Updated: 28 October 2019

Print version

CEE 370
Environmental Engineering Principles

Lecture #20

Water Resources & Hydrology I: streamflow & water balance

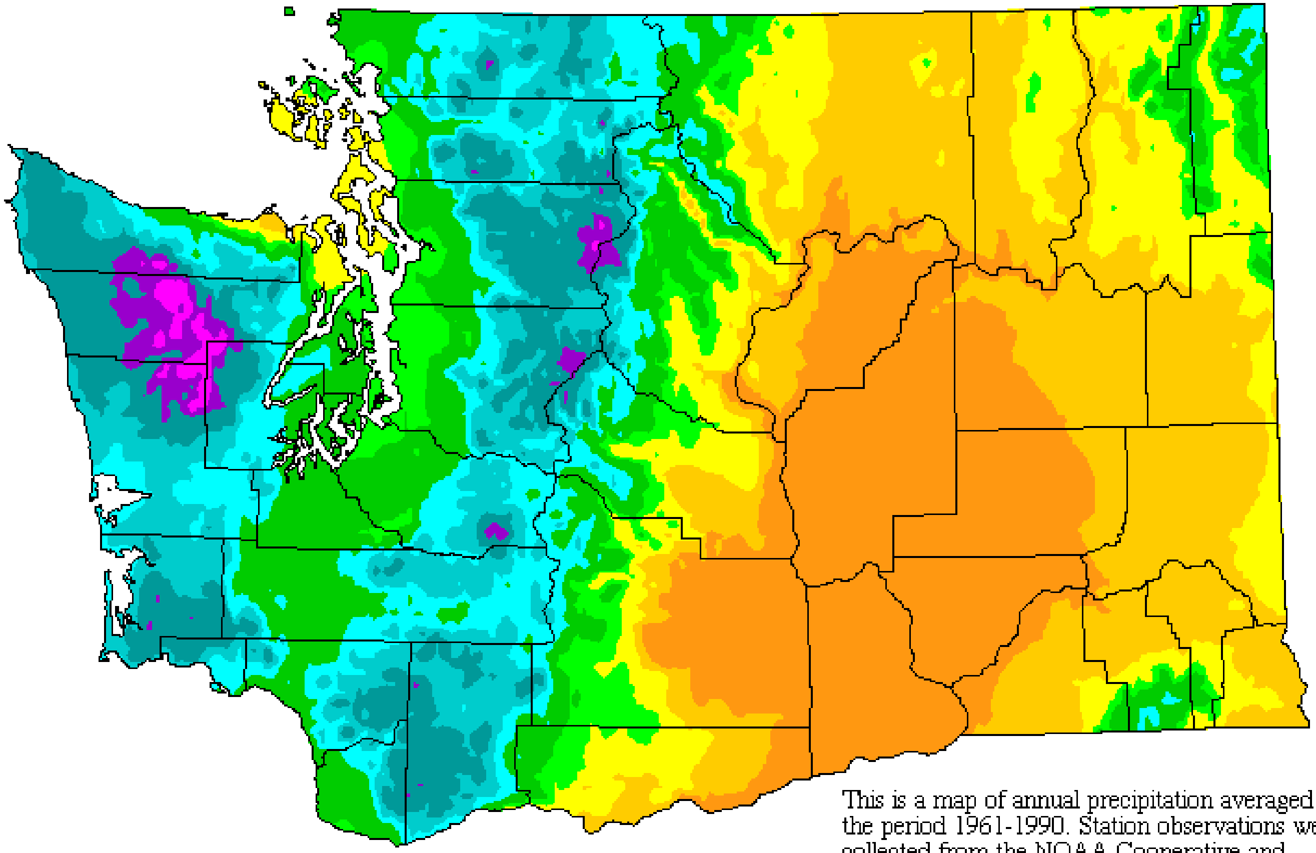
Reading: Mihelcic & Zimmerman, Chapter 7

- Ohio River


NEWPORT
MARKLAND L&D
MELDAHL L&D
MAYSVILLE
VANCEBURG
SOUTH SHORE
GREENUP
RUSSELL
ASHLAND
INDIANA
OHIO
KENTUCKY
WEST VIRGINIA
Fayette
Union
Preble
Montgomery
Greene
Franklin
Butler
Warren
Clinton
Fayette
Ripley
Dearborn
Hamilton
Clermont
Highland
Ohio
Switzerland
Brown
Adams
Scioto
Jackson
Gallia
Lawrence
Cabell
Wayne
BOONE
KENTON
CAMPBELL
GALLATIN
CARROLL
GRANT
PENDLETON
BRACKEN
MASON
LEWIS
GREENUP
TRIMBLE
OWEN
ROBERTSON
HENRY
HARRISON
FLEMING
NICHOLAS
CARTER
BOYD
SCOTT
SHELBY
FRANKLIN
BOURBON
ROWAN
BATH
ELLIOTT
LAWRENCE
WOODFORD
FAYETTE
ANDERSON
CLARK
MONTGOMERY
MENIFEE
MORGAN
JOHNSON
Ohio River Advisory Area
Miles
0
5
10
20
30
40
N
W
E
S

Average Annual Precipitation

Washington



Legend (in inches)

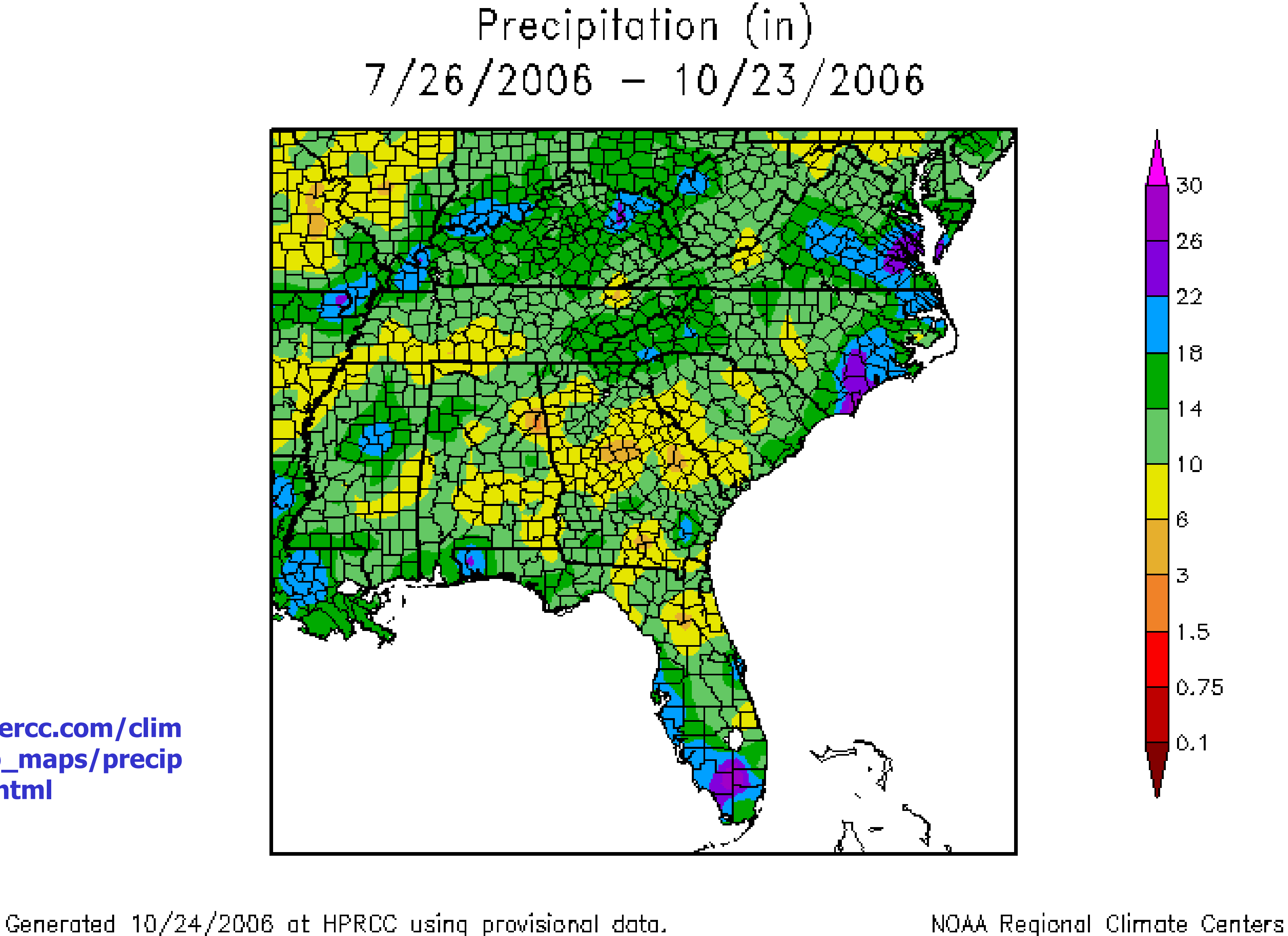
🟧	Under 10	🟦	60 to 80
🟧	10 to 20	🟦	80 to 100
🟨	20 to 30	🟦	100 to 140
🟩	30 to 40	🟪	140 to 180
🟩	40 to 60	🟪	Above 180

This is a map of annual precipitation averaged over the period 1961-1990. Station observations were collected from the NOAA Cooperative and USDA-NRCS SnoTel networks, plus other state and local networks. The PRISM modeling system was used to create the gridded estimates from which this map was made. The size of each grid pixel is approximately 4x4 km. Support was provided by the NRCS Water and Climate Center.

For information on the PRISM modeling system, visit the SCAS web site at http://www.ocs.orst.edu/prism

The latest PRISM digital data sets created by the SCAS can be obtained from the Climate Source at http://www.climatesource.com

Spatial Distribution of Rainfall



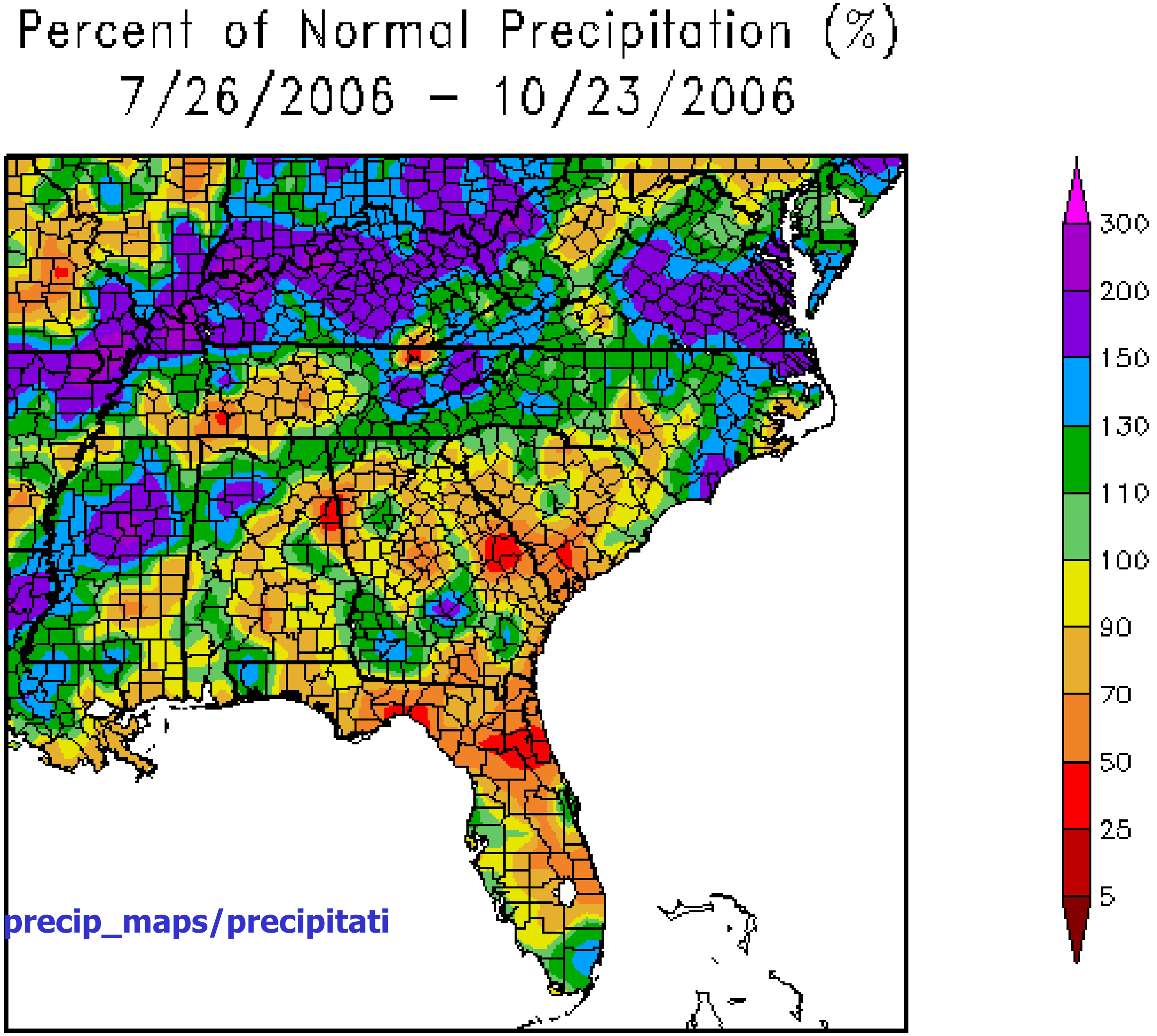
Precipitation (in)
7/26/2006 - 10/23/2006

Generated 10/24/2006 at HPRCC using provisional data.

NOAA Regional Climate Centers

http://www.sercc.com/climateinfo/precip_maps/precipitation_maps.html

Annual Variability


Percent of Normal Precipitation (%)
7/26/2006 – 10/23/2006

Generated 10/24/2006 at HPRCC using provisional data.

NOAA Regional Climate Centers

http://www.sercc.com/climateinfo/precip_maps/precipitation_maps.html

Community Water Use

- Table 1 shows on a percent basis the use of water for community systems in the USA. The percentages are average values for USA.
- Public: municipal buildings, pools, etc.
- Loss: unaccounted-for

Table 1. Types of Community Water Use

Category	**%**
Domestic	45
Industrial	24
Commercial	15
Public	9
Loss	7
Total	100

Home Use question

- What fraction of total home water use is devoted to showers & baths?
  A. 10%
  B. 20%
  C. 30%
  D. 40%
  E. 50%

Home water use

- Table 2 shows the percent indoor use for the domestic category.
  - These data are average values from a survey (year 1998) for Boulder, CO; Denver, CO; Eugene, OR; Seattle, WA; San Diego, CA; Phoenix, AZ; Tempe and Scottsdale, AZ; Waterloo, Ontario; Walnut Valley Water District, CA: Municipal Water District, CA; and Lumpoc, CA
  - For these communities, the average indoor use was **71** gallons per capita per day (gpcd) and outdoor use was **101** gpcd for total domestic water use of **172** gpcd. You would expect much lower domestic water use in the Northeast because of less outdoor water use.
  - Northeast domestic water use is about **<u>100 gpcd</u>**.

