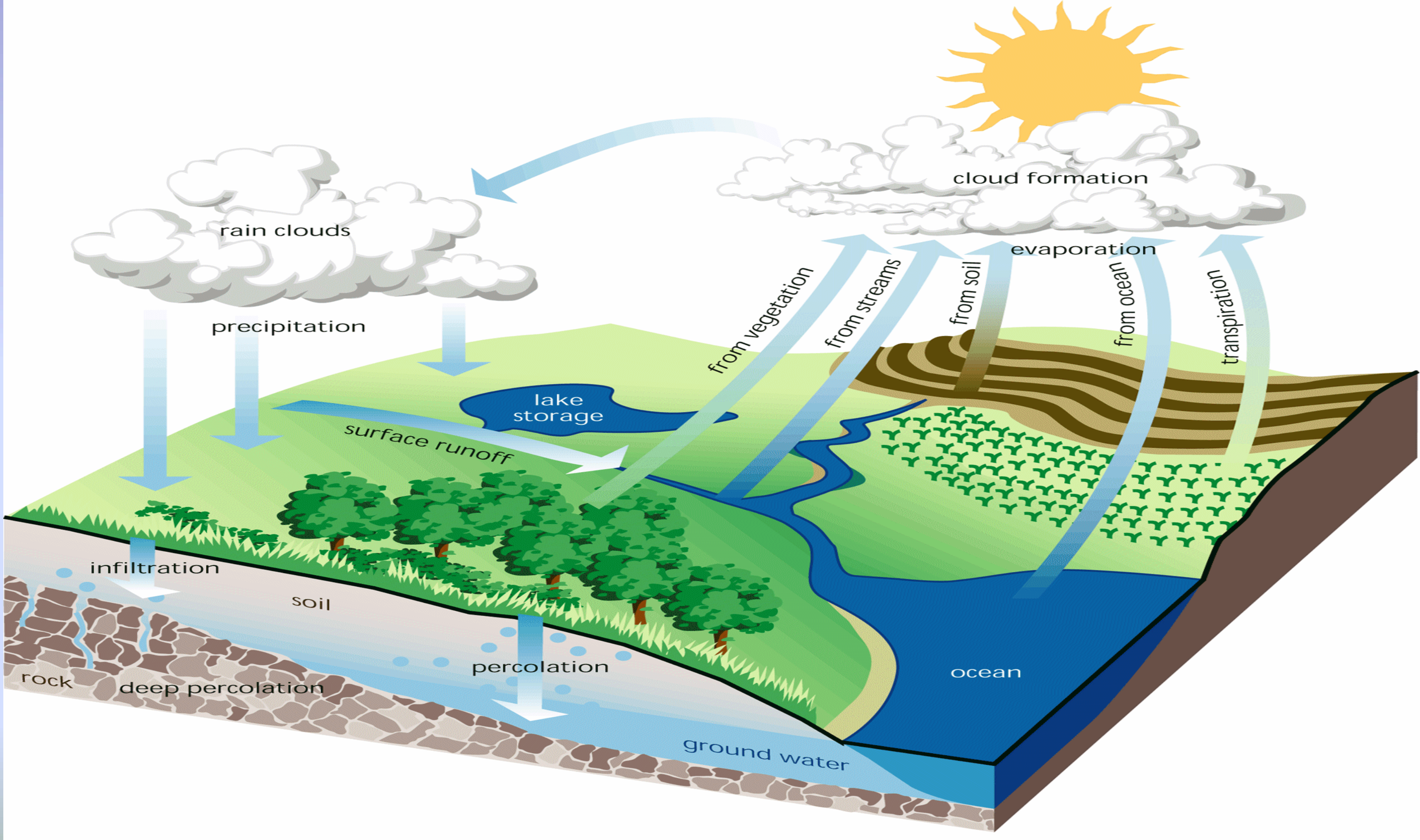
Hydrologic Cycle

Looking at movement of energy through natural systems



http://www.cet.nau.edu/Projects/SWRA/research.html

Hydrologic Cycle

