INTRODUCTION TO HYDROLOGY

Hydrology and Floodplain Analysis, Chapter 1

CEVE 412

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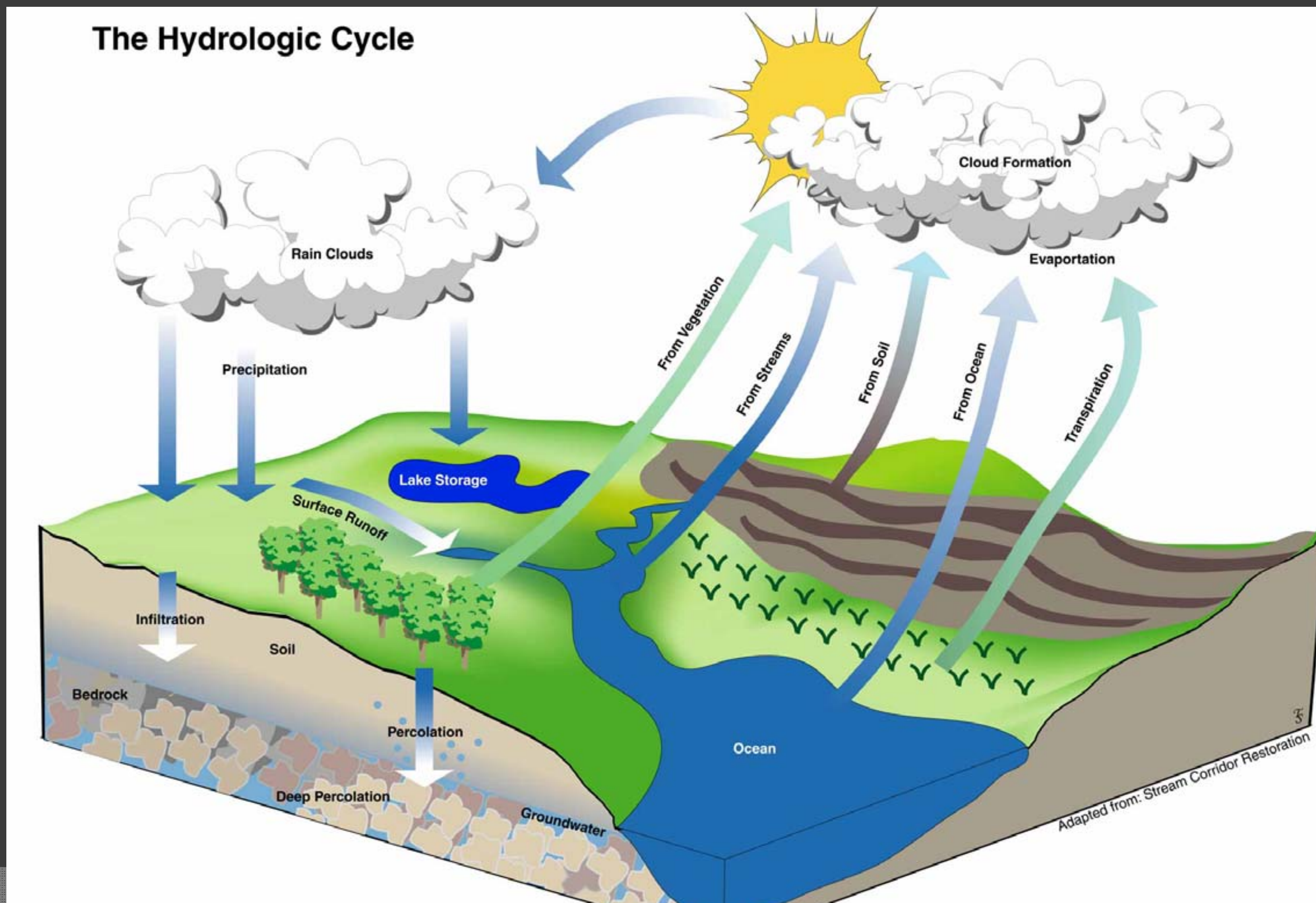
Jan 2012

Hydrology

- The study of the occurrence, circulation, storage and distribution of surface and ground water on the earth.
- Areas of focus:
  - Hydrologic cycle
  - Fluid dynamics
  - Hydrodynamics
  - Water resource engineering
  - Water quality
  - Contaminant transport

The Hydrologic Cycle

- Continuous process in which water is evaporated from water surfaces and oceans, moves in land and precipitation is produced



The Hydrologic Cycle

- **Precipitation (P)** – Rainfall, snow, etc.
- **Evaporation (E)** – conversion of water to water vapor from a water surface
- **Transpiration (T)** – loss of water vapor through plant tissue and leaves
- **Infiltration (F)** – water entering the soil system, function of soil moisture, soil type
- **Ground water (G)** – flows in porous media in the subsurface
- **Runoff (R)** – Overland flow, portion of precipitation that does not infiltrate

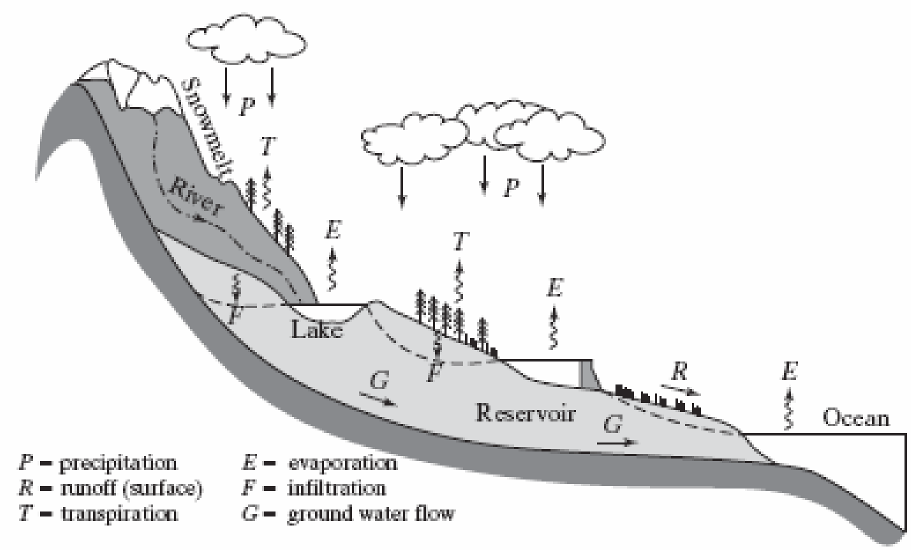


Figure 1–1a
The hydrologic cycle discharges surface water and groundwater from the higher elevation to the lower elevation.

History

- Water resource projects dating as far back as 4000 BC
  - Dam built across the Nile
- First systemic flow measurement in U.S. in 1888 by USGS
- 1930s-1950s saw a boom in hydrologic knowledge in US
- Post 1950, scientists gained a greater understanding of the effects of urbanization in regards to hydrology
- Computer advances have allowed for modeling of complex hydrologic and hydraulic problems

Hydrology and Floodplain Analysis, Chapter 1.2

Weather Systems

The Atmosphere

- Atmosphere is a major hydrologic link between oceans and continents and facilitates the movement of water on the earth

- Major parameters
  1. Atmospheric Pressure
  2. Humidity
  3. Precipitation

Atmospheric Pressure

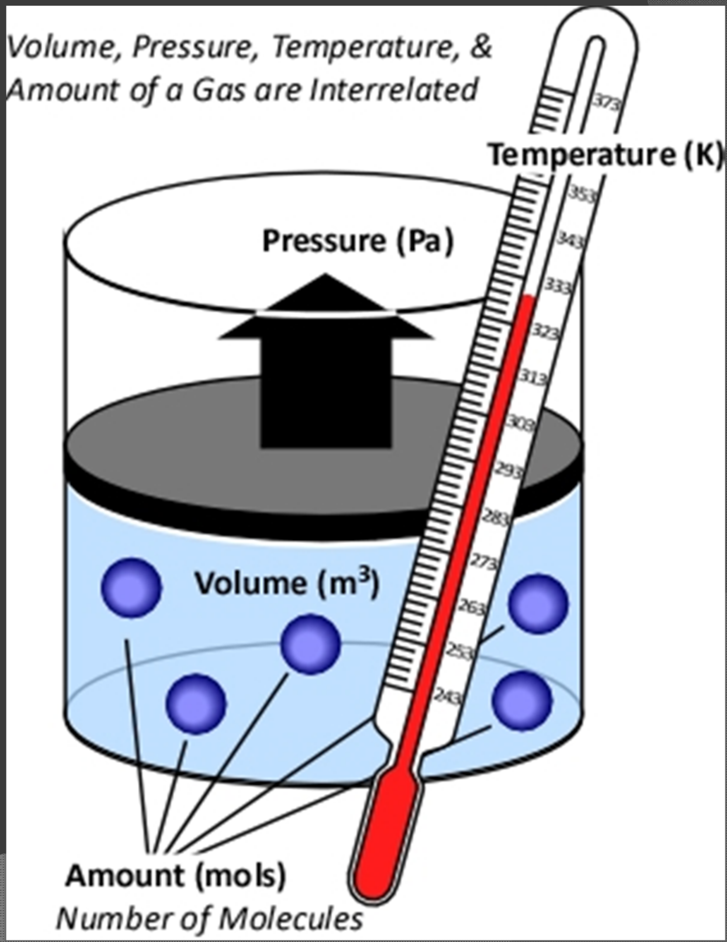
- Pressure = weight of air / unit area

- Average Pressure at sea level (units)
  - 1 atmosphere
  - 1013 millibars (mb)
  - 14.7 psi
  - 760 mm-Hg