Y=37X+69

Table 2

Compare with M&Z, Table 7.8

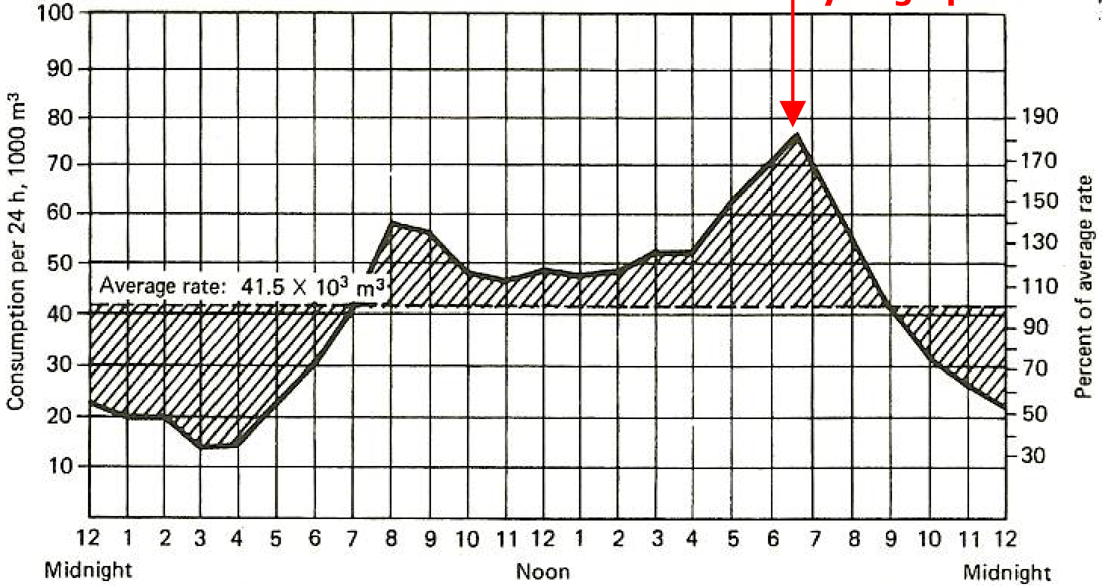
Category	**%**
Flushing Toilets	27
Washing Clothes	22
Shower/Bath	19
Faucet	16
Leak	14
Other	2

Best Targets for reduced use

Summation

- Summary: for design of public water facilities we are interested in the following demands:
  - Average Daily Demand/flow
  - Maximum Daily Demand/flow
  - Peak Hourly Demand/flow
  - Fire Demand
  - Inflow

Diurnal Demand Hydrograph



$$Q_{design} = Q_{avg} x PF$$

McGuire, 1991

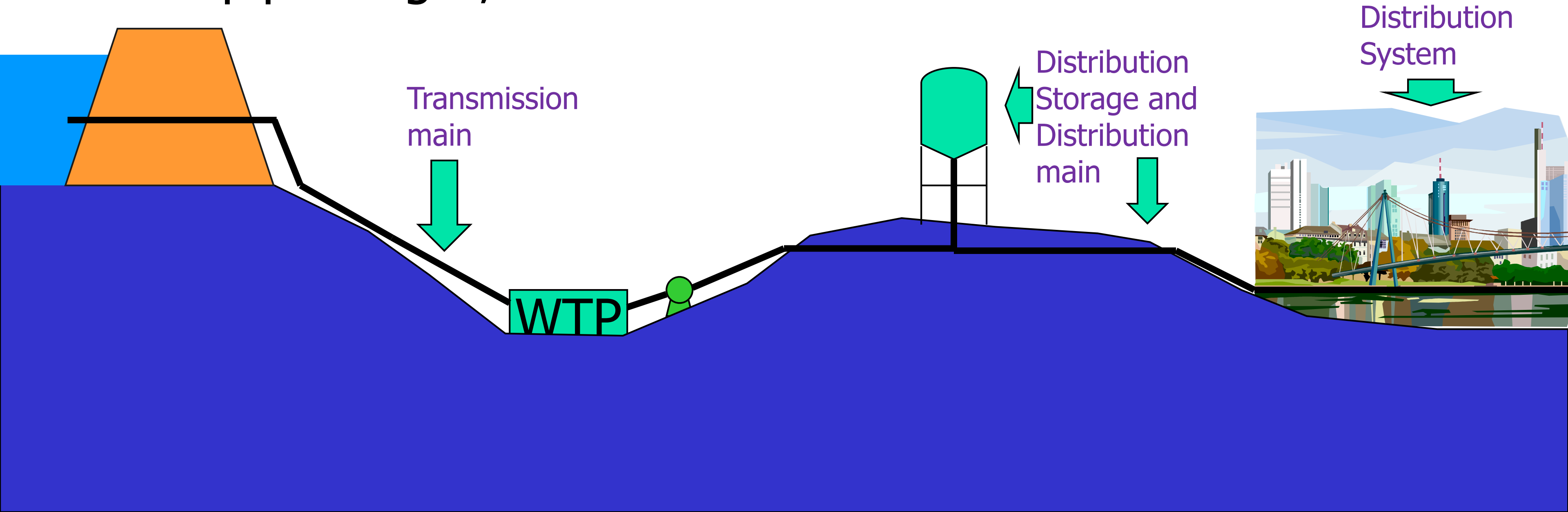
For PFs see M&Z Table 7.14

- **Hourly Variation in Water Demand on the Maximum Day**

From John Tobiason

Hydraulics of water systems

- Used to size hydraulic aspects of water systems
  - Under economic and various physical constraints
  - Focus: transmission mains, distribution storage, distribution pipe network
  - Relate: flow (or velocity), pipe diameter, roughness, pipe length, head loss



Pump Head (h_T)

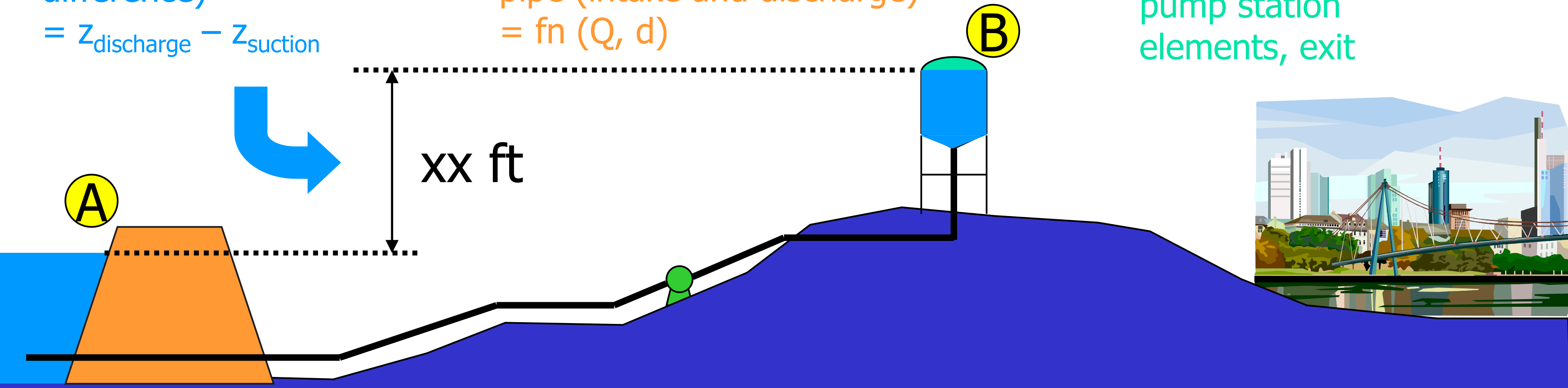
- h_T (Q) = energy (head) that must be supplied to achieve desired Q (= system head)

$$h_T = \boxed{h_s} + \boxed{h_f} + \boxed{h_m}$$

net static lift (elevation difference)
$= z_{discharge} - z_{suction}$

friction losses on long straight pipe (intake and discharge)
= fn (Q, d)

minor losses for pipe system entrance, pump station elements, exit

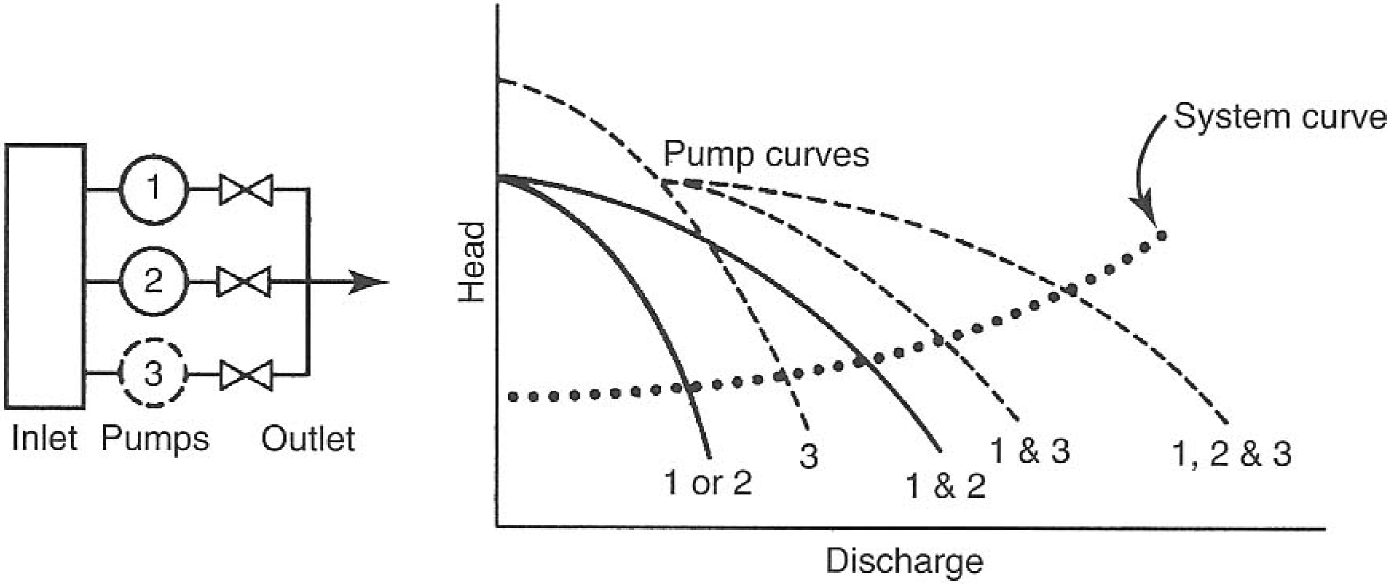


Compare with M&Z figure 7.20

Multiple Pumps

- Parallel operation (a)
- Head-discharge curves for various combinations (b)

H&H, Figs 4-17, pg 109



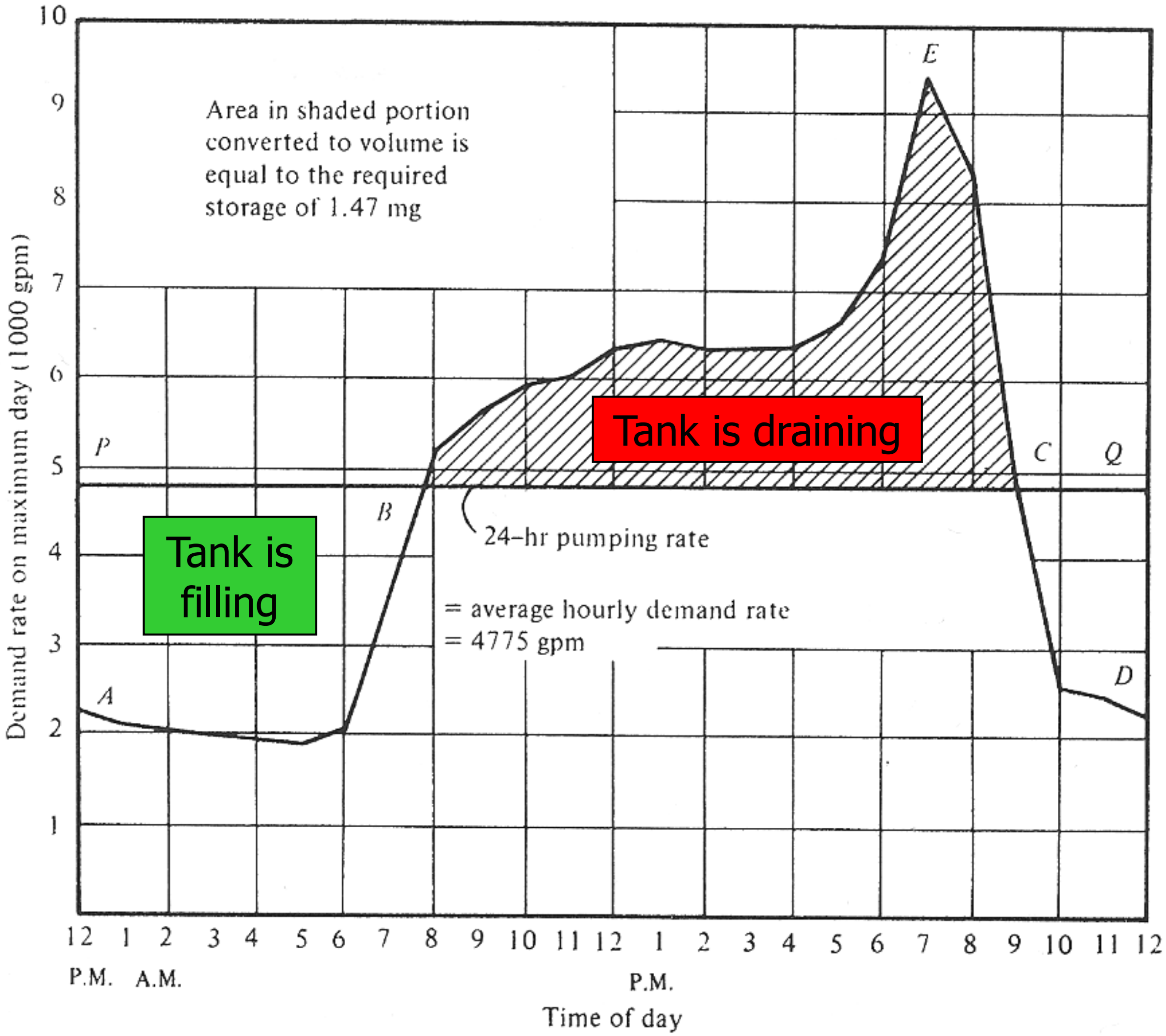
(a) (b)

T/F Question

- Consider 2 cities of the same size, both having the same maximum day water demands, and both pumping at that rate for 24 hours.
- The city with the more uniform hourly water demand will have higher system storage needs
  A. True
  B. False