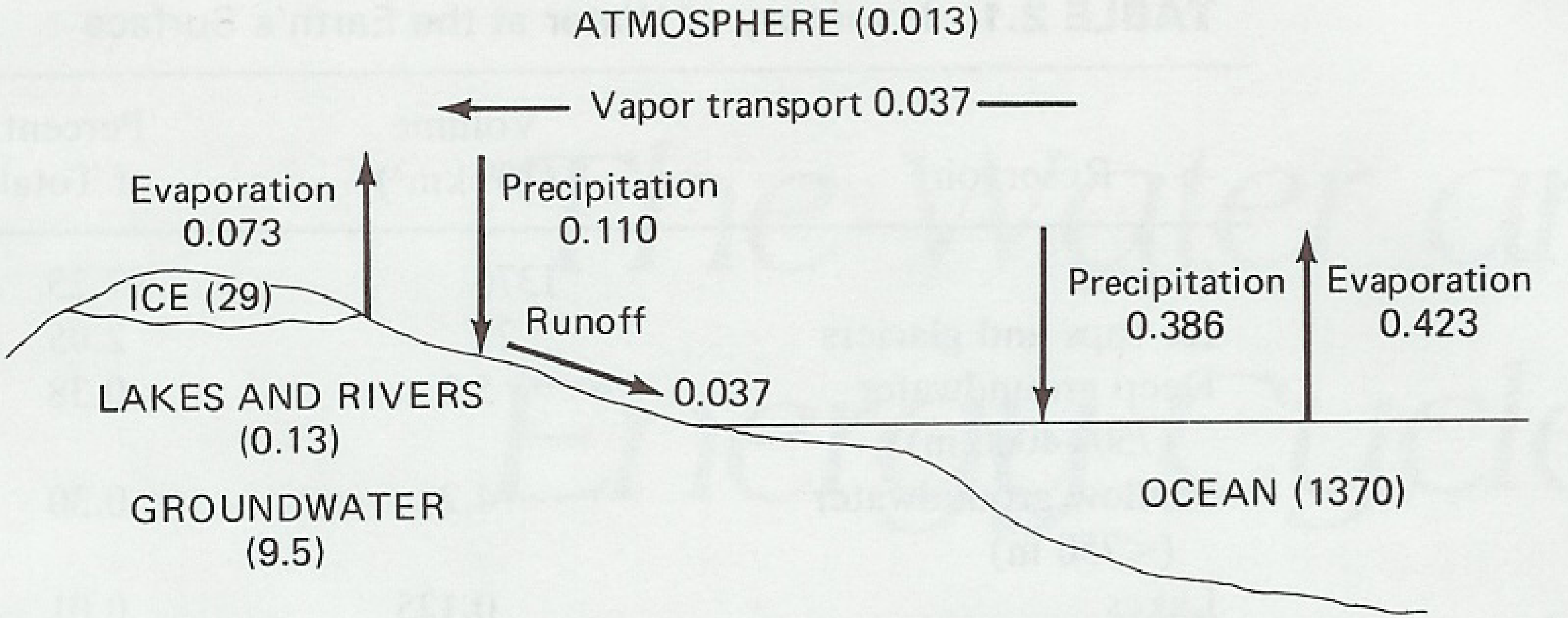


Figure 2.1 The hydrologic cycle. Numbers in parentheses represent inventories (in 10^6 km^3) for each reservoir. Fluxes are in 10^6 km^3 per year. (Data from Tables 2.1 and 2.2).