Ideal Gas Law

- Describes behavior of gas under different conditions

- $PV = nRT$
  - P = Pressure
  - V = Volume
  - n = moles of gas
  - R = ideal gas constant
  - T = Temperature (Kelvin)

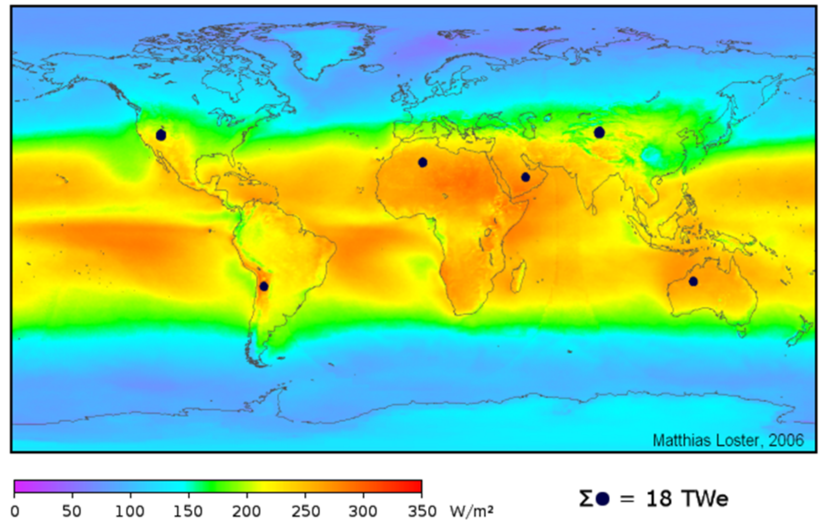


Gas Law and Atmosphere

- Pressure and Temperature are directly related at constant density
- Temperature and Air Density (n/V) are inversely related
  - Decrease in temperature increases density
- Affects movement of air masses
  - High pressure moves toward low pressure

Atmospheric Circulation

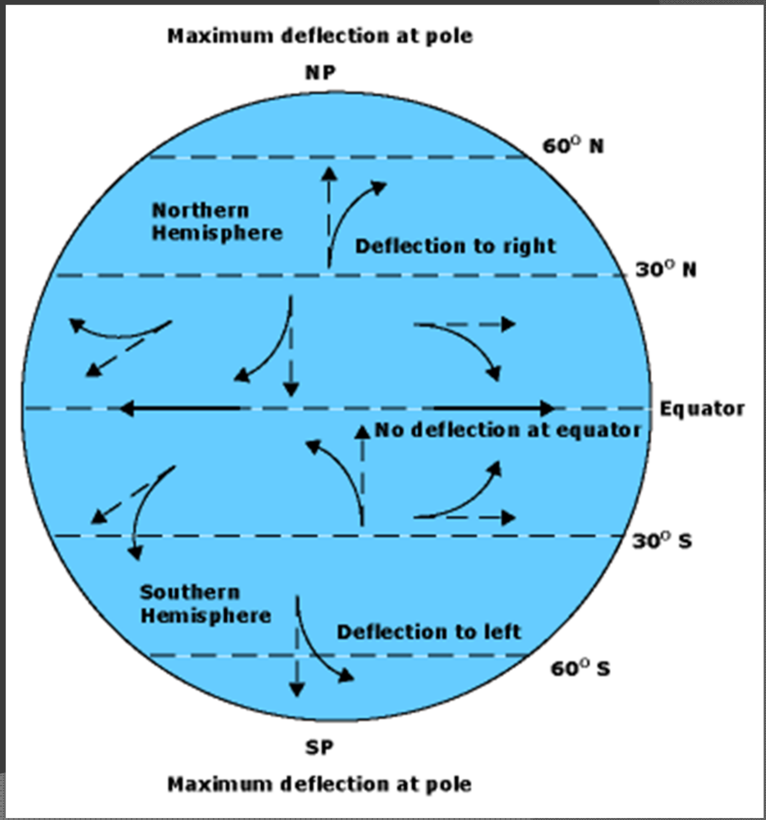
- Fueled by solar energy
  - Uneven heating of the Earth
  - Concentrated at the equator



- Warm air (low pressure) travels upwards from the equator and then towards the poles
  - Air shifts direction due to the *Coriolis Force*

Coriolis Force

- Causes air masses to "turn right" in northern hemisphere, "turn left" in southern
- Maintains angular momentum
  - Mass of air wants to maintain same speed, so it must speed up as it leaves equator, or slow down as it moves towards equator
    - Point at the equator moves faster than point near the pole



Atmospheric Circulation

- Coriolis effect creates **westerlies**, winds that blow west to east in the northern hemisphere
  - Drive major weather systems in the U.S.

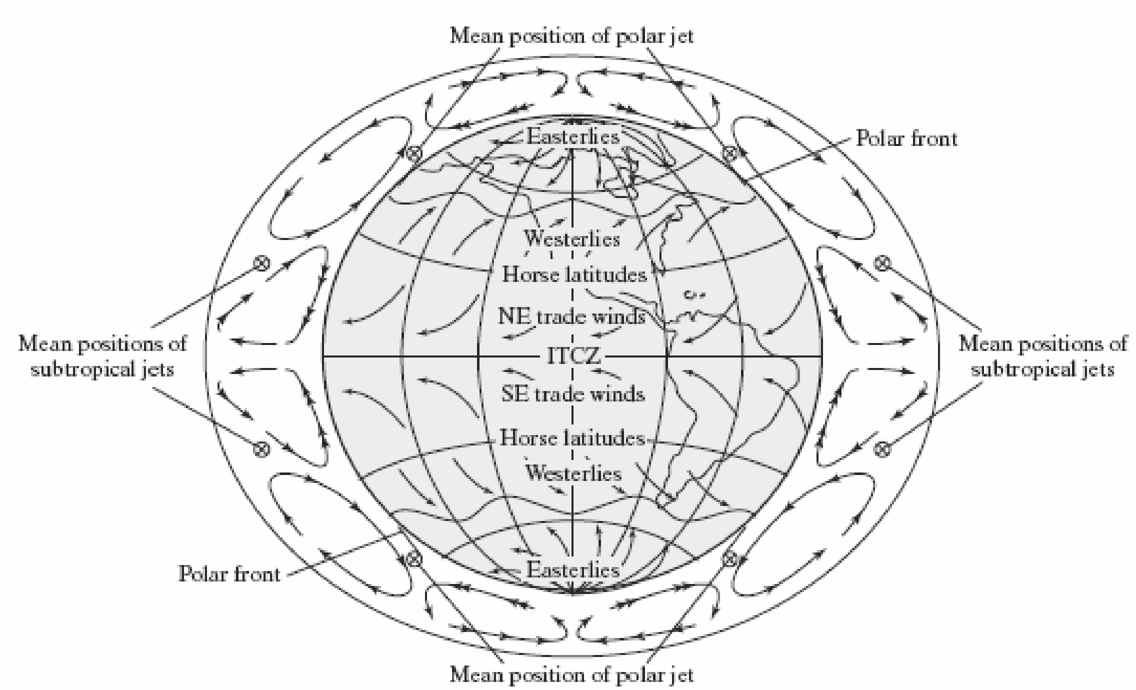


Figure 1–3
General circulation of currents and wind patterns across the earth.