Demand Hydrograph

- analysis for 24 hr cycle



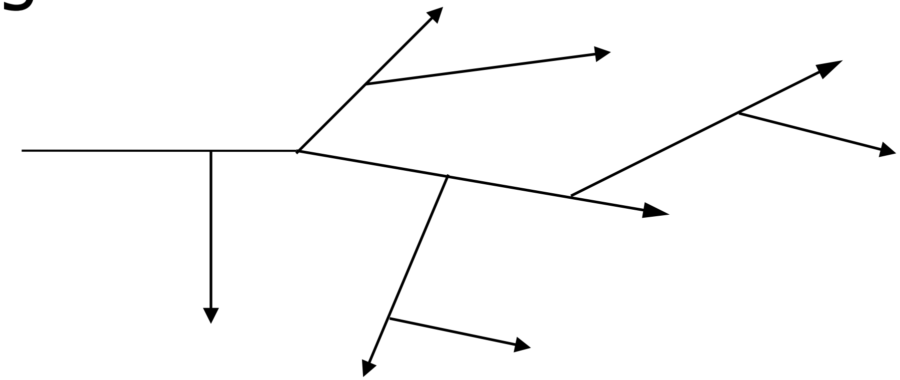
Tank is filling

Tank is draining

Compare with M&Z figure 7.19

Pipe Patterns I

- Branching

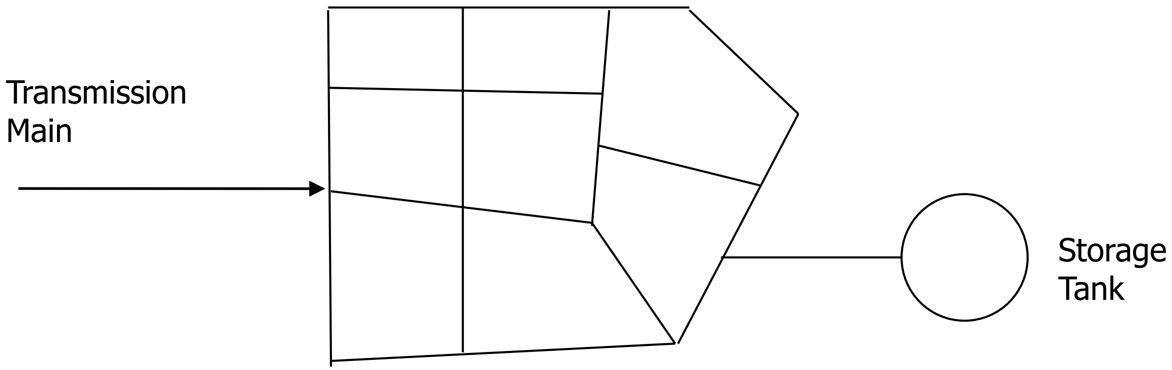


  - Avoid this system except where necessary such as on the outskirts of a community
  - Have “dead ends” where water may be stagnant and lead to water quality problems
  - When a pipe break occurs, isolating break leads to interruption of service to the area beyond the break (only one path to a point of use)

Compare with M&Z figure 7.19

Pipe Patterns II

- Grid

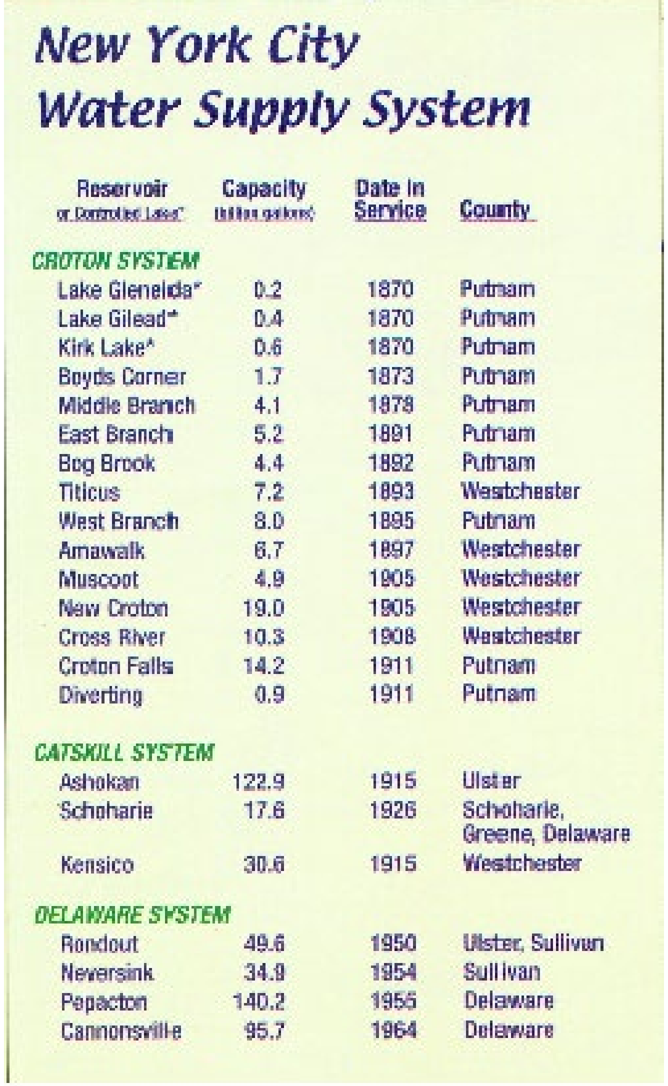


  - Head loss is minimized by multiple parallel pipe paths
  - Can isolate breaks and maintain service to most of water system due to parallel routes
  - Avoids dead ends and deterioration in water quality which can occur at dead ends
  - 6 inch minimum diameter for pipe in grid system (8 inch for dead end pipe)

Open Channels

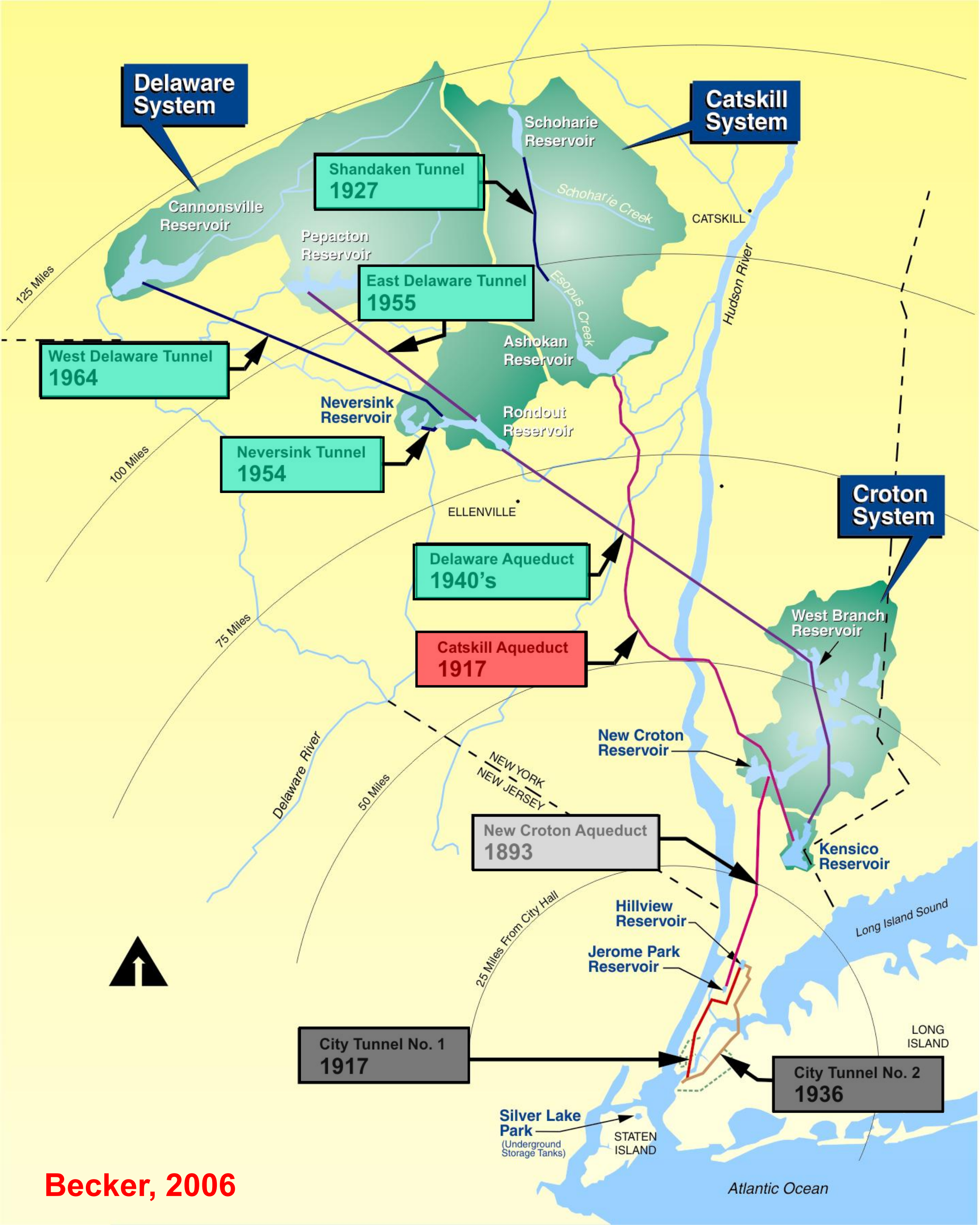
- Los Angeles Aqueduct
    - Owens Lake to LA Aqueduct Plant
- HGL and water surface are coincident
    - Topography has to be right

Tunnels



New York City Water Supply System

Reservoir (or Controlled Lake*)	Capacity (billion gallons)	Date in Service	County
CROTON SYSTEM			
Lake Gleneida*	0.2	1870	Putnam
Lake Gilead*	0.4	1870	Putnam
Kirk Lake*	0.6	1870	Putnam
Boyds Corner	1.7	1873	Putnam
Middle Branch	4.1	1878	Putnam
East Branch	5.2	1891	Putnam
Bog Brook	4.4	1892	Putnam
Titicus	7.2	1893	Westchester
West Branch	8.0	1895	Putnam
Amawalk	6.7	1897	Westchester
Muscoot	4.9	1905	Westchester
New Croton	19.0	1905	Westchester
Cross River	10.3	1908	Westchester
Croton Falls	14.2	1911	Putnam
Diverting	0.9	1911	Putnam
CATSKILL SYSTEM			
Ashokan	122.9	1915	Ulster
Schoharie	17.6	1926	Schoharie, Greene, Delaware
Kensico	30.6	1915	Westchester
DELAWARE SYSTEM			
Rondout	49.6	1950	Ulster, Sullivan
Neversink	34.9	1954	Sullivan
Pepacton	140.2	1955	Delaware
Cannonsville	95.7	1964	Delaware



Becker, 2006

NYC Tunnel

- Well suited for mountain terrain or river crossings
  - An arch is constructed to prepare the tunnel to be lined with concrete.

Videos

Tunnel #3 intro

https://www.youtube.com/watch?v=YWwgcBodAFo

Tunnel #3: sandhogs (1:32)

https://www.youtube.com/watch?v=dShvdsRTNrY

Rainfall: temporal variation

FIGURE 6–9

Seasonal variations in precipitation in the Michigan–Huron basin (for 1994). (*Source:* Data from Yee, P. *A Report: On the 1994 Water Levels of the Great Lakes and St. Lawrence River.* Environment Canada, Cornwall, Ontario, 1995.)

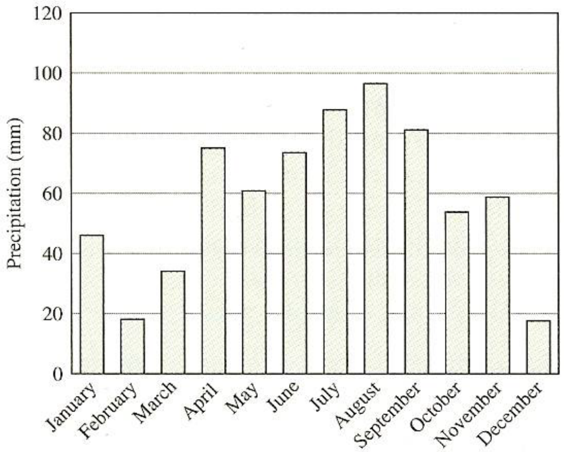
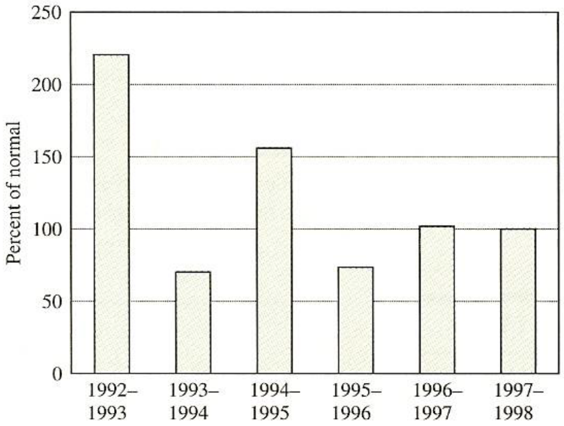


FIGURE 6–10

Annual variations in precipitation in the Mojave Desert. (*Source:* Hereford, R., C. Longpré. *Climate History of the Mojave Desert Region, Including Data from 48 Long-term Weather Stations and an Overview of Regional Climate Variation.* Flagstaff, Arizona. http://wgsc.wr.usgs.gov/mojave/climate-history http://atmos.washington.edu/pdo)



implications for water resource management. As shown in Figure 6–9, monthly precipitation rates in the Michigan–Huron basin varied by a factor of almost 5. This phenomenon is not unusual. Yearly variations can also be significant as shown in Figure 6–10. Here variations in precipitation rates vary as much as threefold. These yearly variations make it important to design reservoirs that are adequate during years of low rainfall and dams that have the capacity to ensure adequate flood control even in times of high precipitation rates.

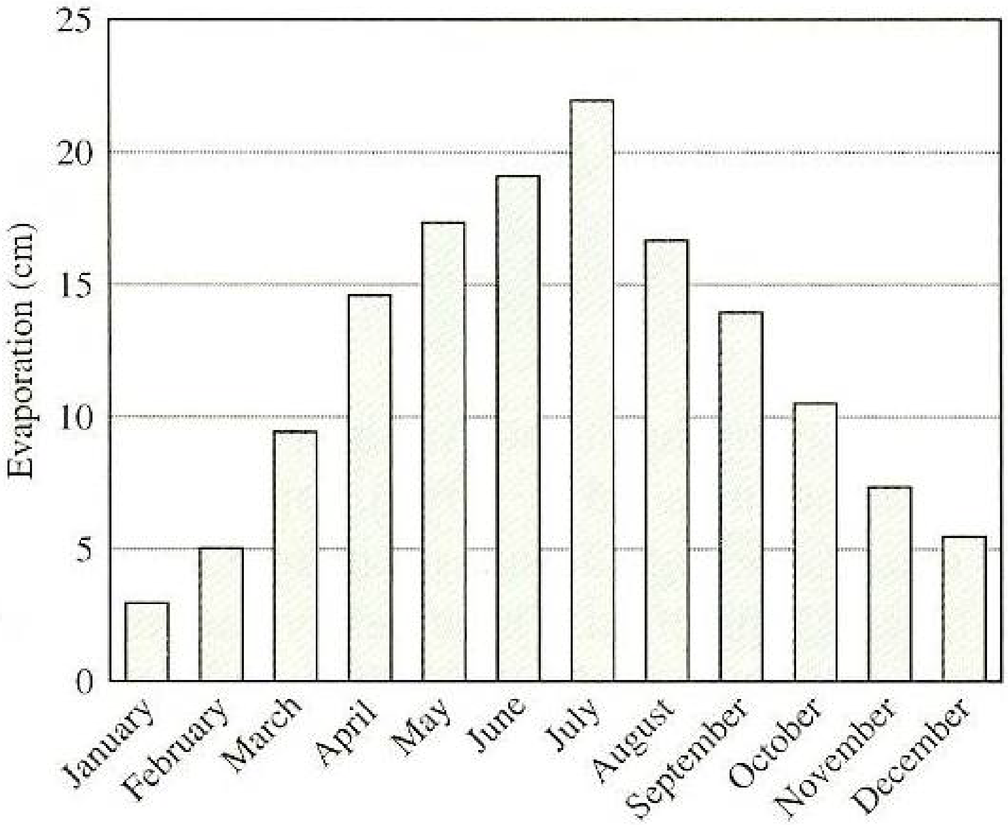
Evaporation

---

*Stochastic means that the occurrence of floods can be predicte
flood data that have been collected over time.