Berner and Berner, *The Global Water Cycle*, 1987

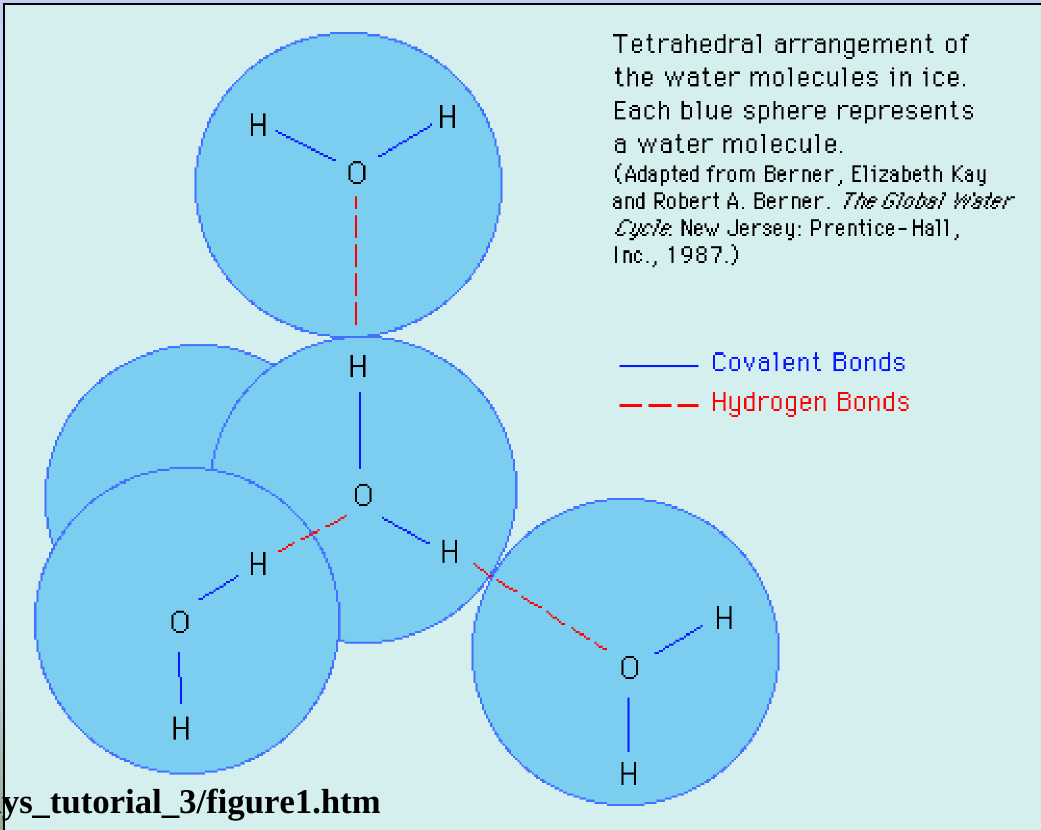
Hydrologic Cycle

Important in terms of examining other chemical cycles

***Water*:**

- Due to the structure of water (dipole properties- having both a positive and a negative end), it forms hydrogen bonds between the water molecules which are weak in comparison to the covalent bonds (about 20x stronger) between the oxygen and hydrogen within a water molecule.

•However, the presence of these hydrogen bonds do serve to make the molecule more stable than other hydrogen compounds such as hydrogen sulfide which exists as a gas at normal temperature.



Tetrahedral arrangement of the water molecules in ice. Each blue sphere represents a water molecule.
(Adapted from Berner, Elizabeth Kay and Robert A. Berner. *The Global Water Cycle*. New Jersey: Prentice-Hall, Inc., 1987.)

http://www.ldeo.columbia.edu/edu/dees/ees/lithosphere/hays_tutorial_3/figure1.htm