Air Masses and Fronts

- **Air Masses** - large bodies of air with fairly consistent temperature and humidity gradients in horizontal direction
  - High Pressure System = Cold Weather
  - Low Pressure System = Warm Weather

- Fronts are the boundaries between two air masses

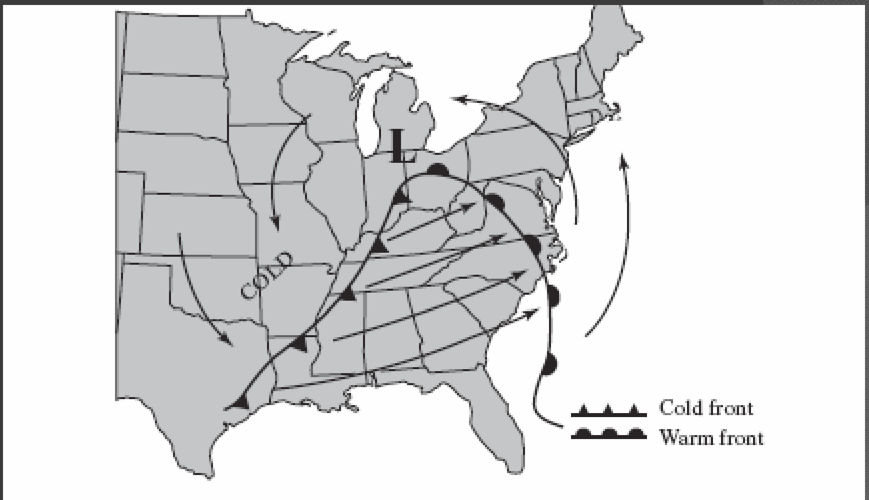


Figure 1–4
Direction of the cold and warm fronts in the eastern United States. The cold fronts come from the North toward the Gulf and the warm fronts start from the Gulf to push inland.

Humidity

- Measure of amount of water vapor in atmosphere
  - **Specific Humidity** - the mass of water vapor in a unit mass of moist air at a given temperature
  - **Relative Humidity** – ratio of (air's actual water vapor content) to (amount of water vapor at saturation for that temperature)

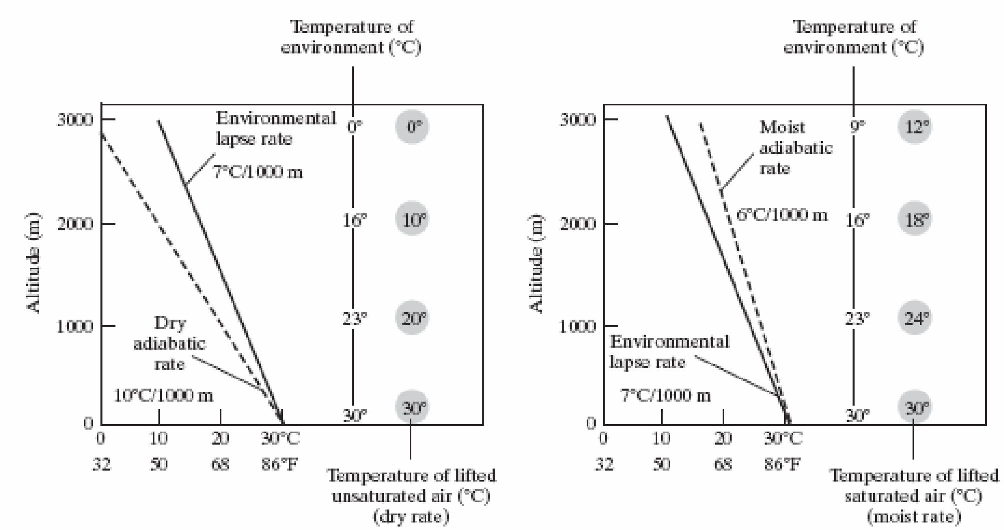
- As air is lifted, it cools
  - Cool air "holds" less water
  - Eventually cools to the point that relative humidity is saturated, and water vapor is condensed to liquid

Moisture Relationships

- **Specific Humidity (q)**
  - q = (0.622*e) / (P - 0.378*e)
- **Vapor Pressure (e)** – partial pressure exerted by water vapor
  - $e = (\rho_w * R * T) / (0.622)$
    - ρ_w = vapor density or absolute humidity (g/cm^3)
    - R = dry air gas constant
    - T = temperature (Kelvin)
- **Dew Point Temperature (T_d)** – temperature that an air mass with constant pressure and moisture content becomes saturated

Atmospheric Stability

- Adiabatic Lapse Rate (ALR)
  - Rate of temperature change of air parcel with change in elevation
  - Dry ALR = 9.8 ^{o}C/km
  - Rate varies with moisture conditions
  - Causes stable or unstable atmospheric conditions



(a) The unsaturated parcel of air at each elevation is colder than its surroundings. The atmosphere is stable with respect to unsaturated, rising air.

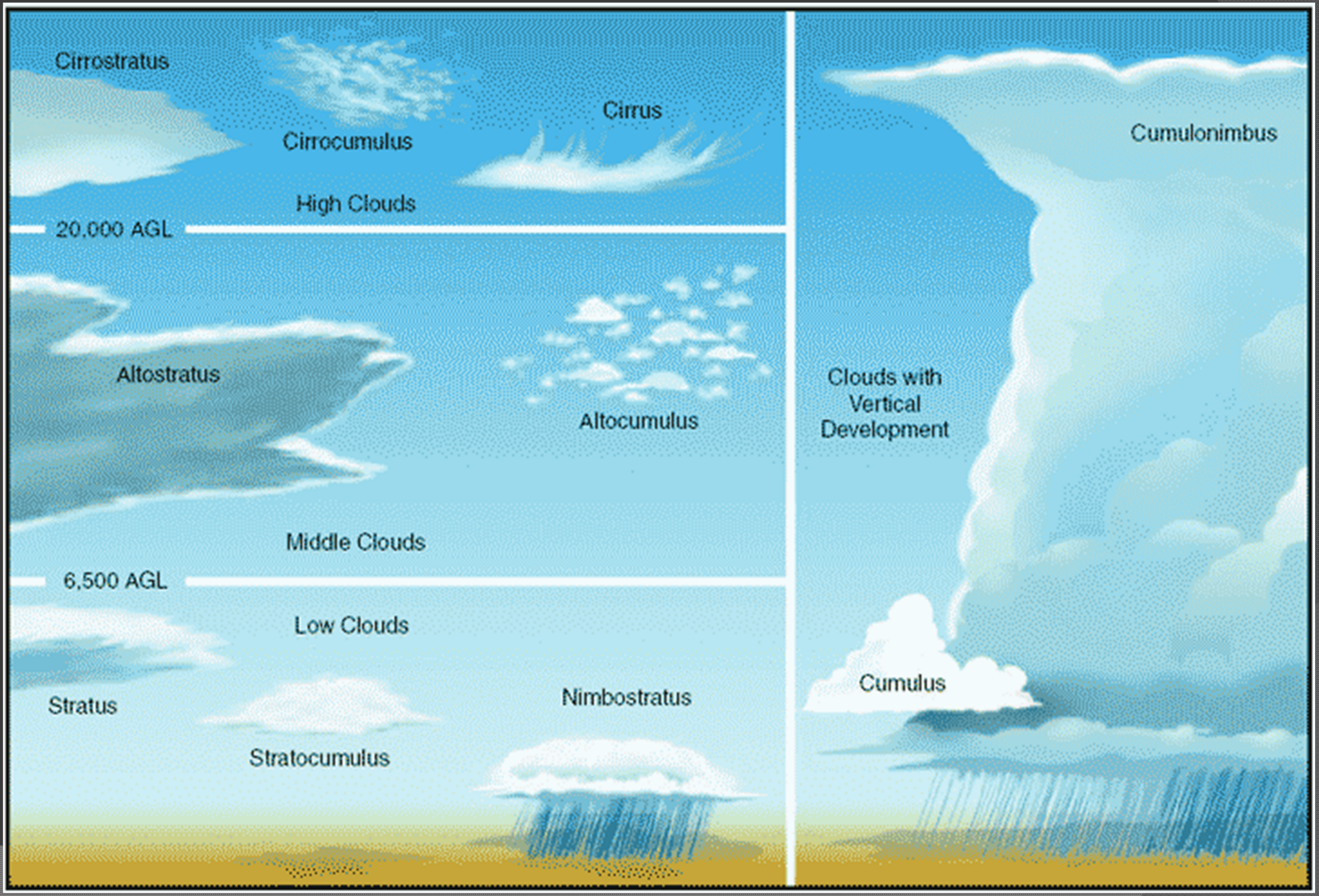
(b) The lifted, saturated air parcel is warmer at each elevation than its surroundings. The atmosphere is unstable with respect to saturated, rising air.

Figure 1–8
Variation of lapse rates and different types of atmospheric conditions. When air is colder than its surroundings and rises, it results in what is called a stable atmosphere. On the other hand, when warmer air rises, it results in an unstable atmosphere (greater movement of air).