FIGURE 6–11

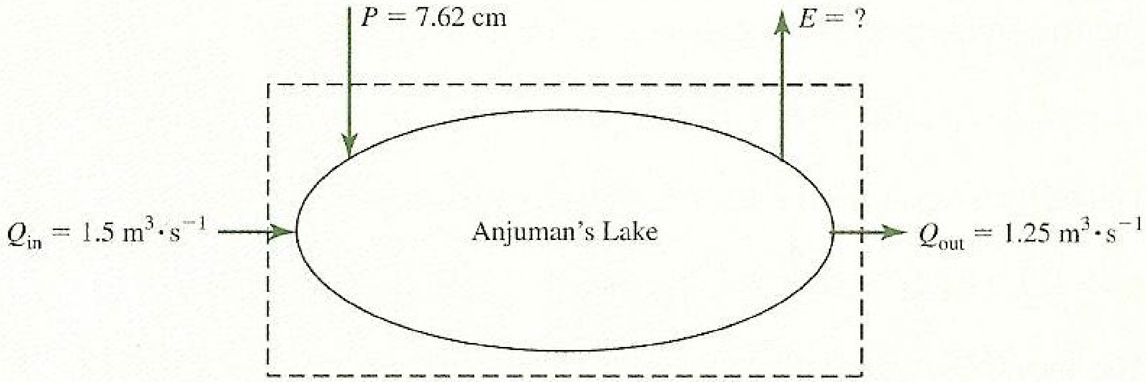
Average monthly pan evaporation rates for Athens University of Georgia (for 1970–1971). (*Source: Data courtesy of South Carolina State Climatology Office* http://water.dnr.state.sc.us/climate/sco/pan_tables.html)



Example 3

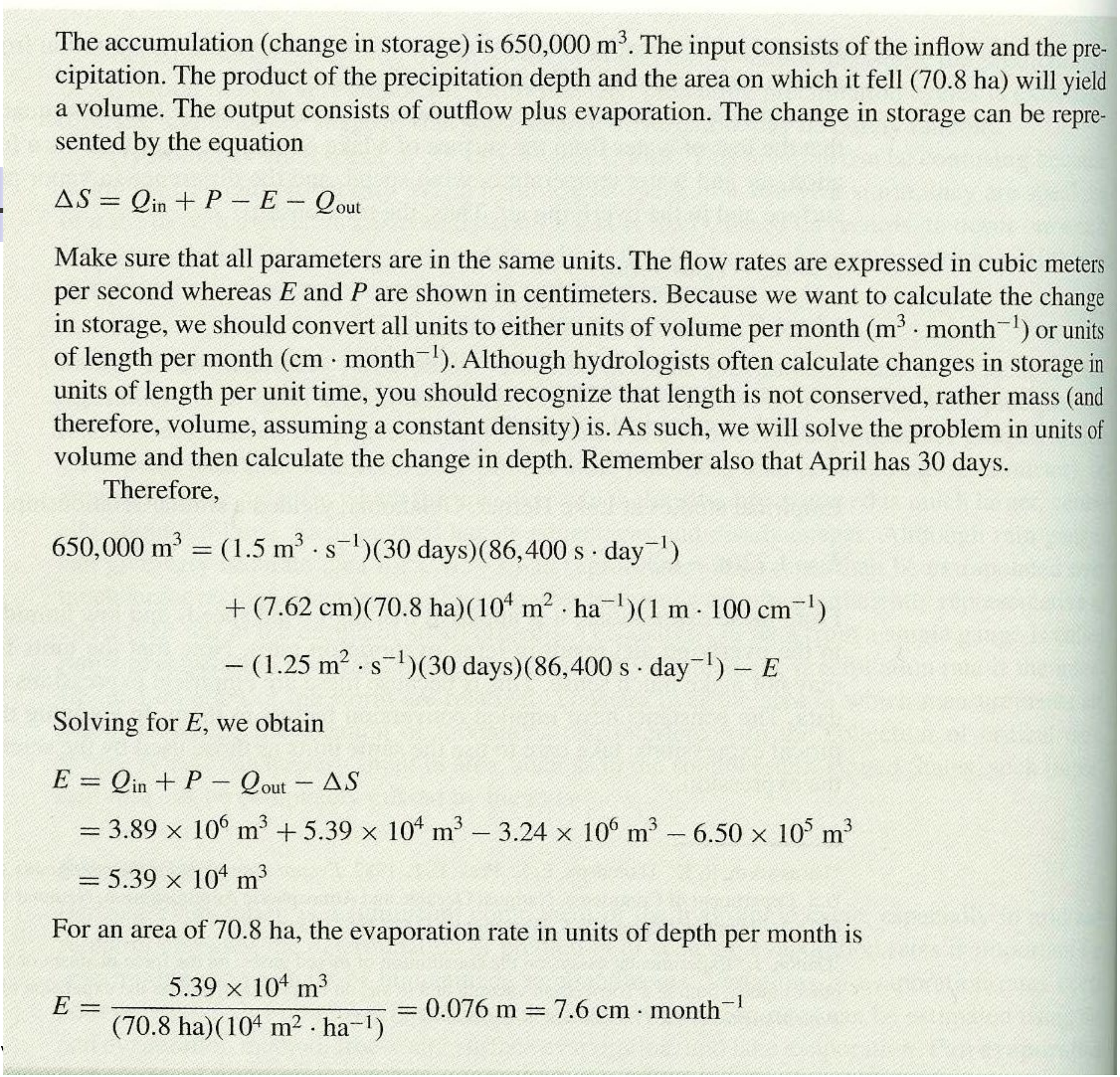
EXAMPLE 6–3 Anjuman's Lake has a surface area of 70.8 ha. For the month of April the inflow was 1.5 $m^3 \cdot s^{-1}$. The dam regulated the outflow (discharge) from Anjuman's Lake to be 1.25 $m^3 \cdot s^{-1}$. If the precipitation recorded for the month was 7.62 cm and the storage volume increased by an estimated 650,000 m^3, what is the estimated evaporation in cubic meters and centimeters? Assume that no water infiltrates into or out of the bottom of Anjuman's Lake.

Solution Begin by drawing the mass-balance diagram.



The mass-balance equation is.

Accumulation = input − output



The accumulation (change in storage) is 650,000 m^3. The input consists of the inflow and the precipitation. The product of the precipitation depth and the area on which it fell (70.8 ha) will yield a volume. The output consists of outflow plus evaporation. The change in storage can be represented by the equation

$$\Delta S = Q_{\text{in}} + P - E - Q_{\text{out}}$$

Make sure that all parameters are in the same units. The flow rates are expressed in cubic meters per second whereas E and P are shown in centimeters. Because we want to calculate the change in storage, we should convert all units to either units of volume per month ($m^3 \cdot \text{month}^{-1}$) or units of length per month ($\text{cm} \cdot \text{month}^{-1}$). Although hydrologists often calculate changes in storage in units of length per unit time, you should recognize that length is not conserved, rather mass (and therefore, volume, assuming a constant density) is. As such, we will solve the problem in units of volume and then calculate the change in depth. Remember also that April has 30 days.

Therefore,

$$\begin{aligned}650{,}000\ \text{m}^3 = {} & (1.5\ \text{m}^3 \cdot \text{s}^{-1})(30\ \text{days})(86{,}400\ \text{s} \cdot \text{day}^{-1}) \\ & + (7.62\ \text{cm})(70.8\ \text{ha})(10^4\ \text{m}^2 \cdot \text{ha}^{-1})(1\ \text{m} \cdot 100\ \text{cm}^{-1}) \\ & - (1.25\ \text{m}^2 \cdot \text{s}^{-1})(30\ \text{days})(86{,}400\ \text{s} \cdot \text{day}^{-1}) - E\end{aligned}$$

Solving for E, we obtain

$$\begin{aligned}E &= Q_{\text{in}} + P - Q_{\text{out}} - \Delta S \\ &= 3.89 \times 10^6\ \text{m}^3 + 5.39 \times 10^4\ \text{m}^3 - 3.24 \times 10^6\ \text{m}^3 - 6.50 \times 10^5\ \text{m}^3 \\ &= 5.39 \times 10^4\ \text{m}^3\end{aligned}$$

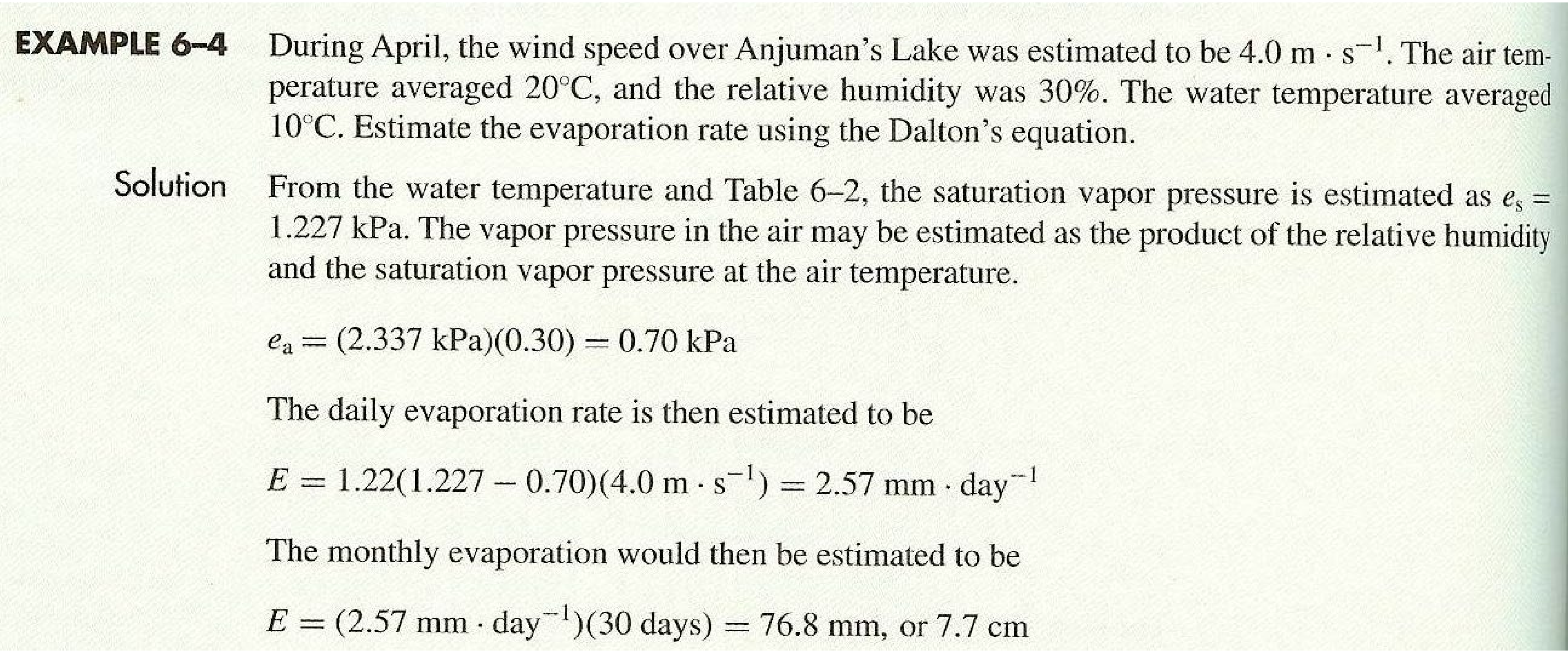
For an area of 70.8 ha, the evaporation rate in units of depth per month is

$$E = \frac{5.39 \times 10^4\ \text{m}^3}{(70.8\ \text{ha})(10^4\ \text{m}^2 \cdot \text{ha}^{-1})} = 0.076\ \text{m} = 7.6\ \text{cm} \cdot \text{month}^{-1}$$

Estimating Evaporation

- Pan Evaporation
  - Land: direct measurement
  - Lake: multiply pan evaporation by 0.7
- Correlations: semi-empirical
  - Based on
    - Saturation vapor pressure (e_s) in kPa
    - Vapor pressure in overlying air (e_a) in kPa
    - Wind speed (u) in m/s
  - Dalton's Equation $E = (e_s - e_a)(a + bu)$
  - Lake Hefner Equation $E = 1.22(e_s - e_a)u$

Example 4



EXAMPLE 6–4 During April, the wind speed over Anjuman's Lake was estimated to be 4.0 m · s^{-1}. The air temperature averaged 20°C, and the relative humidity was 30%. The water temperature averaged 10°C. Estimate the evaporation rate using the Dalton's equation.