Properties of Water

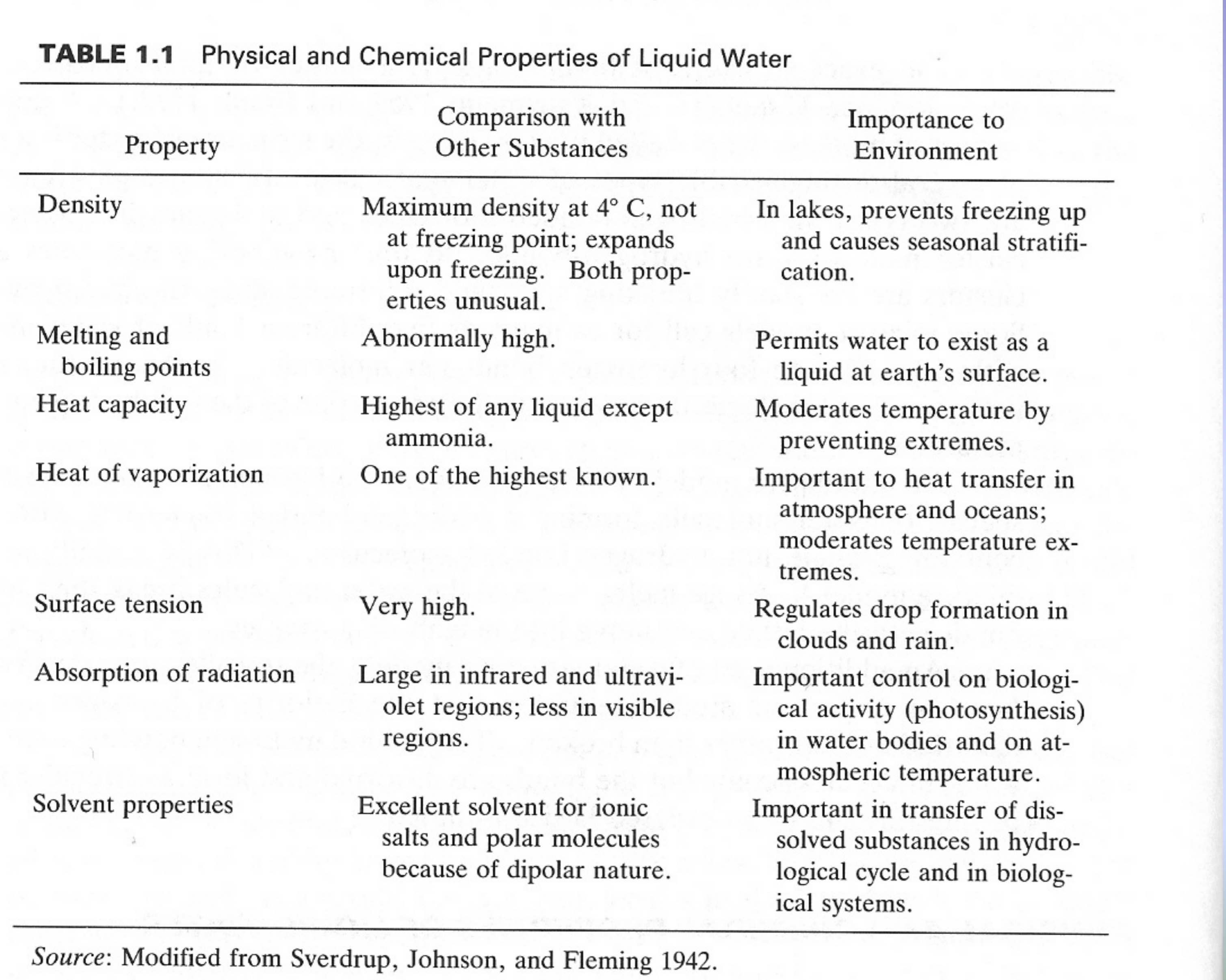