Cloud Types

- Cirrus – feathery or fibrous clouds
- Stratus – layered clouds
- Cumulus – towering, puffy clouds
- Alto – middle-level clouds
- Nimbus – rain clouds
- Cumulonimbus – thunderstorm clouds

Clouds



Cirrostratus
Cirrocumulus
Cirrus
High Clouds
20,000 AGL
Altostratus
Altocumulus
Middle Clouds
6,500 AGL
Low Clouds
Stratus
Stratocumulus
Nimbostratus
Cumulonimbus
Clouds with Vertical Development
Cumulus

Precipitation

- Condensed water vapor that falls to earth
- Occurs when air parcel reaches saturation
  - i.e. the Dew Point Temperature is reached
- Heat must be removed from moist air to allow for condensation
  - **Latent Heat**
  - Major energy source for storm systems

Precipitation Formation

- Requires the following:
  1. Moisture source
  2. Lifting and resultant cooling
  3. Phase change occurs with condensation onto small nuclei in the air
     - Range from 0.1 u – 10 u
     - Come from ocean salt, dust, etc
  4. Droplets grow large enough to overcome drag and evaporation

Lifting Mechanisms

- Precipitation often classified by vertical lifting
  - **Convective** – Intense heating of the ground → expansion and vertical rise of air
  - **Cyclonic** – Movement of large air-mass systems (warm/cold fronts)
  - **Orographic** – Mechanical lifting of moist air masses over the windward side of mountain ranges

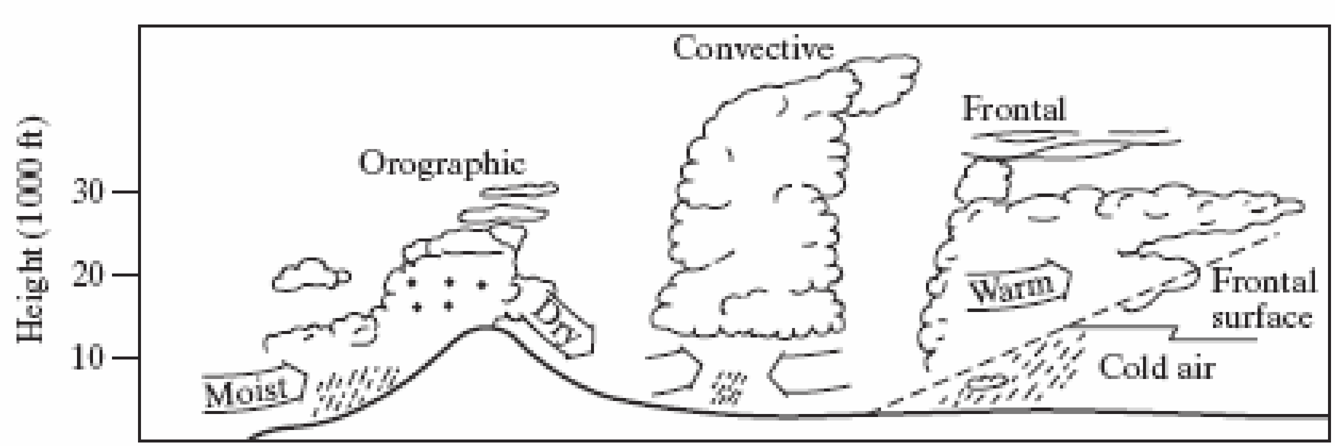


Figure 1–9
The three different precipitation lifting mechanisms that result when air at different temperatures meet in different topographies.

Thunderstorms

- Thunderstorms
  - Heavy rainfall, thunder, lightning, hail
  - Result from strong vertical movements or warm, moist air
  - Generally occur due to instability caused by:
    - Low-pressure systems
    - Surface heating
    - Forced ascent over mountains

Thunderstorm Stages

- Cumulus Stage
  - Moist air rises, cools and condenses into cumulus clouds and continues to rise and condense
    - Updraft
- Mature Stage
  - Rain begins to fall
  - Surrounding dry air is drawn into storm, evaporates some drops and cools the air
    - Denser, cold air descends (downdraft) and creates cool gusts of wind at ground level

Thunderstorm Stages (cont)

- Dissipating Stage
  - When the updraft is cutoff
  - Rate of precipitation decreases
  - Downdrafts die-off
  - Clouds dissolve

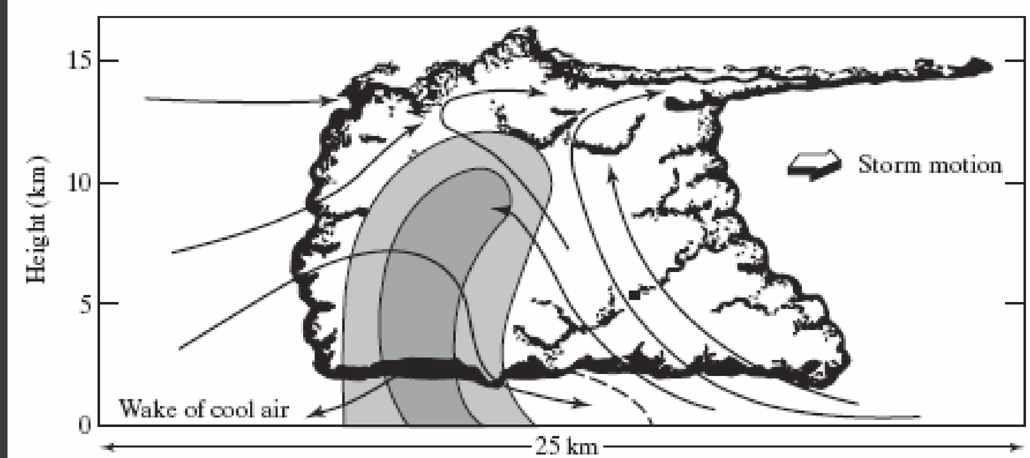


Figure 1–6
Typical thunderstorm cloud evolution. The typical anvil-shaped clouds that are present during a thunderstorm are caused by the movement of cold air and warm air. As the cold air moves downward and the warm air moves upward, the warm air above spreads out in order to cool, resulting in the following shape, very much like an anvil.

Hurricanes

- Intense cyclonic storms
- Form over tropical oceans
  - Have localized names
    - Hurricane (N. Americe)
    - Cyclone (India)
    - Typhoon (East Asia)
    - Baguio (China Sea)

- Energy comes from the condensation of very warm, humid, tropical air
- Categorized by the Saffir-Simpson Hurricane Windscale

Saffir-Simpson Wind Scale

Category	Wind Speed (mph)	Extent of Damage	Damage Description
Tropical Storm	39 – 73	Minor	Some flooding
1	74 – 95	Minimal	Limited damage, unanchored mobile homes, trees
2	96 – 110	Moderate	Some roof, door and window damage
3	111 – 130	Extensive	Some structural damage to residences and utility buildings
4	131 – 155	Extreme	Extensive curtainwall failures, complete roof failures, all signs blown down
5	156+	Catastrohpic	Complete roof failure and some complete building failures

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Measuring Precipitation

Precipitation Trends

- Varies geographically
  - Greater near coasts
  - Greater on windward side of mountains
    - Western side in US
- Varies from season to season

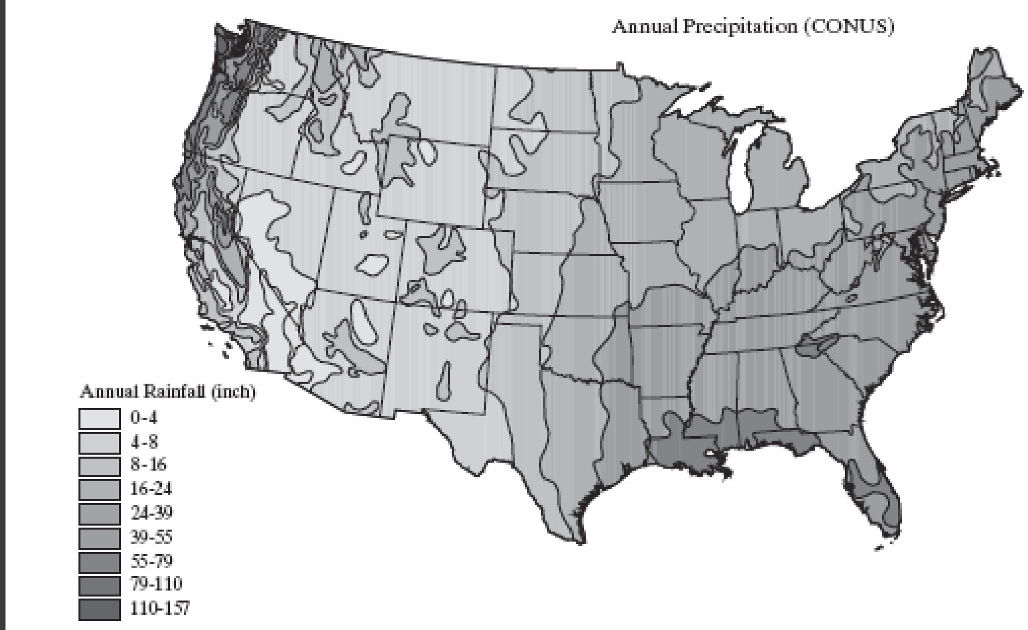


Figure 1–10
Distribution of average annual precipitation across the United States.