Solution From the water temperature and Table 6–2, the saturation vapor pressure is estimated as e_s = 1.227 kPa. The vapor pressure in the air may be estimated as the product of the relative humidity and the saturation vapor pressure at the air temperature.

$$e_a = (2.337 \text{ kPa})(0.30) = 0.70 \text{ kPa}$$

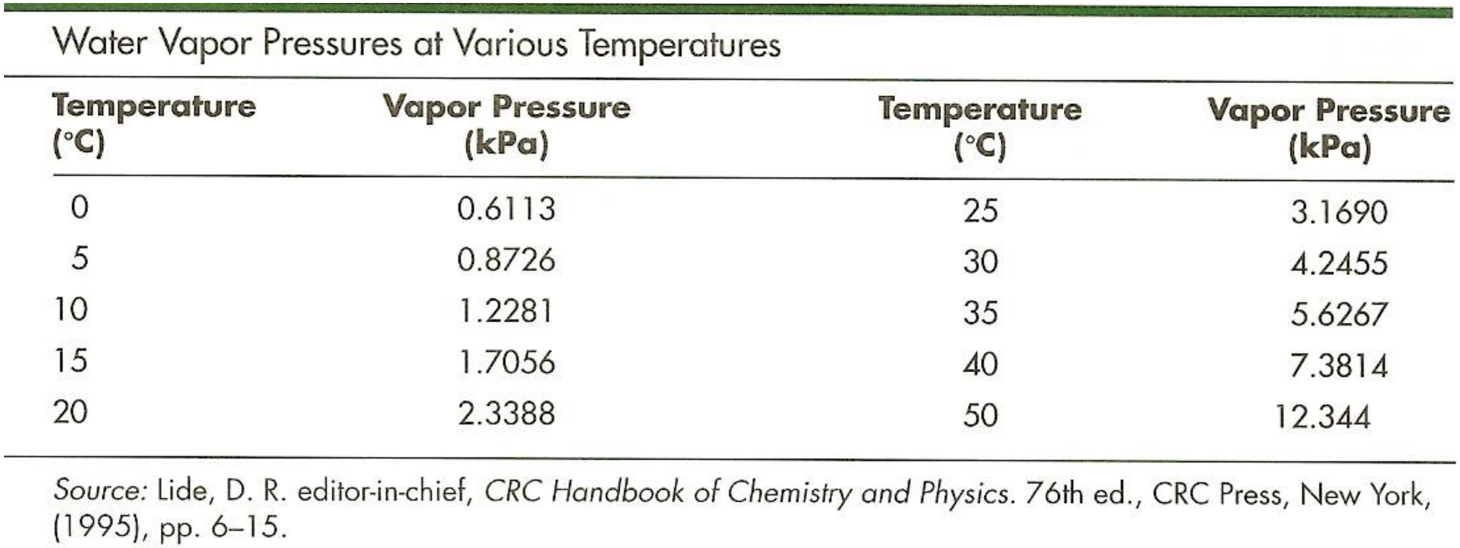
The daily evaporation rate is then estimated to be

$$E = 1.22(1.227 - 0.70)(4.0 \text{ m} \cdot \text{s}^{-1}) = 2.57 \text{ mm} \cdot \text{day}^{-1}$$

The monthly evaporation would then be estimated to be

$$E = (2.57 \text{ mm} \cdot \text{day}^{-1})(30 \text{ days}) = 76.8 \text{ mm, or } 7.7 \text{ cm}$$

Vapor Pressure



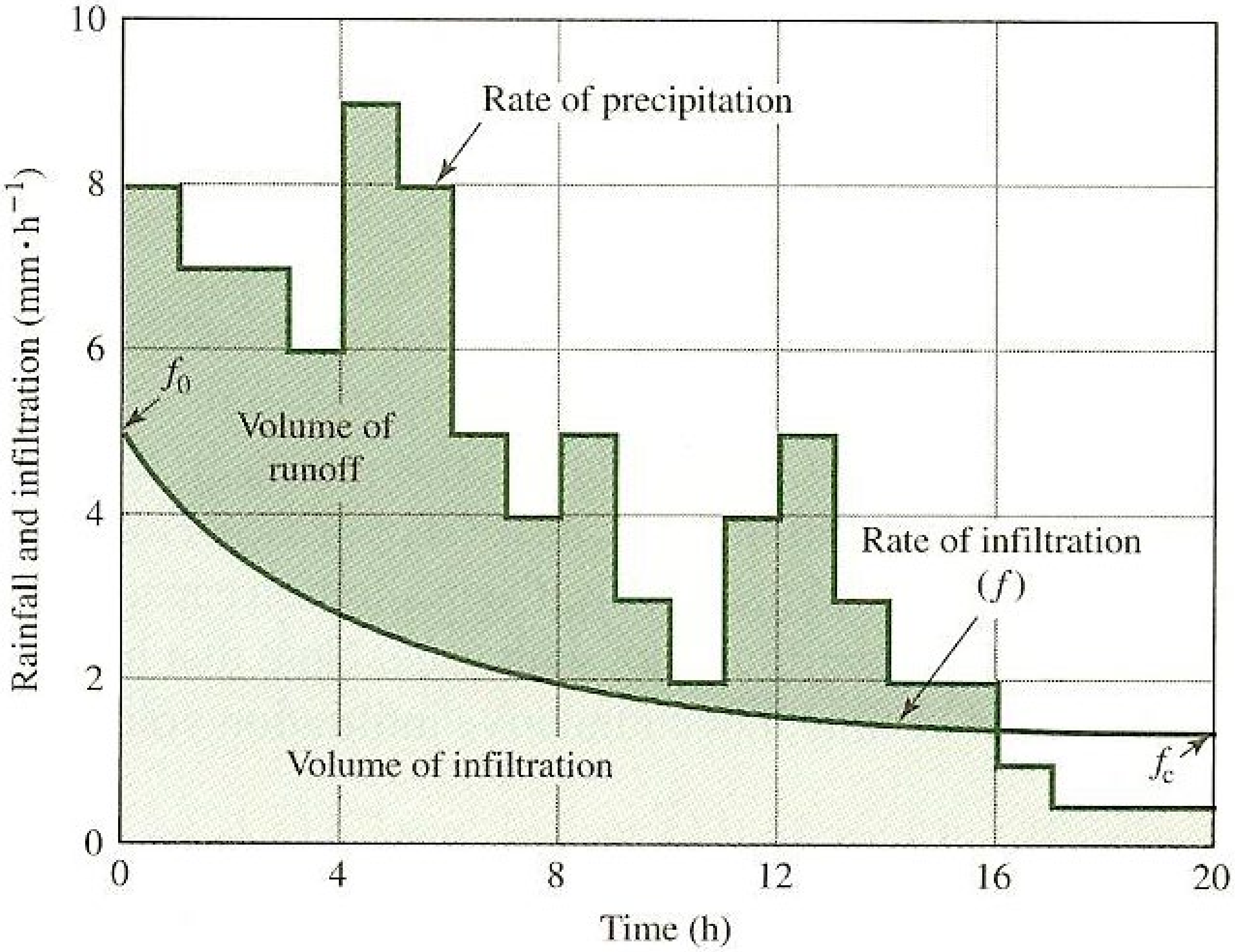
Water Vapor Pressures at Various Temperatures

Temperature (°C)	**Vapor Pressure (kPa)**	**Temperature (°C)**	**Vapor Pressure (kPa)**
0	0.6113	25	3.1690
5	0.8726	30	4.2455
10	1.2281	35	5.6267
15	1.7056	40	7.3814
20	2.3388	50	12.344

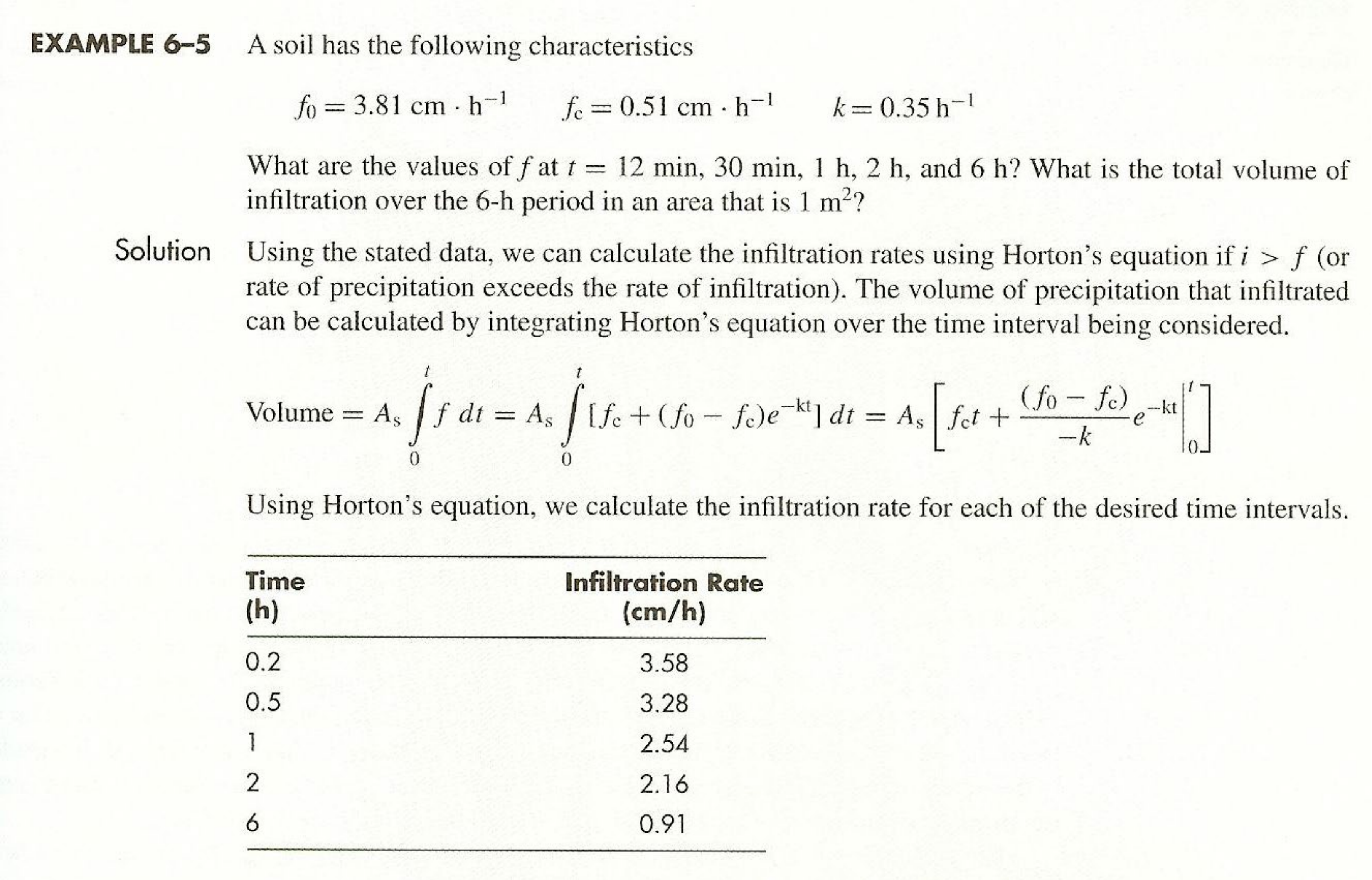
Source: Lide, D. R. editor-in-chief, *CRC Handbook of Chemistry and Physics*. 76th ed., CRC Press, New York, (1995), pp. 6–15.

Infiltration Rate vs time

- Example
- Precip can exceed infiltration rate at first then drop below
- D&M Fig 7-13



Example 5



EXAMPLE 6–5 A soil has the following characteristics

$$f_0 = 3.81\ \text{cm} \cdot \text{h}^{-1} \qquad f_c = 0.51\ \text{cm} \cdot \text{h}^{-1} \qquad k = 0.35\ \text{h}^{-1}$$

What are the values of f at $t = 12$ min, 30 min, 1 h, 2 h, and 6 h? What is the total volume of infiltration over the 6-h period in an area that is 1 m^2?

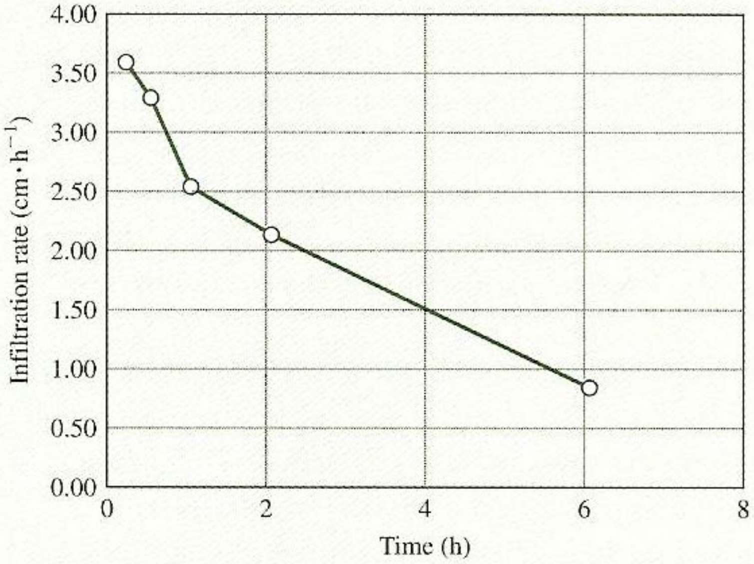
Solution Using the stated data, we can calculate the infiltration rates using Horton's equation if $i > f$ (or rate of precipitation exceeds the rate of infiltration). The volume of precipitation that infiltrated can be calculated by integrating Horton's equation over the time interval being considered.

$$\text{Volume} = A_s \int_0^t f\,dt = A_s \int_0^t [f_c + (f_0 - f_c)e^{-kt}]\,dt = A_s\left[f_c t + \frac{(f_0 - f_c)}{-k}e^{-kt}\Big|_0^t\right]$$

Using Horton's equation, we calculate the infiltration rate for each of the desired time intervals.

Time (h)	Infiltration Rate (cm/h)
0.2	3.58
0.5	3.28
1	2.54
2	2.16
6	0.91

The data calculated can be plotted to show how the infiltration rate decreases with time.



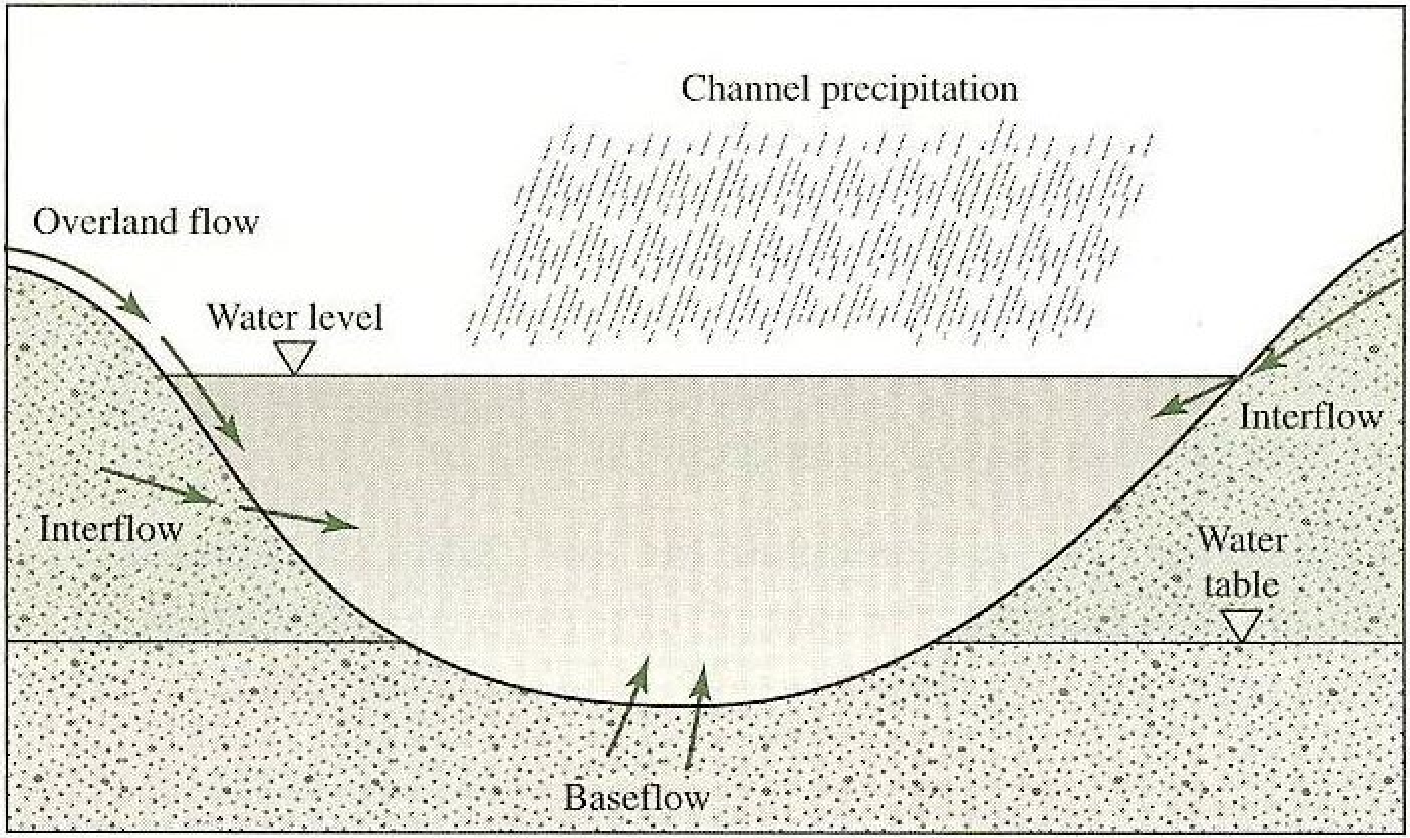
The volume of water that would have infiltrated over the 6 h can be calculated.