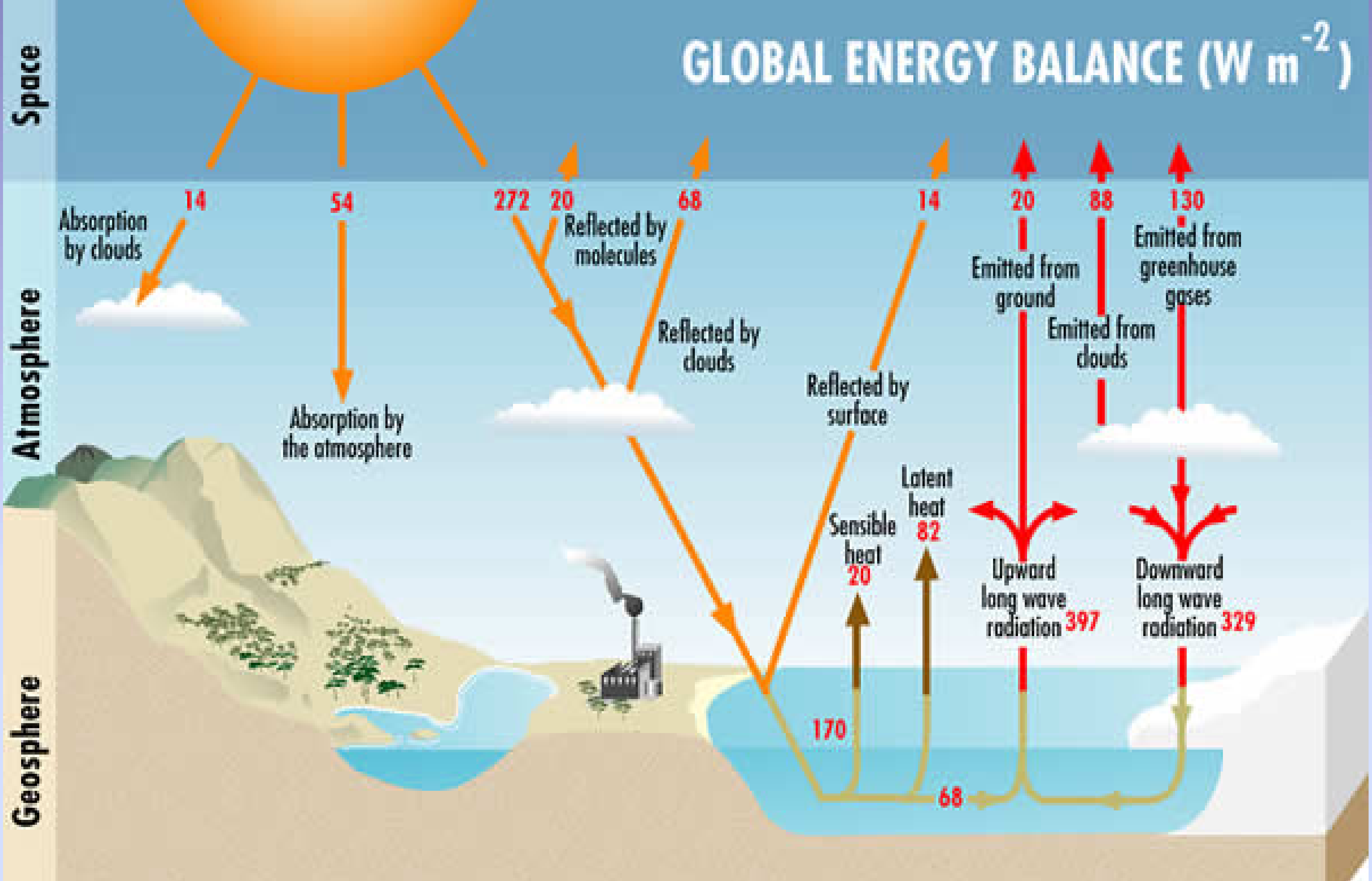