Rainfall Measurement

- Why measure rainfall?
  - Water resource planning (annual)
    - California Water Project supplies water to Southern California from Northern California
  - Urban drainage (hourly)
    - Reduce localized flooding
    - Need intensity and duration of rainfall
    - Spatial variation inside watershed

Point Measurement

- Rainfall gage networks
  - Maintained by NWS, USGS or local organizations
  - Typical gauge design →
- Methods of representation
  - Accumulated total rainfall
    - “Cumulative mass curve”
  - Rainfall Intensity vs. time
    - “Hyetograph”

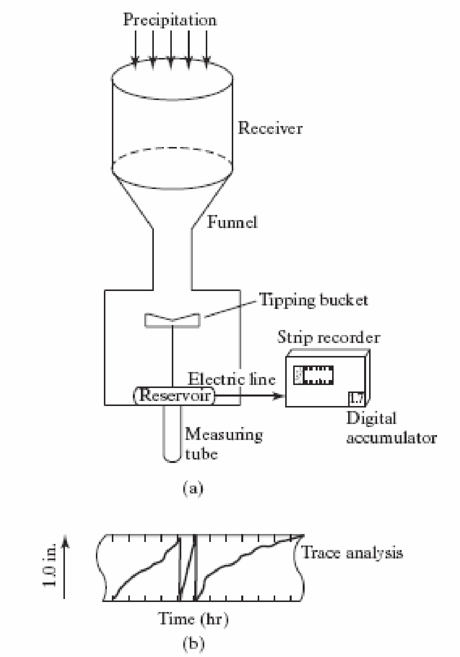
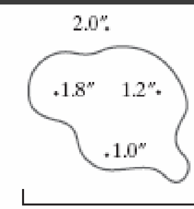


Figure 1–14a
Recording tipping bucket gage. Trace returns to zero after each inch of rainfall. The slope of the trace registers intensity (in./hr).

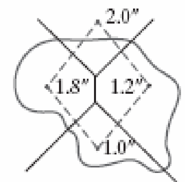
Areal Precipitation

- The average depth of precipitation over a specific area (watershed)
- Use point measurements to determine avg.
- Three Methods
  - Arithmetic Mean
  - Thiessen Polygon Method
  - Isohyetal Method



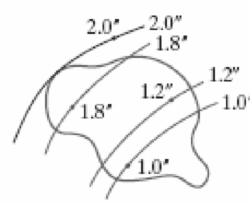
$$\frac{1.8 + 1.2 + 1.0}{3} = 1.33 \text{ in.}$$

(a) Arithmetic mean



P_i (in.)	A_i (mi²)	A_i/A_T	$(P_i)(A_i/A_T)$ (in.)
2.0	1.5	0.064	0.13
1.8	7.2	0.305	0.55
1.2	5.1	0.216	0.26
1.0	9.8	0.415	0.42
Σ =	23.6	1.000	1.35 in.

(b) Thiessen polygon method



Isohyet (in.)	A (mi²)	P_{av} (in.)	V (in.–mi²)
2.0	5.1	1.9	9.69
1.8	9.8	1.5	14.7
1.2	3.1	1.1	3.41
1.0	5.6	0.5*	2.8
	23.6		30.6

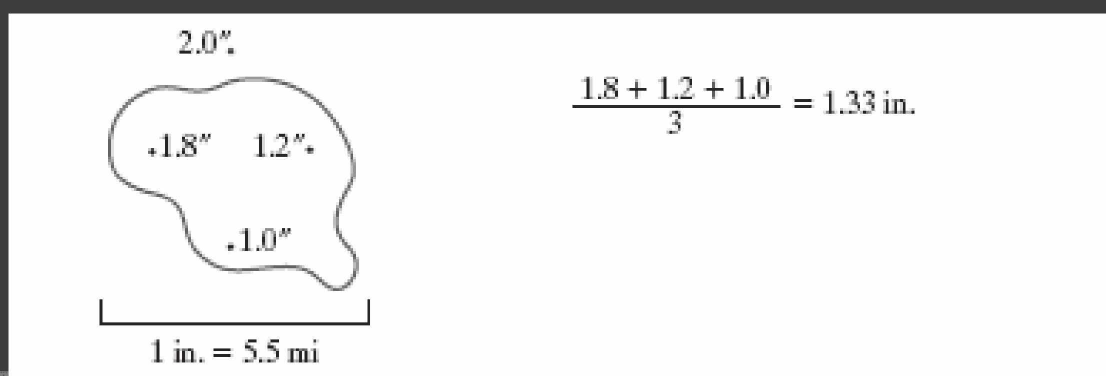
Average rainfall = 30.6/23.6 = 1.30 in.

* Estimated

(c) Isohyetal method

Arithmetic Mean

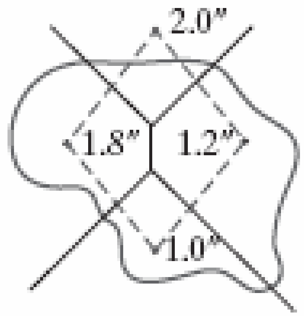
- Takes arithmetic mean of rainfalls from available gages
- Not accurate for large areas with variable distribution
- Only works if gages are uniformly distributed



(a) Arithmetic mean

Thiessen Polygon Method

- Areal weighting of rainfall for each gage
- Series of polygons created by lines connecting eat gauge and perpendicular bisectors
  - Uses ratio of polygon area to total area of interest
- Most widely used method

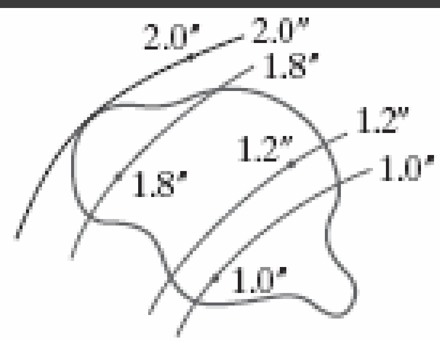


P_i (in.)	A_i (mi^2)	A_i/A_T	$(P_i)(A_i/A_T)$ (in.)
2.0	1.5	0.064	0.13
1.8	7.2	0.305	0.55
1.2	5.1	0.216	0.26
1.0	9.8	0.415	0.42
Σ =	23.6	1.000	1.35 in.

(b) Thiessen polygon method

Isohyetal Method

- Draw contours of equal precipitation based on gauge data
  - Uses area between each contour
- Needs an extensive gauge network
- Most accurate method



Isohyet (in.)	A (mi^2)	P_{av} (in.)	V (in.$-mi^2$)
2.0	5.1	1.9	9.69
1.8	9.8	1.5	14.7
1.2	3.1	1.1	3.41
1.0	5.6	0.5*	2.8
	23.6		30.6

Average rainfall = 30.6/23.6 = 1.30 in.

* Estimated

(c) Isohyetal method

Next-Generation Radar (NEXRAD)

- Allows for measurement of rainfall rates and cumulative totals
- Aided flood prediction
- Specs
  - 10-cm wave length
  - Records
    - Reflectivity
    - Radial Velocity
    - Spectrum width

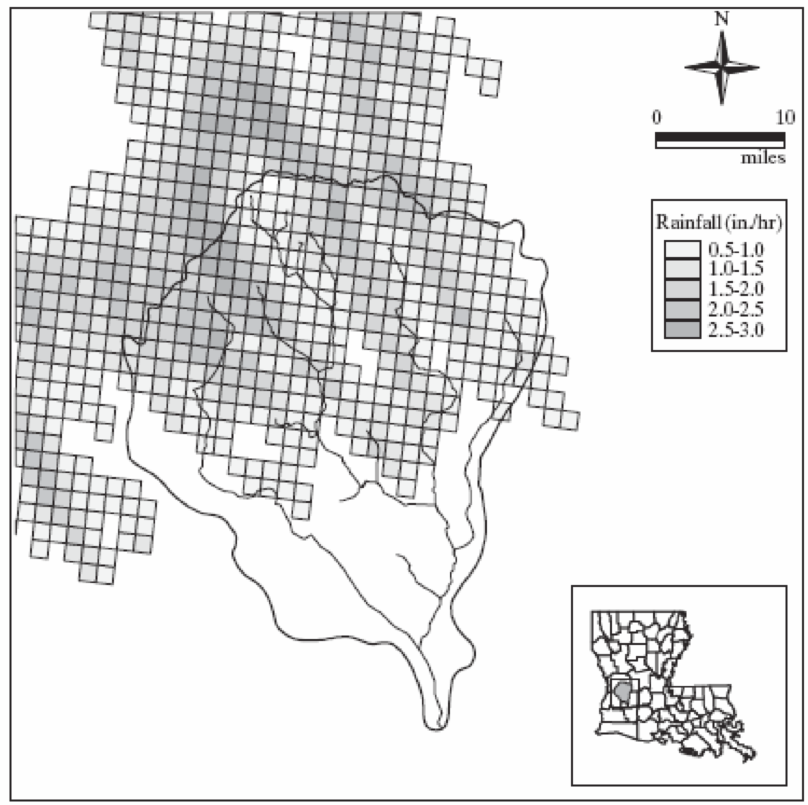


Figure 1–17
Typical NEXRAD rainfall data for a watershed located in central Louisiana.