$$\text{Volume} = A_s\left[\left\{(0.51)(6) + \frac{(3.81 - 0.51)}{-0.35}e^{-(0.35)(6)}\right\} - \left\{(0.51)(0) + \frac{(3.81 - 0.51)}{-0.35}e^{-(0.35)(0)}\right\}\right]$$

$$= A_s(11.3\ \text{cm}) = 1\ \text{m}^2(11.3\ \text{cm})(1\ \text{m} \cdot 100\ \text{cm}^{-1}) = 0.113\ \text{m}^3$$

Origin of Streamflow

- Three major sources
  - D&M: Fig 7-14

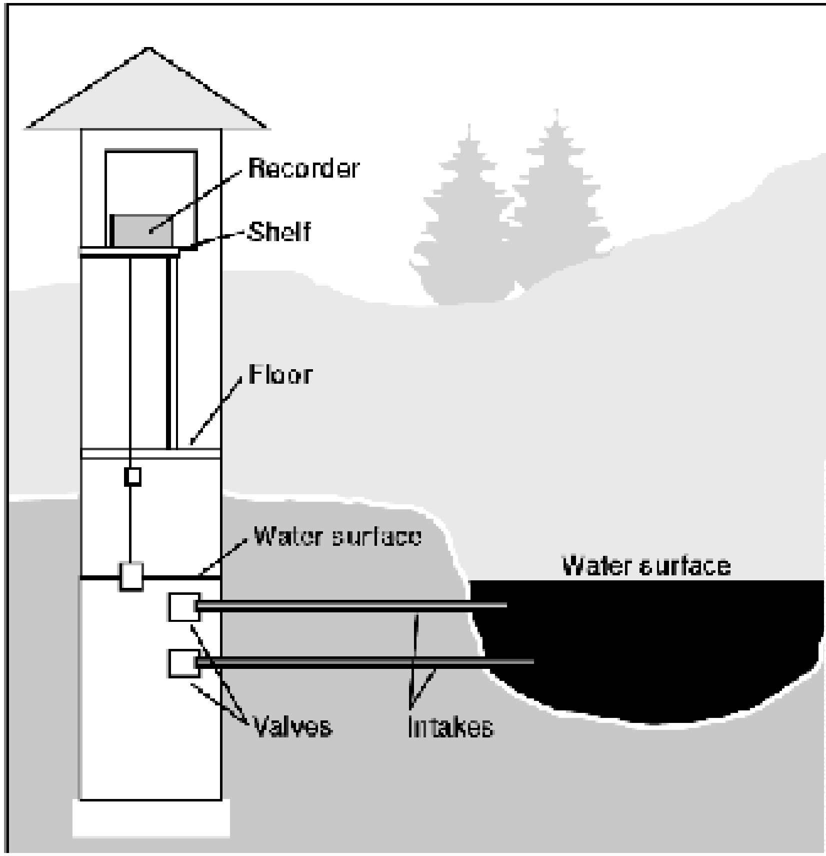


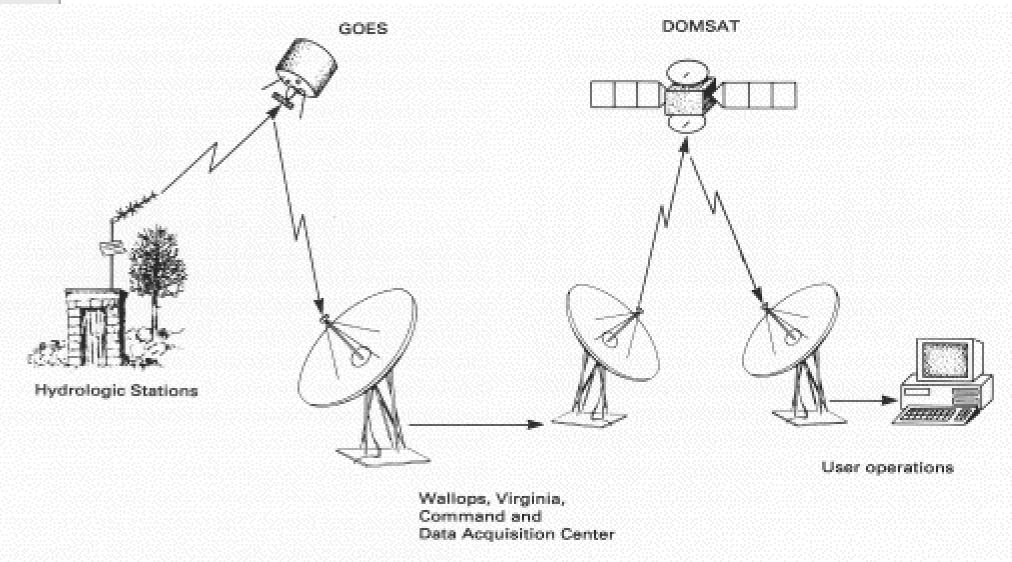
Watershed & Hydrogeometric Parameters

- Geometry
  - Width and Depth
  - Slope
- Hydrology
  - Velocity and Flow
  - Mixing characteristics (dispersion)
- Drainage Area
- Dams, Reservoirs & flow diversions
- Geographical location of basin

USGS Gaging Stations

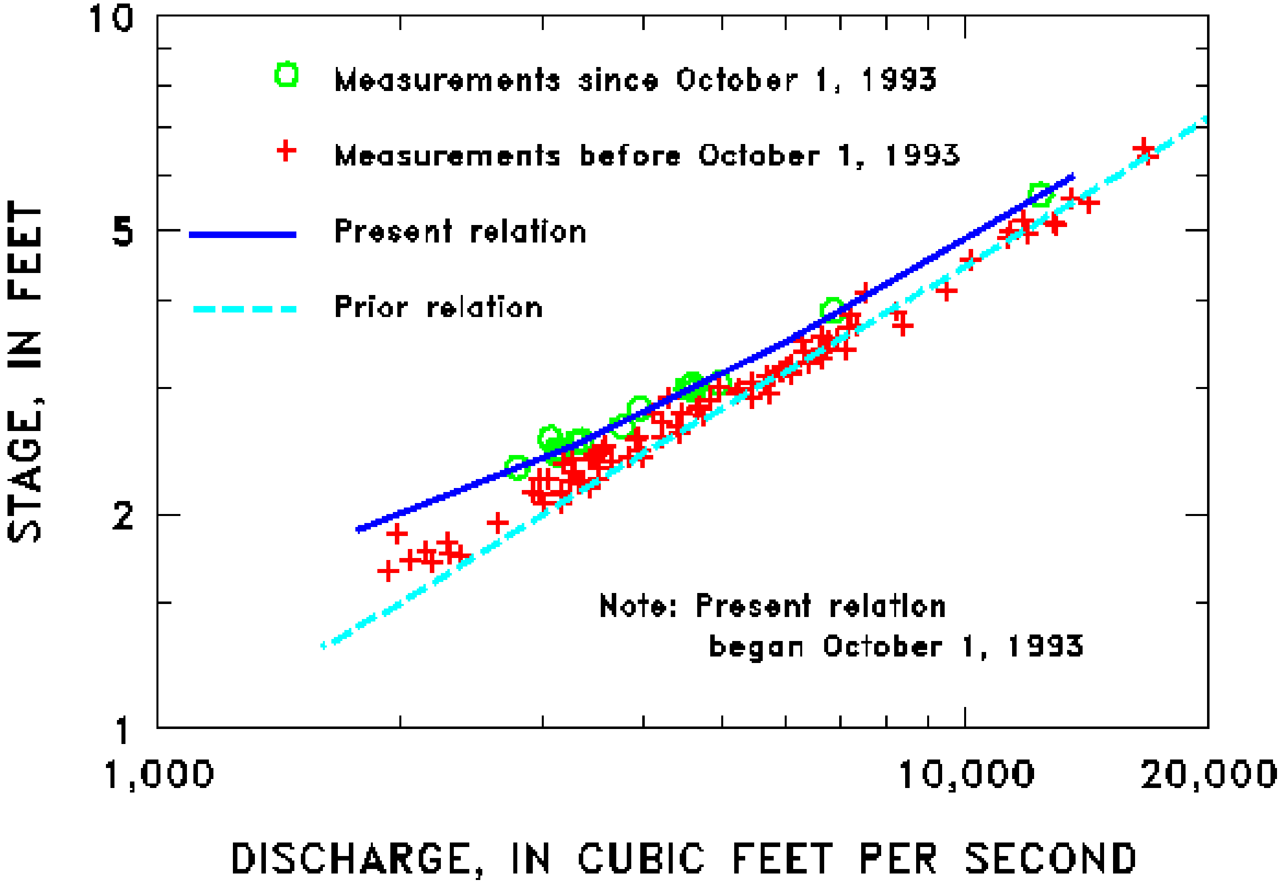
- Hardware & telemetry





Stage vs Discharge

- Sections of stage-discharge relations for the Colorado River at the Colorado--Utah State line



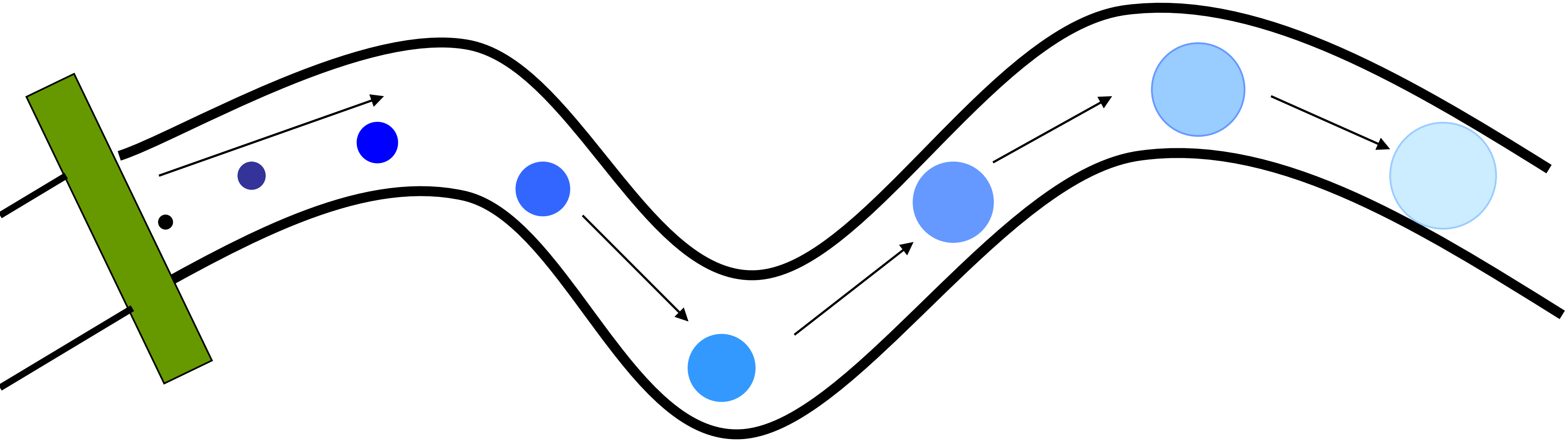
Mass Transport Processes

- Processes that move chemicals through the air, surface water, subsurface environment or engineered systems
  - e.g., From point of generation to remote locations
- Very important to:
  - design of treatment systems
  - prediction of pollutant impacts in the environment
  - determination of waste load allocations
  - determination of sources of pollutants.

Advection and Dispersion

- Advection
  - Transport with the mean fluid flow
- Dispersion
  - Transport in directions other than that of the mean fluid flow
    - Some is due to “random” motions

- Blue dye dropped in a flowing river



- Dispersion occurs along with clear advection

Assessing Hydrogeometry

- Point Estimates vs. Reach Estimates
- Flow
  - often requires velocity
  - May use stage
    - USGS gaging stations