TABLE 1.1 Physical and Chemical Properties of Liquid Water

Property	Comparison with Other Substances	Importance to Environment
Density	Maximum density at 4° C, not at freezing point; expands upon freezing. Both properties unusual.	In lakes, prevents freezing up and causes seasonal stratification.
Melting and boiling points	Abnormally high.	Permits water to exist as a liquid at earth's surface.
Heat capacity	Highest of any liquid except ammonia.	Moderates temperature by preventing extremes.
Heat of vaporization	One of the highest known.	Important to heat transfer in atmosphere and oceans; moderates temperature extremes.
Surface tension	Very high.	Regulates drop formation in clouds and rain.
Absorption of radiation	Large in infrared and ultraviolet regions; less in visible regions.	Important control on biological activity (photosynthesis) in water bodies and on atmospheric temperature.
Solvent properties	Excellent solvent for ionic salts and polar molecules because of dipolar nature.	Important in transfer of dissolved substances in hydrological cycle and in biological systems.

Source: Modified from Sverdrup, Johnson, and Fleming 1942.

Berner and Berner, The Global Water Cycle, 1987



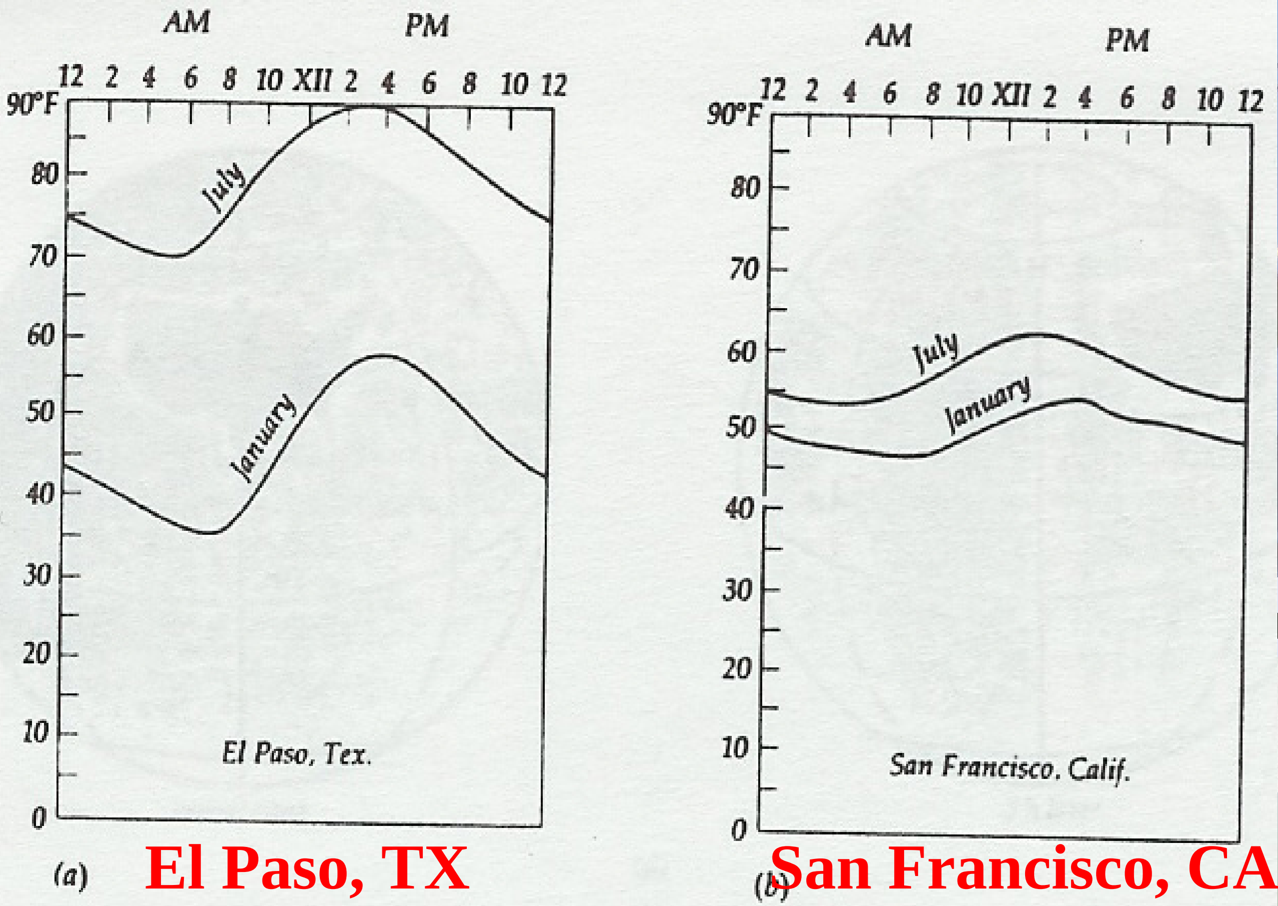
The global radiation balance at the top of the atmosphere and at the earth's surface. Part of the total incoming solar energy 340 W m^{-2} is absorbed by clouds and atmospheric gases and part is reflected by clouds, atmospheric gases and the ground (land and water surfaces). Approximately half (170 W m^{-2}) is absorbed by the ground. Some of this energy is re-radiated upward and some transferred to the atmosphere as ‘sensible’ and ‘latent’ heat by turbulence and convection. The atmosphere radiates infrared radiation in all directions. When balance is achieved in the atmosphere, the total (short wave and long wave) upward radiation from the top of the atmosphere equals the 340 W m^{-2} received from the sun. http://www.bom.gov.au/info/climate/change/gallery/7.shtml