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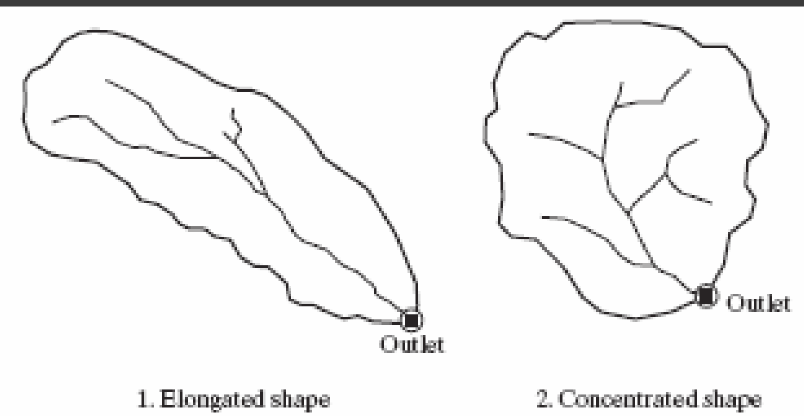
Hydrologic Cycle

The Watershed

- Def: Contiguous area that drains to an outlet, specifically in regards to precipitation
- Basic hydrologic unit within which all measurements, calculations and predictions are made

Figure 1–19a
Typical watershed area shapes. The difference in shape affects timing and peak flow of runoff to the outlet.



Water Balance

- $I - Q = (dS/dt)$
  - I = Inflow (L^3/t)
  - Q = outflow (L^3/t)
  - dS/dt = change in storage (L^3/t)

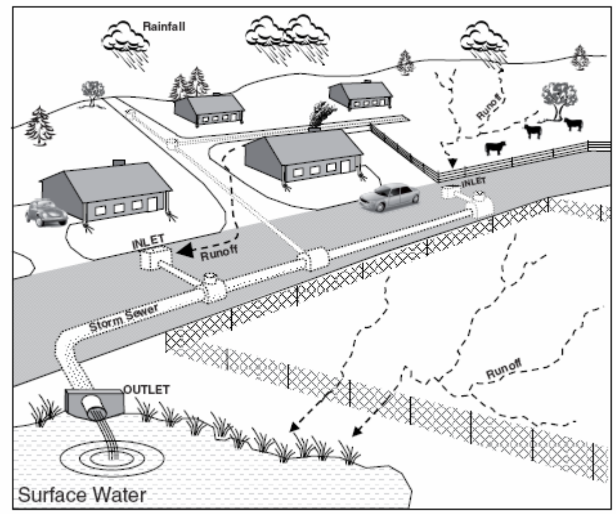


Figure 1–18
Urban hydrologic cycle. A combination of runoff from natural surroundings and man-made drainage systems, these runoffs come together at a single outlet.

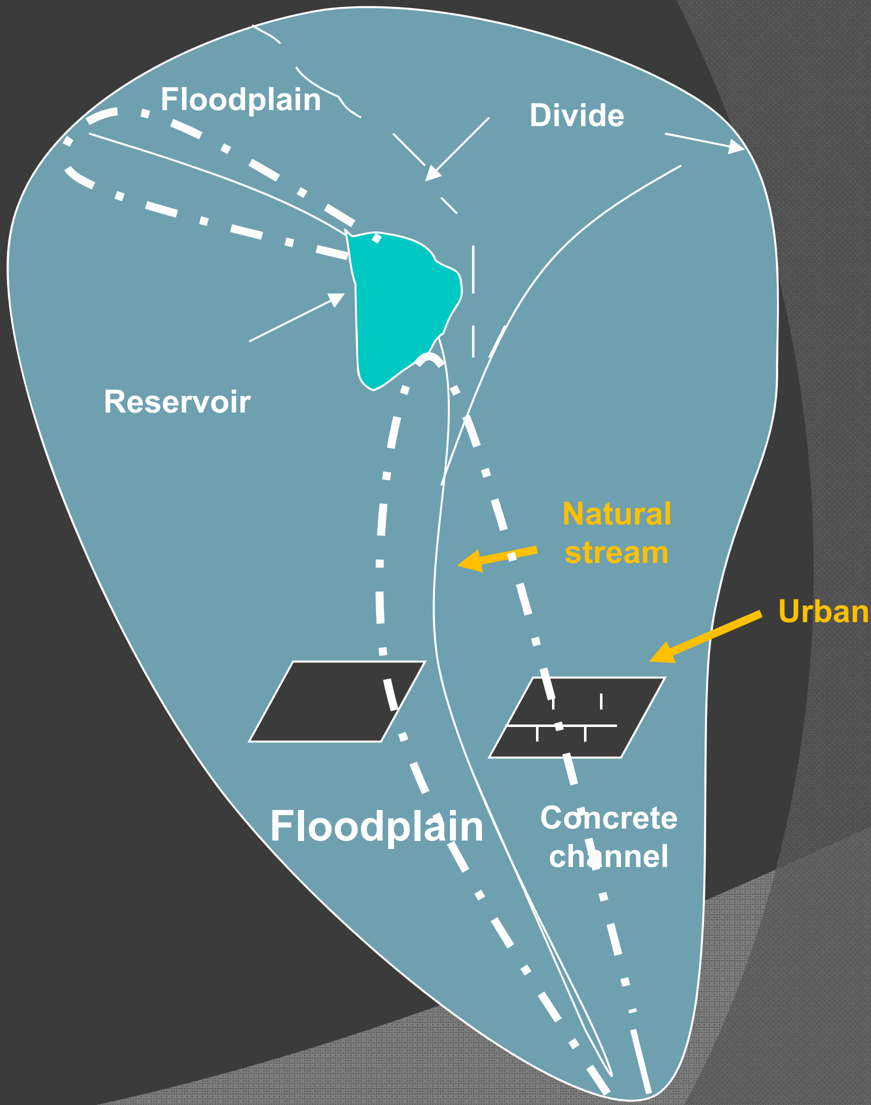
- Volume out of watershed =
  - (flow rate)*(time) OR
  - (depth)*(watershed area)

Water Balance

- $P - R - G - E - T = \Delta S$
  - P = Precipitation
  - R = Surface Runoff
  - G = Groundwater Flow
  - E = Evaporation
  - T = Transpiration
  - ΔS = Change in Storage
- Water balance for each area is different
  - Characteristics of the area alter how water leaves watershed or basin

Parameters that Affect Response in a Watershed

1. Rainfall intensity and duration
2. Size, Slope, Shape, Soil, Storage
3. Channel morphology
4. Location of Developments
5. Land use and cover
6. Soil type
7. Percent impervious



Rainfall Runoff

- Want to develop relationship of rainfall minus losses vs. runoff for flood control
  - Allows hydrologists to determine flood conditions based upon rainfall totals