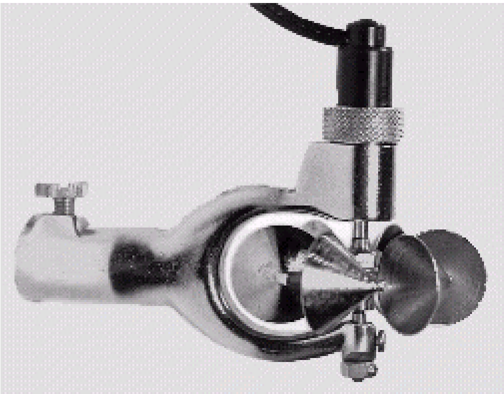
$$Q = UA_c$$

$$U = \frac{Q}{A_c}$$

- Velocity
  - Current Meter
  - Weighted Markers or Dye

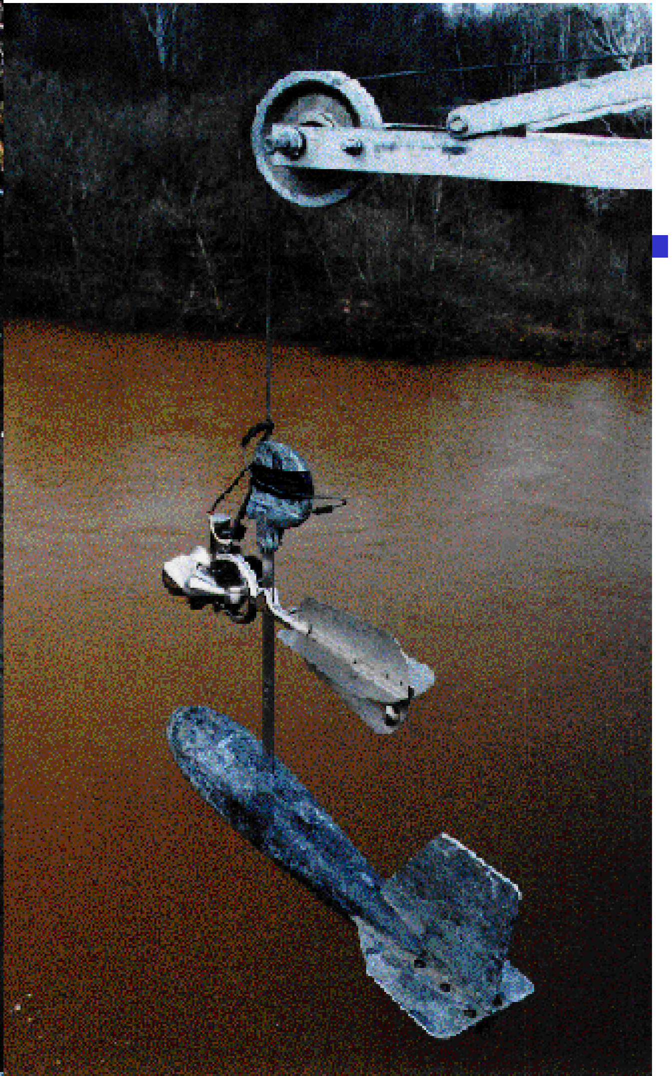
Current Meters

- Price
- Pygmy



http://advmnc.com/Rickly/currmet.htm
http://www.swoffer.com/2200.htm

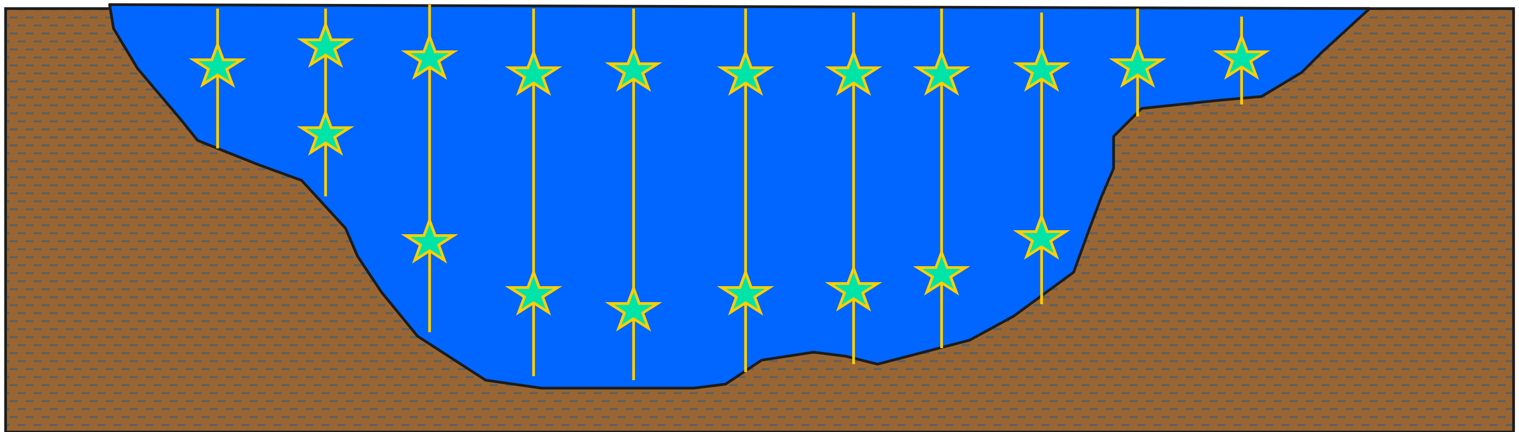
Current Meter Deployment



- Current meter and weight suspended from a bridge crane
- Wading rod and current meter used for measuring the discharge of a river

Current Meter Method

- Divide stream cross section into transects
- Measure velocity in each with meter
  - at 60% depth in shallow water (<2ft)
  - or 20% and 80% depth in deep water



Deployment cont.

- Crane, current meter, and weight used for measuring the discharge of a river from a bridge

From: U.S. GEOLOGICAL SURVEY CIRCULAR 1123; on the www at:

http://h2o.usgs.gov/public/pubs/circ1123/index.html

Moving Marker Methods

- Best for low velocity (<0.2 ft/s)
- Several types
  - Drogues (current at depth)
  - Dye (mixing too)
  - Surface objects (Oranges, Frisbees)
- Velocity from change in location with time

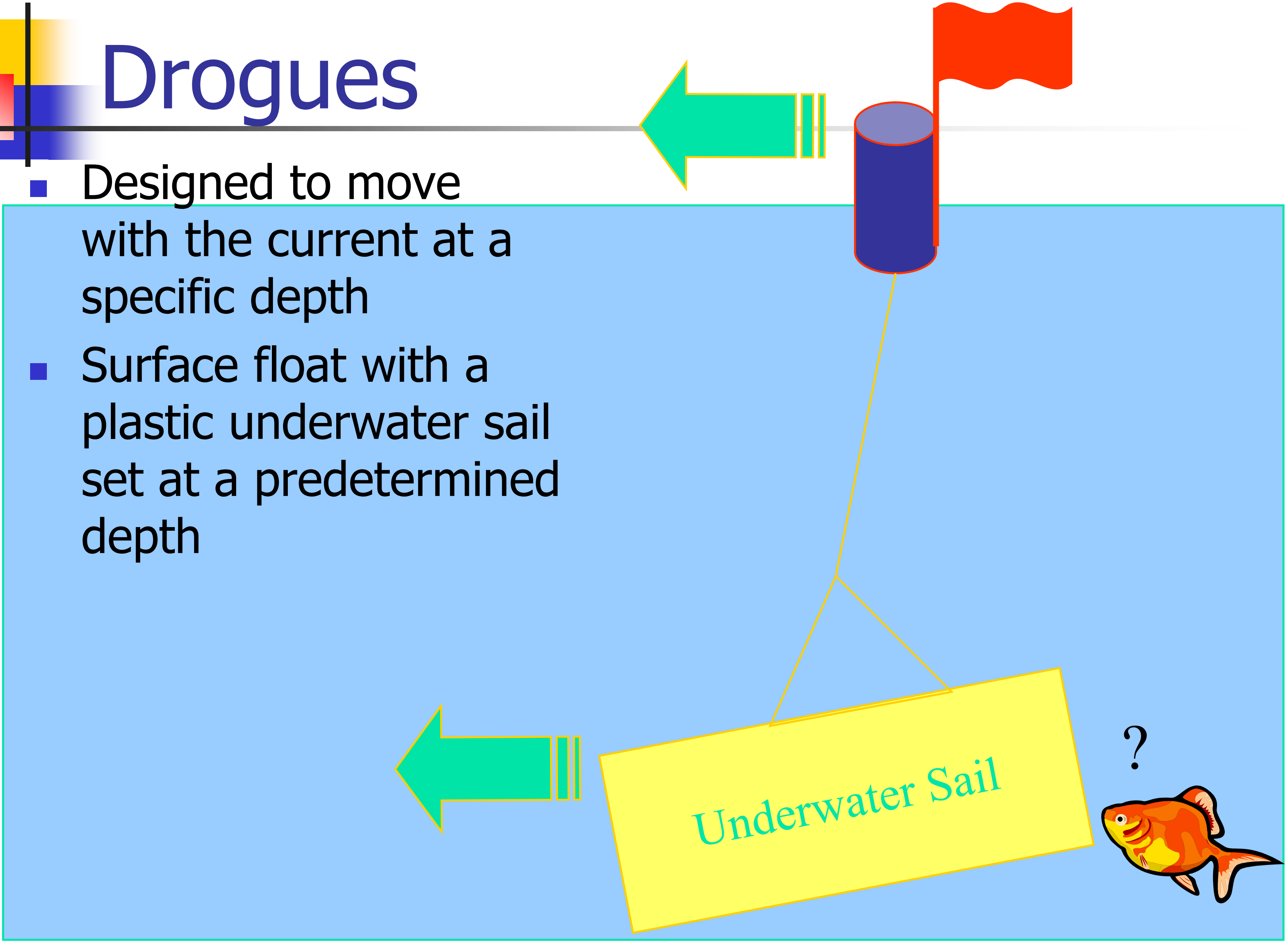
$$U_{avg} = \frac{\Delta x}{t^*}$$

Time of travel

$$Q_{avg} = U_{avg}\left(\frac{A_1 + A_2}{2}\right)$$

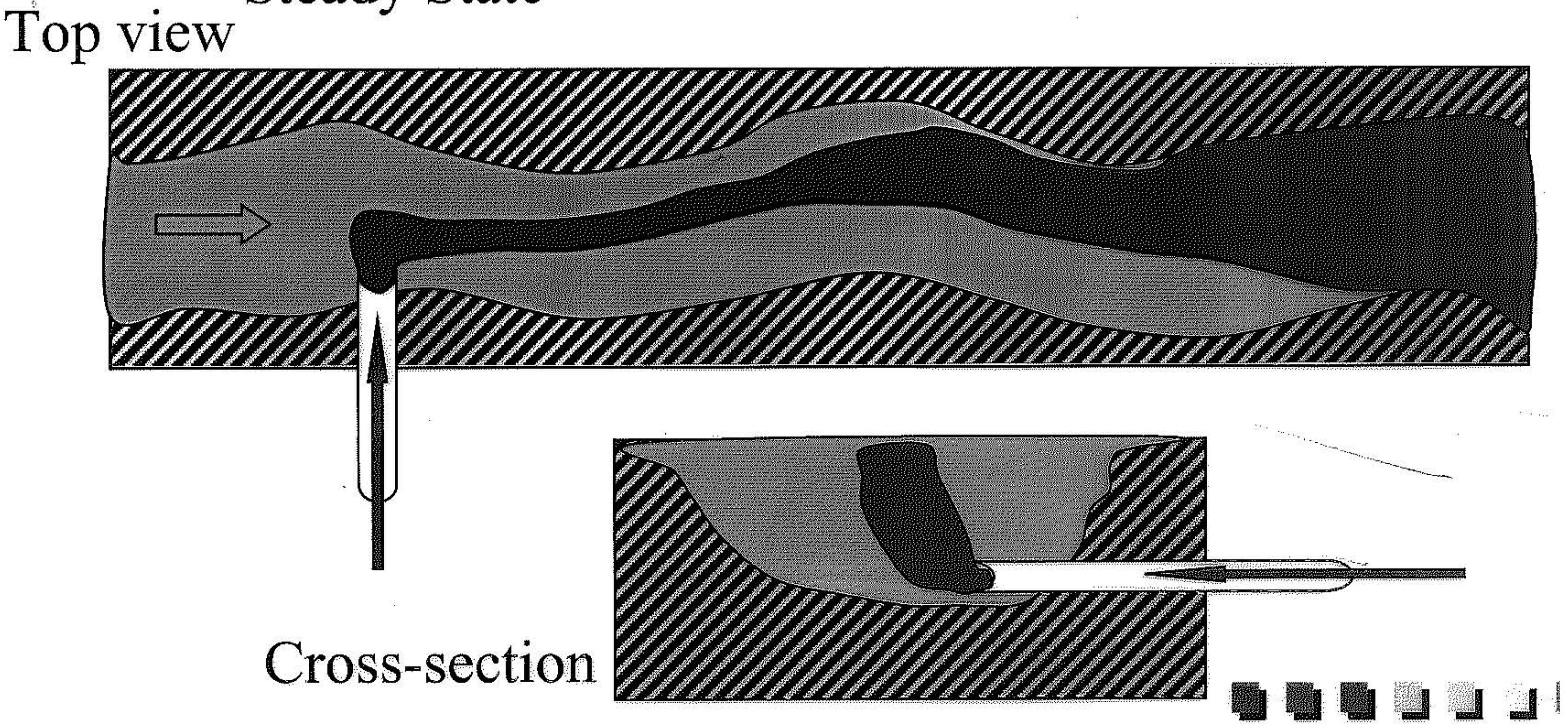
Drogues

- Designed to move with the current at a specific depth
- Surface float with a plastic underwater sail set at a predetermined depth

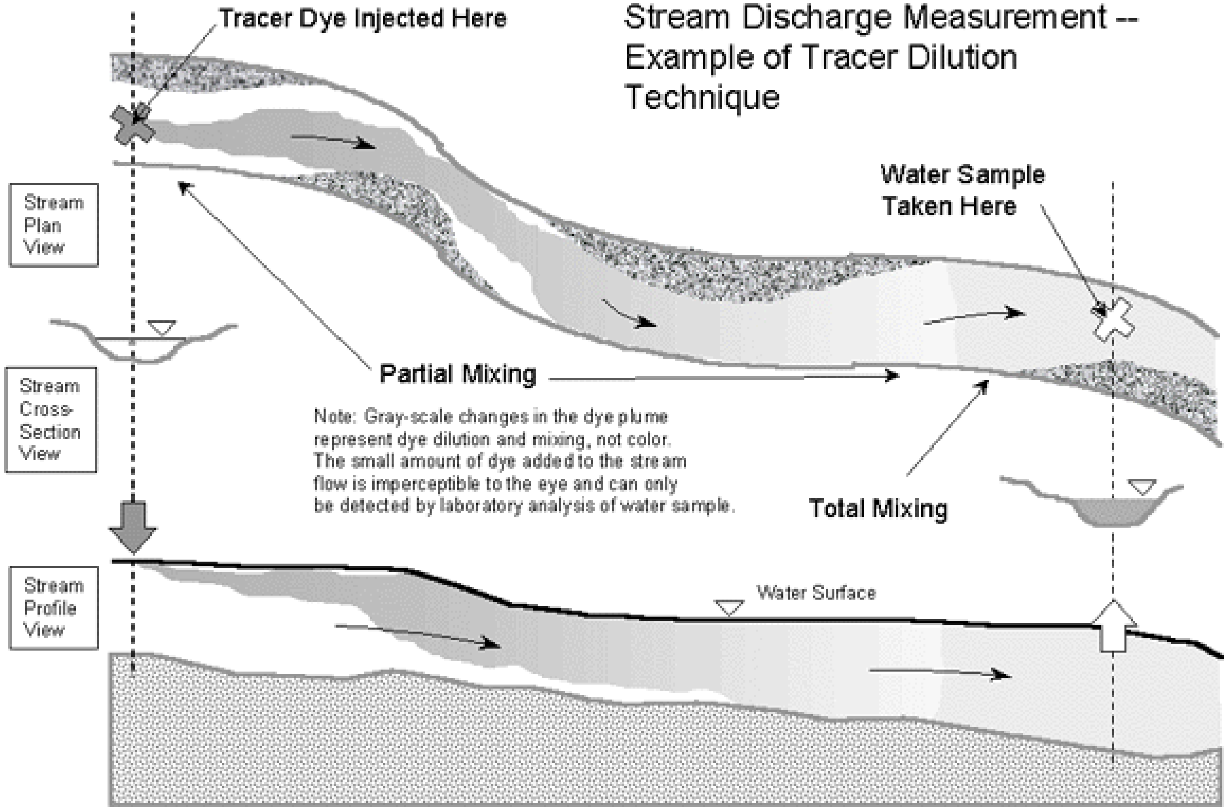


Assumptions

- The ideal reactor is:
  - Completely mixed in cross-section
  - Without longitudinal (downstream) mixing
  - Steady State



Dye studies



Stream Discharge Measurement -- Example of Tracer Dilution Technique

Note: Gray-scale changes in the dye plume represent dye dilution and mixing, not color. The small amount of dye added to the stream flow is imperceptible to the eye and can only be detected by laboratory analysis of water sample.

