3 or m^3), remaining some time, t (T; s), after the start of a baseflow recession is given by

$$V_t = \frac{V_{tp}}{10^{(t/t_1)}} \qquad \textbf{(2.10)}$$

This analysis assumes that there are no consumptive uses of ground water in the basin so that all ground-water discharge is by means of baseflow to streams. If there are such uses as pumpage or evapotranspiration of ground water by phreatophytes, this use must be added to the amount determined by the baseflow recession method to get total recharge to the ground-water reservoir.



▲ FIGURE 2.21
Semilogarithmic stream hydrograph showing baseflow recessions.

Refer to Figure 2.21. Determine the amount of ground-water recharge that takes place from the end of the baseflow recession of runoff year 1 to the start of the baseflow recession of runoff year 2.

The value of Q_0 for the first recession is 760 m^3/s and it takes 6.3 months (mo) for the recession to reach 0.1 Q_0:

$$V_{tp} = \frac{Q_0 t_1}{2.3026}$$

$$= \frac{760 \text{ m}^3\text{s} \times 6.3 \text{ mo} \times 30 \text{ d/mo} \times 1440 \text{ min/d} \times 60 \text{ s/min}}{2.3026}$$

$$= 5.4 \times 10^9 \text{ m}^3$$

The value of V_t at the end of the recession, which lasts 7.5 mo, is

$$V_t = \frac{V_{tp}}{10^{(t/t_1)}} = \frac{5.4 \times 10^9 \text{ m}^3}{10^{(7.5/6.3)}} = \frac{5.4 \times 10^9 \text{ m}^3}{15.5} = 3.5 \times 10^8 \text{ m}^3$$

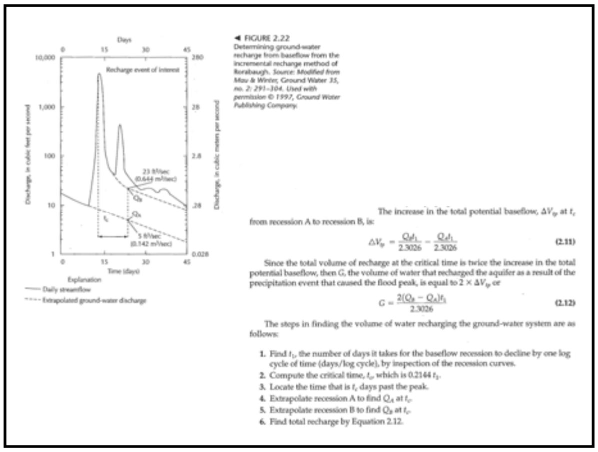
For the next year's recession, the value of Q_0 is 1000 m^3, and t_1 is again 6.3 mo. Therefore,

$$V_{tp} = \frac{1000 \text{ m}^3\text{/s} \times 6.3 \text{ mo} \times 30 \text{ d/mo} \times 1440 \text{ min/d} \times 60 \text{ s/min}}{2.3026}$$

$$= 7.1 \times 10^9 \text{ m}^3$$

The amount of recharge is equal to the total potential baseflow remaining at the end of the first baseflow recession subtracted from V_{tp} for the beginning of the next recession.

$$\text{Recharge} = 7.1 \times 10^9 \text{ m}^3 - 3.5 \times 10^8 \text{ m}^3 = 6.8 \times 10^9 \text{ m}^3$$



◄ FIGURE 2.22
Determining ground-water recharge from baseflow from the incremental recharge method of Rorabaugh. *Source: Modified from Mau & Winter, Ground Water 35, no. 2: 291–304. Used with permission © 1997, Ground Water Publishing Company.*

The increase in the total potential baseflow, ΔV_{tp} at t_c from recession A to recession B, is:

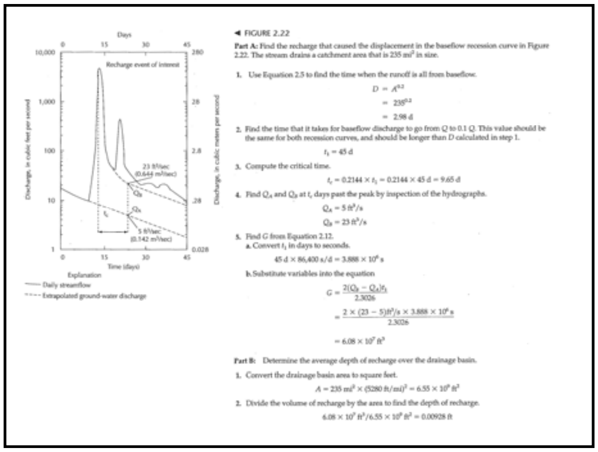
$$\Delta V_{tp} = \frac{Q_B t_1}{2.3026} - \frac{Q_A t_1}{2.3026} \qquad \textbf{(2.11)}$$

Since the total volume of recharge at the critical time is twice the increase in the total potential baseflow, then G, the volume of water that recharged the aquifer as a result of the precipitation event that caused the flood peak, is equal to $2 \times \Delta V_{tp}$ or

$$G = \frac{2(Q_B - Q_A)t_1}{2.3026} \qquad \textbf{(2.12)}$$

The steps in finding the volume of water recharging the ground-water system are as follows:

1. Find t_1, the number of days it takes for the baseflow recession to decline by one log cycle of time (days/log cycle), by inspection of the recession curves.
2. Compute the critical time, t_c, which is 0.2144 t_1.
3. Locate the time that is t_c days past the peak.
4. Extrapolate recession A to find Q_A at t_c.
5. Extrapolate recession B to find Q_B at t_c.
6. Find total recharge by Equation 2.12.



◄ FIGURE 2.22

Part A: Find the recharge that caused the displacement in the baseflow recession curve in Figure 2.22. The stream drains a catchment area that is 235 mi² in size.

1. Use Equation 2.5 to find the time when the runoff is all from baseflow.

$$\begin{aligned} D &= A^{0.2} \\ &= 235^{0.2} \\ &= 2.98 \text{ d} \end{aligned}$$

2. Find the time that it takes for baseflow discharge to go from Q to 0.1 Q. This value should be the same for both recession curves, and should be longer than D calculated in step 1.

$$t_1 = 45 \text{ d}$$

3. Compute the critical time.

$$t_c = 0.2144 \times t_1 = 0.2144 \times 45 \text{ d} = 9.65 \text{ d}$$

4. Find Q_A and Q_B at t_c days past the peak by inspection of the hydrographs.

$$Q_A = 5 \text{ ft}^3/\text{s}$$
$$Q_B = 23 \text{ ft}^3/\text{s}$$

5. Find G from Equation 2.12.
   a. Convert t_1 in days to seconds.

$$45 \text{ d} \times 86{,}400 \text{ s/d} = 3.888 \times 10^6 \text{ s}$$

   b. Substitute variables into the equation

$$\begin{aligned} G &= \frac{2(Q_B - Q_A)t_1}{2.3026} \\ &= \frac{2 \times (23 - 5)\text{ft}^3/\text{s} \times 3.888 \times 10^6 \text{ s}}{2.3026} \\ &= 6.08 \times 10^7 \text{ ft}^3 \end{aligned}$$

Part B: Determine the average depth of recharge over the drainage basin.

1. Convert the drainage basin area to square feet.

$$A = 235 \text{ mi}^2 \times (5280 \text{ ft/mi})^2 = 6.55 \times 10^9 \text{ ft}^2$$

2. Divide the volume of recharge by the area to find the depth of recharge.

$$6.08 \times 10^7 \text{ ft}^3 / 6.55 \times 10^9 \text{ ft}^2 = 0.00928 \text{ ft}$$