Rainfall Runoff

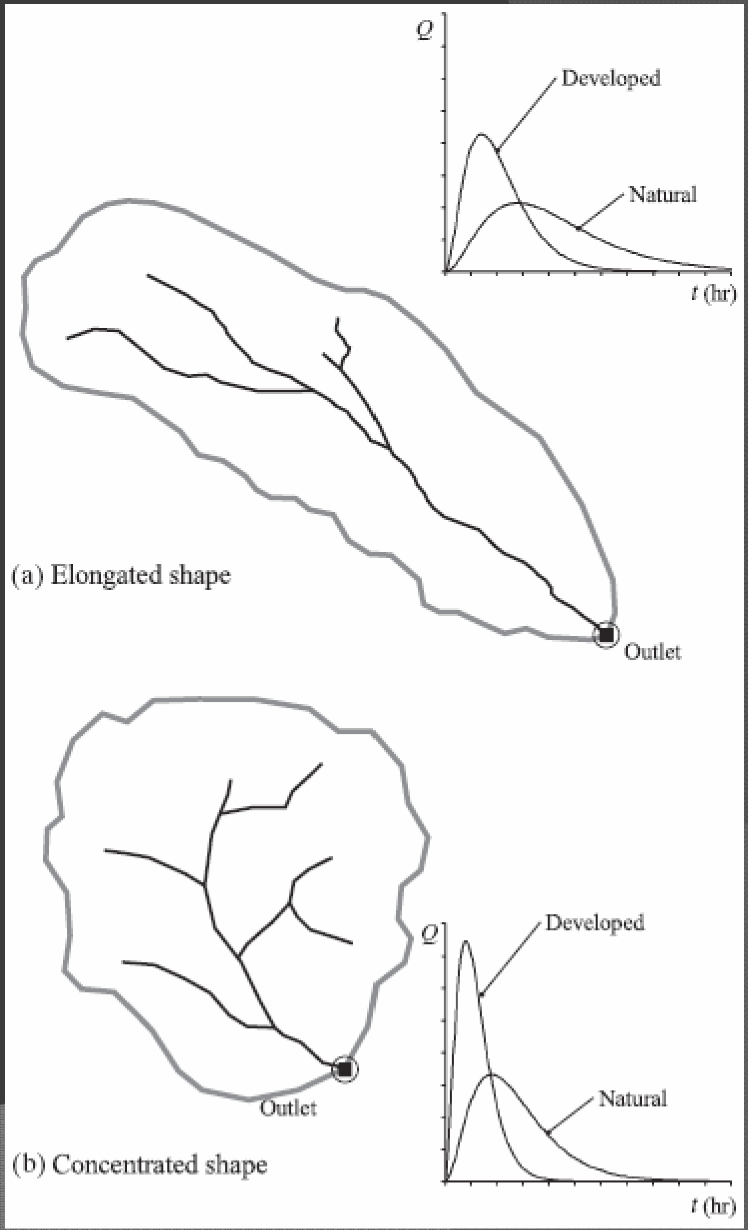
- Rational Method
  - Simplest rainfall-runoff formulas
  - $Q_P = CiA$
    - Q_P = peak flow (cfs)
    - C = runoff coefficient, varies with land use
    - i = rainfall intensity (in/hr) for a duration equal to time of concentration (t_c)
    - t_c = time for a wave of water to propagate from the most distant point of a watershed to the outlet
    - A = area of watershed (acres)

Hydrology and Floodplain Analysis, Chapter 1.6-1.7

Hydrographs and Analysis

Hydrographs

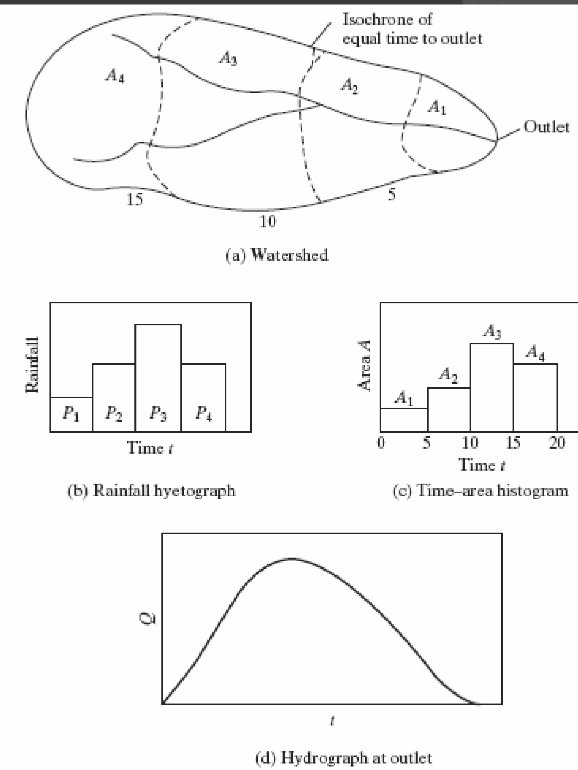
- Plot of flow rate vs. time
  - Measured at a given stream cross section
- Mainly used to describe stream flow response from rainfall
- Watershed characteristics affect the shape
  - i.e. urbanization



Time Area Histogram

- Computes hydrograph response for a watershed
- Breaks water shed into distinct areas (A_i), have equal travel time to outlet
- Uses rainfall periods (P_i)
- Rainfall from P_1 in A_2 reaches the outlet at the same time at P_2 in A_1

Figure 1–23 Time Area Method for a hypothetical watershed with four rainfalls recorded and four areas delineated by isochrone lines. This method is used to create a hydrograph at the outlet.



Hydrographs – Broken Down

- Typically characterized by:
  - **Base Flow**
  - **Rising Limb**
    - Increase in flow
  - **Crest Segment**
    - Peak flow rate
  - **Recession Curve**
    - Decrease in flow
  - **Inflection Point**
    - Point where direct runoff ends

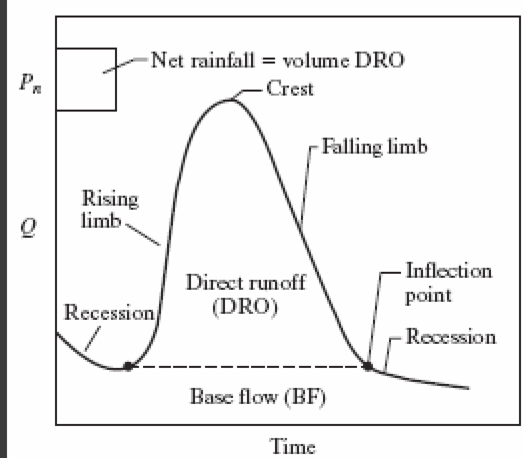


Figure 1–26
Components of an outflow hydrograph. When baseflow is removed, the result is the direct runoff outflow (DRO).

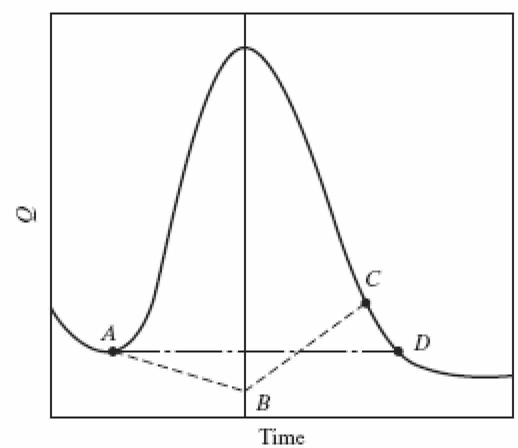


Figure 1–27
Two methods for base flow separation (Straight line and Concave).

Hydrograph Analysis

- Total storm hydrograph is made up of **Base Flow** and **Direct runoff**

- Base Flow
  - Comes from ground water in absence of rainfall
  - Relatively small in urban environments
- Direct Runoff (DRO)
  - Discharge caused by rainfall after infiltration losses have been subtracted
  - “Rainfall Excess”

Hydrograph Analysis

- How to separate Base Flow from DRO
  - Recession curves
    - $q_t = q_0 e^{-kt}$
      - q_0 = specified initial discharge
      - q_t = discharge at a later time, t
      - k = recession constant
  - Create these for each area of interest
  - More of an art than a science

Hydrograph Analysis

- Hydrograph peak
  - Occurs when all areas contribute flow to the outlet
  - Dependent on watershed geography, storm intensity/duration
  - Developed area
    - Higher, quicker peak flow
  - Natural, wooded area
    - Lower, slower peak

Hydrograph Analysis

- Response to rainfall
  - Duration of rainfall is often shorter than time base of hydrograph
  - Peak flow does NOT correspond to peak rainfall

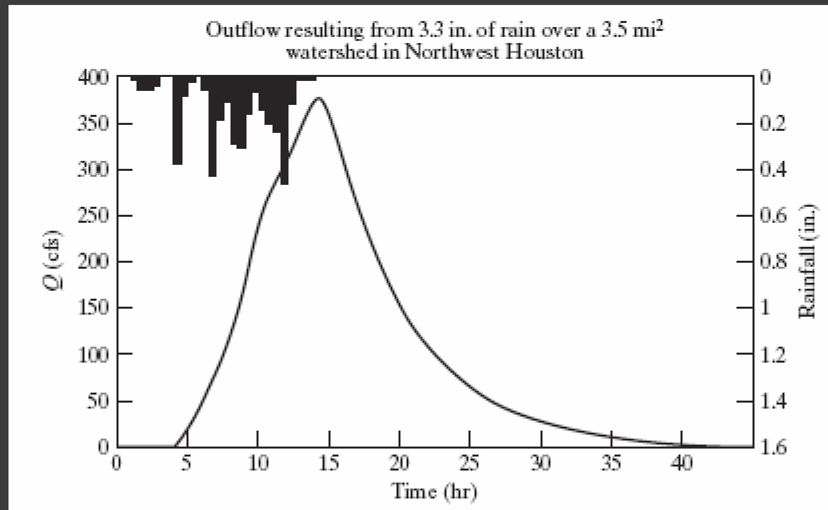


Figure 1–24
Actual rainfall and hydrograph resulting from 3.3 in. of rain for little Cypress Creek.