Drawing courtesy of R. D. Mac Nish, University of Arizona, Tucson (http://www.tucson.ars.ag.gov/salsa/research/research_1997/AMS_Posters/gw-sw_interactions/gw-sw_f1.html)

Lateral Mixing: USGS guidance

- Lateral or transverse dispersion coefficient for a stream:

Mean depth

$$E_{lat} = 0.6HU^{*}$$

Shear velocity

$$U^{*} = \sqrt{gHS}$$

- Length required for complete mixing:

Center discharge:

$$L_m = 0.10U\frac{B^2}{E_{lat}}$$

Width

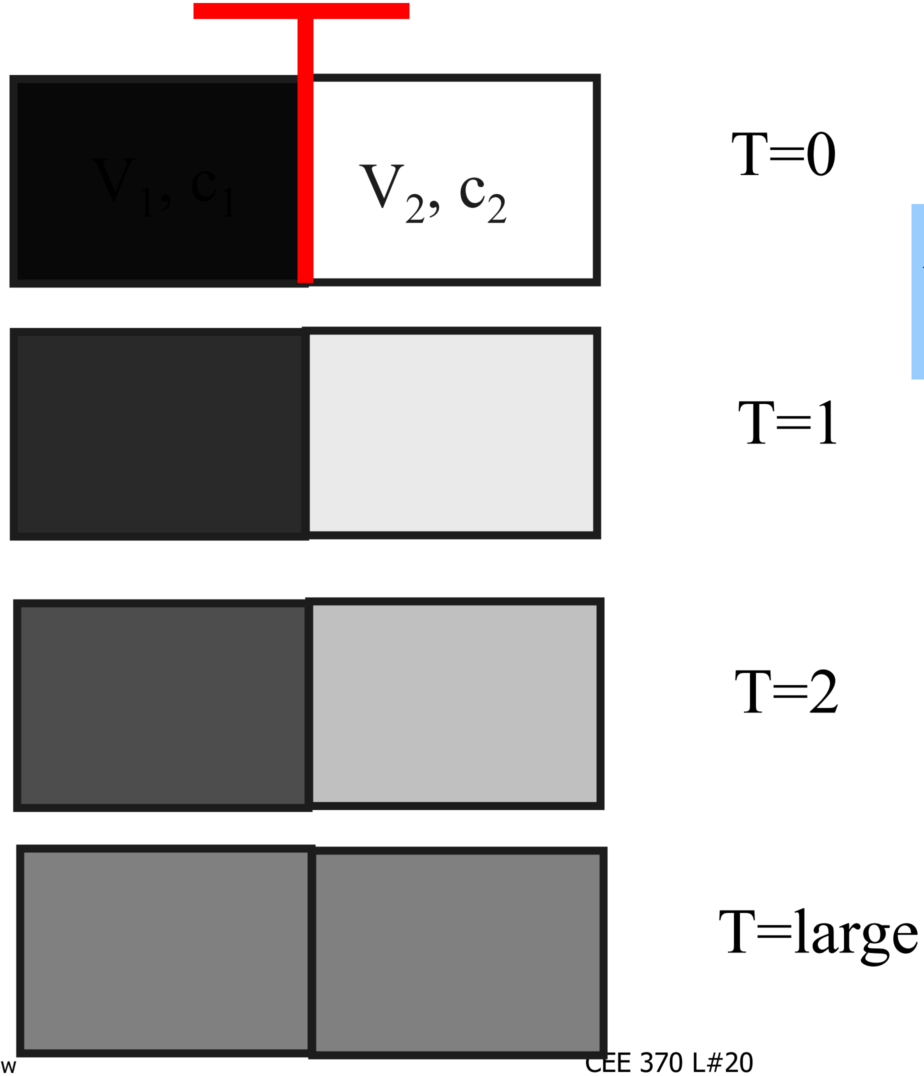
For Fort River

~1000 ft
or t=20 min

Liquid Water Transport

- Advection: unidirectional flow
- Diffusion: movement of mass that is not unidirectional flow; usually movement in an unorganized fashion
  - Dispersion
  - Eddy Diffusion
  - Molecular Diffusion

Mass Diffusion



Incorporates molecular movement and interfacial area

Bulk Diffusion (m^2/yr)

$$V_1 \frac{dc_1}{dt} = D'\underbrace{\left(c_2 - c_1\right)}_{\text{Concentration Gradient}}$$

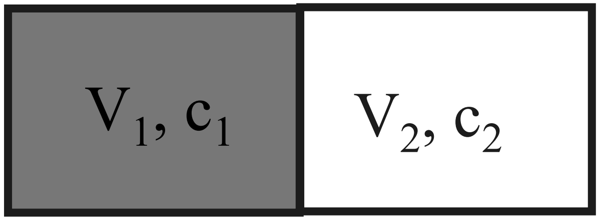
Fick's First Law

- Mass flux is proportional to the concentration gradient and a diffusion coefficient

$$J_x = -D\frac{dc}{dx}$$

Units for diffusion coefficient: (Length^{2}time^{-1})

Bulk Diffusion Coefficient



$$V_1 \frac{dc_1}{dt} = -JA_c$$

The mixing length

$$J_x = -D\frac{dc}{dx}$$

$$\frac{dc}{dx} \cong \frac{c_2 - c_1}{\ell}$$

And combining all three:

$$V_1 \frac{dc_1}{dt} = \underbrace{\frac{DA_c}{\ell}}_{D'}(c_2 - c_1)$$

$$E' = \frac{EA_c}{\ell}$$

Similar for Eddy Diffusion

Some diffusion coefficients

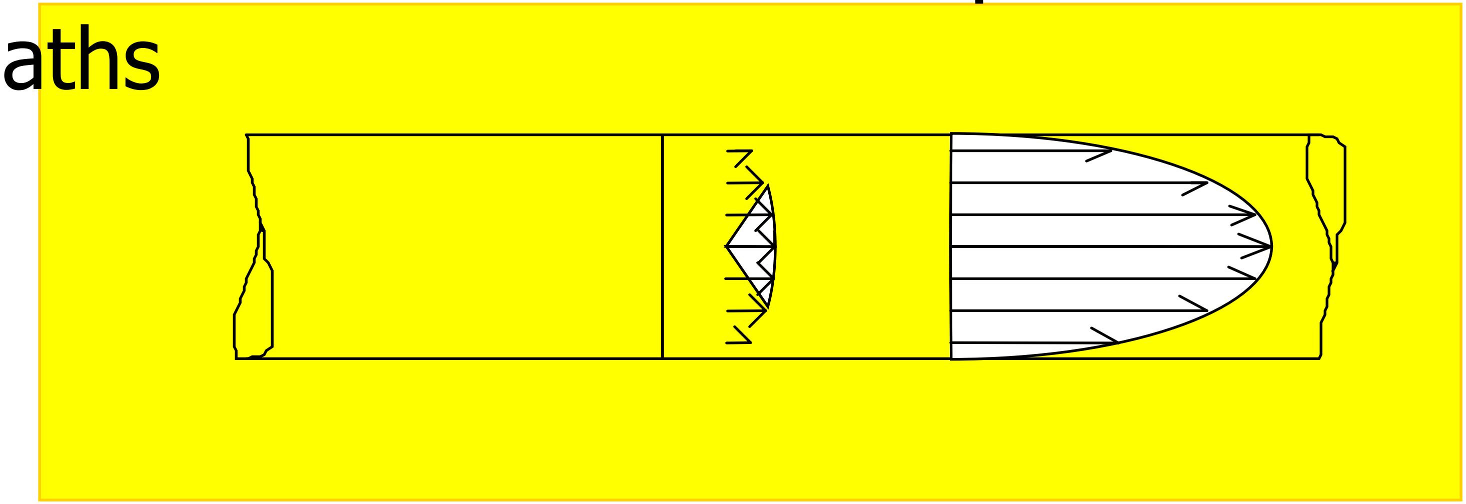
Compound	Temp (C)	D (cm^2s^{-1})
Methanol in H_2O	15	$1.26\mathrm{x}10^{-5}$
Ethanol in H_2O	15	$1.00\mathrm{x}10^{-5}$
Acetic Acid in H_2O	20	$1.19\mathrm{x}10^{-5}$
Ethylbenzene in H_2O	20	$0.81\mathrm{x}10^{-5}$
CO_2 in Air	20	0.151

Turbulent Dispersion

- Turbulent eddies
  - Large scale “random movement”
    - Whirlpools in a river
    - Circulatory flows in the ocean
  - Occurs only at flows above a “critical” level
    - Determined by the Reynolds number
  - Almost always dominates over molecular diffusion
    - Exception: transport across a boundary

Dispersion (Mechanical)

- Differences in velocities of parallel flow paths



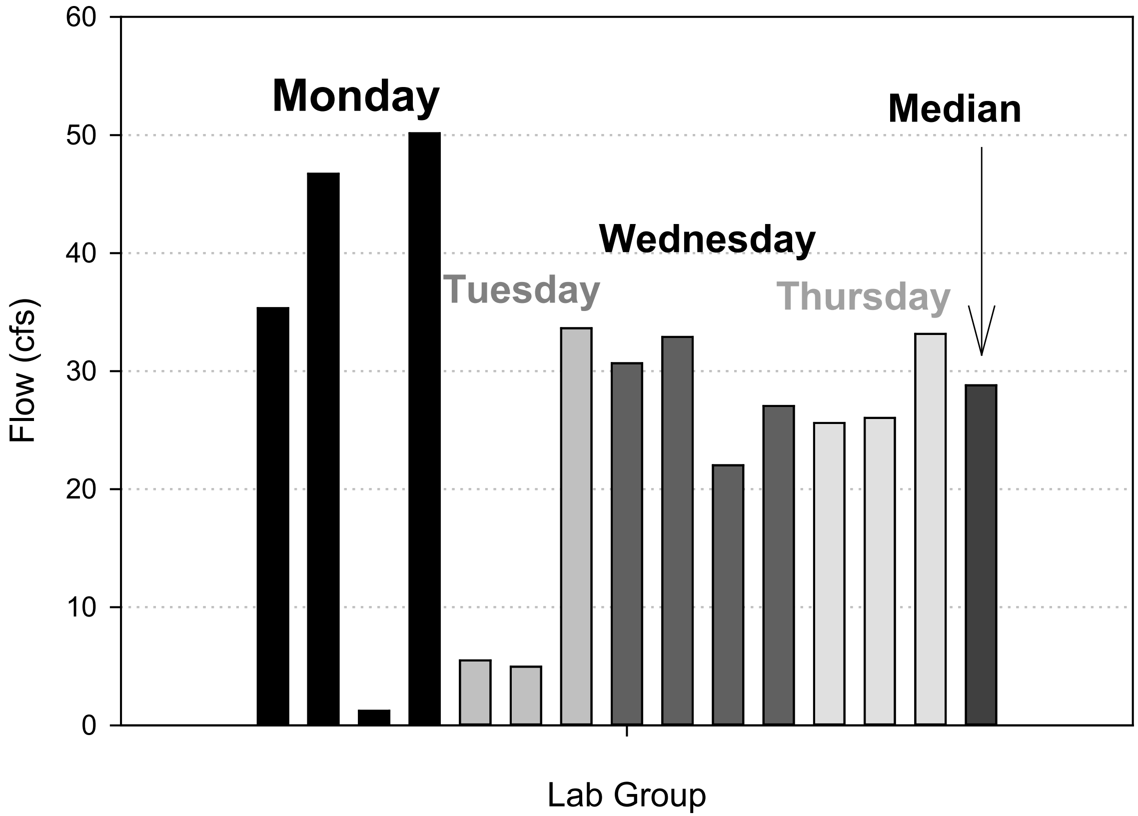
- Different paths in porous media

- To next lecture

Lab #1 - 2015

- Citrus float method

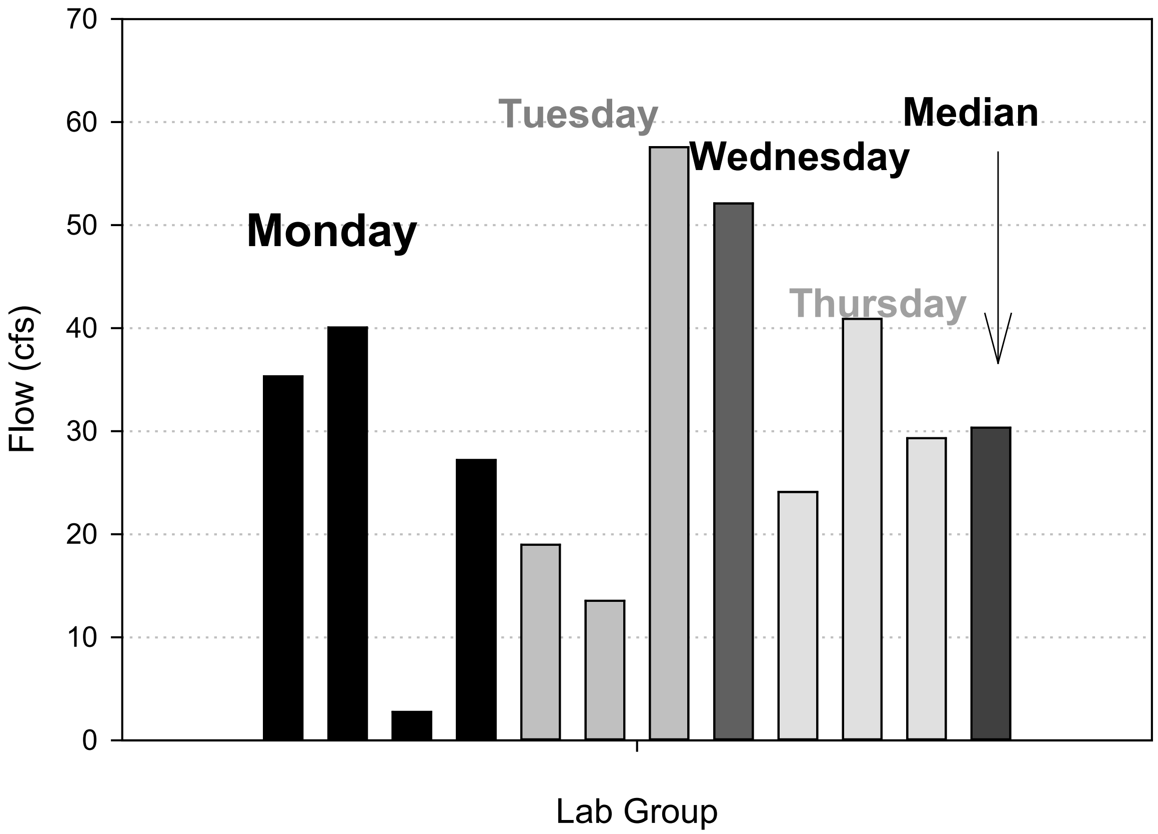
Median: 28.8 cfs



Lab #1 - 2015

- Swoffer Meter method

Median: 29.3 cfs



Lab #1

- Tracer method

Median: 7.7 cfs