- Volume of water under hydrograph should equal volume of precipitation minus base flow and loses

Hydrograph Analysis

- Infiltration and response
  - Rainfall (*i*) lose to infiltration (*f*) depends on
    - Soil Moisture Storage (S_D)
    - Field Capacity (*F*)
      - Amount of water in a soil after gravity has drained it
  - If $i < f$
    - No overland runoff; all rainfall infiltrates
  - If $i > f$
    - Overland flow occurs
  - ϕ Index is simplest infiltration method
    - (gross precipitation) – (observed surface runoff)

Hydrograph Analysis

- Infiltration and response
  - **Horton Infiltration Method**
    - When rainfall rate > infiltration rate, water infiltrates at a rate that decreases
  - **ϕ Index** is simplest infiltration method
    - (gross precipitation) – (observed surface runoff)
    - Often underestimates losses at beginning
- **INSERT FIGURE 1-28 HERE**

Hydrograph Analysis

- Net vs. Gross rainfall
  - Gross Rainfall = depression storage + evaporation + infiltration + surface runoff
  - Rainfall Excess = DRO = gross rainfall – infiltration + depression storage

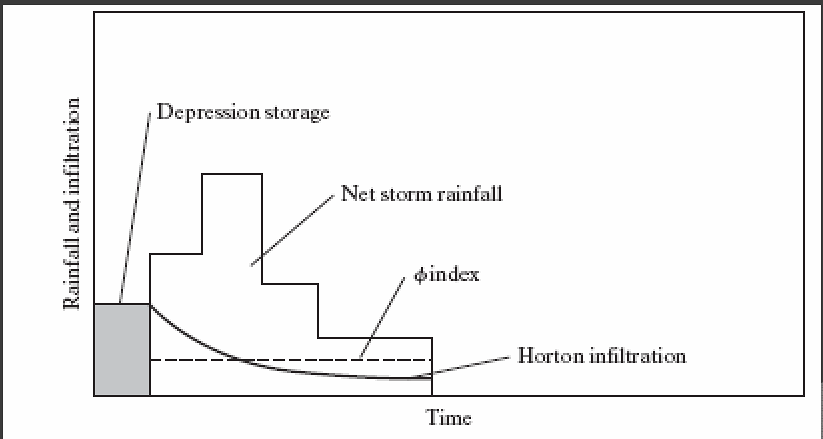


Figure 1–28
Infiltration loss curves used to find rainfall excess. Horton's infiltration curve and the phi index with initial loss for depression storage.

Hydrology and Floodplain Analysis, Chapter 1.8

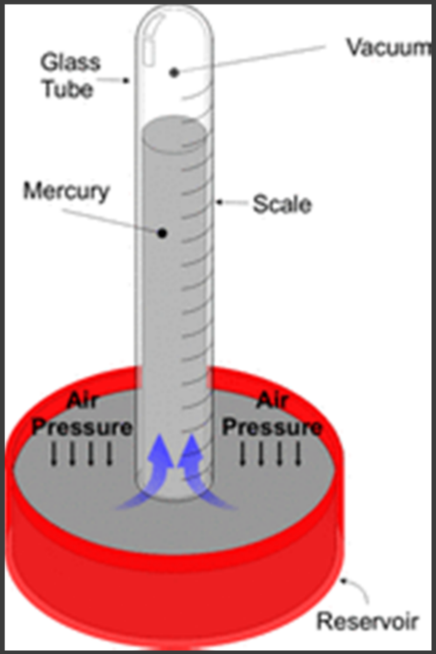
Hydrologic Measurement

Measurement Process

1. Sensing rainfall
   - Transforms intensity to measurement
2. Recording the data
3. Transmitting to central location
4. Translating data
5. Editing or checking for errors
6. Storing in database
7. Retrieving for further use

Measurement Devices

- Barometer
  - Atmospheric pressure
- Psychrometer
  - Relative Humidity
- Gages
  - Precipitation
- Radar
  - Rainfall rates



Evaporation Measurement

- Evaporation is a major path of water lose
  - Rates vary location to location
  - Important to know rates for large-scale water resource projects

- Use instruments to measure rate in area
  - Class A pan →

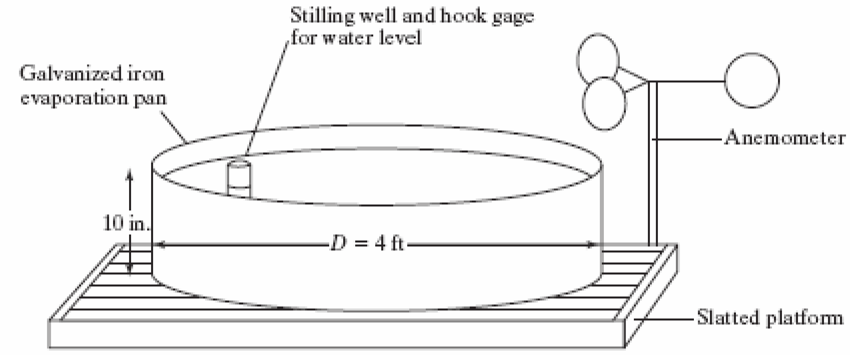


Figure 1–29
Standard class A evaporation pan with cup anemometer and rain gage.

Infiltration Measurement

- Small Scale: Ring Infiltrometer
  - 2 ft. diameter ring driven into soil
  - Water is dumped into ring
  - Rate of infiltration is measured as water level drops
- Large Scale: actual measurements
  - (Gross Rainfall) – (Direct Runoff from hydrograph)

Streamflow Measurement

- What's measured
  - Stage
    - Water elevation above datum
    - Floating or bubbling gages
- Use rating curves to determine discharge
- USGS must locate these at sites that are accessible and have flow rates that relate to depth

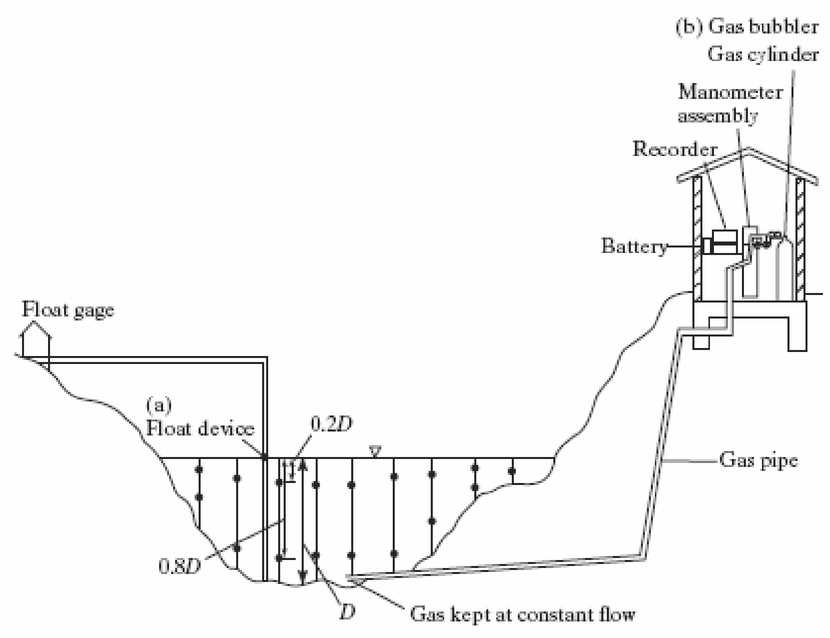


Figure 1–30a
Typical USGS streamflow gages with a float-type device to measure stage (a) or a gas bubbler to measure pressure (b).

Rating Curves

- Relate stage to flow rate at a cross section
- Must be developed to determine discharge
  - Site specific
- Created through actual measurements of velocity at different stages
  - Use procedure that takes velocity measurements at different depths at different parts of the section

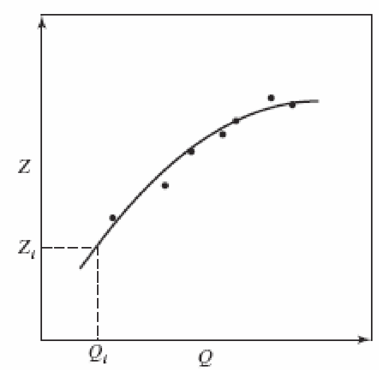


Figure 1–31
Rating curve. A rating curve is obtained for a particular cross section by finding the total Q at a particular stage z. The other points are obtained by finding different velocities to obtain Q at different stages. These can change as watersheds change due to land use and channel types.