Hydrologic Cycle

- The transfer of heat and mass occurs through oceans and atmosphere. This movement is ultimately derived from the Sun.
- The sun influences the atmosphere which influences wind currents which influences ocean surface currents which effectively transfers heat from low to high latitudes.
- Otherwise, we would be in a perpetual deep freeze. In glacial times, this heat/energy transport mechanism probably shut down to some extent.

Because of these qualities, water acts as a thermostat to lessen extreme temperatures such as the west coast of Europe and the west coast of the US.In close proximity to the oceans, the temperatures vary less.

- San Francisco varies by about 10°C while Washington DC varies by about 30°C.



El Paso, TX **San Francisco, CA**

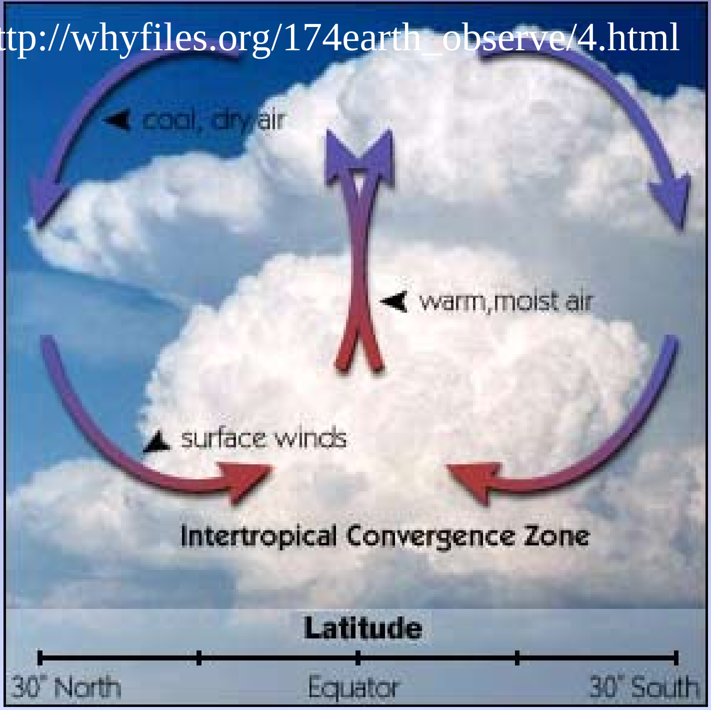
http://www.lord.ca/offices/usa/usa.html

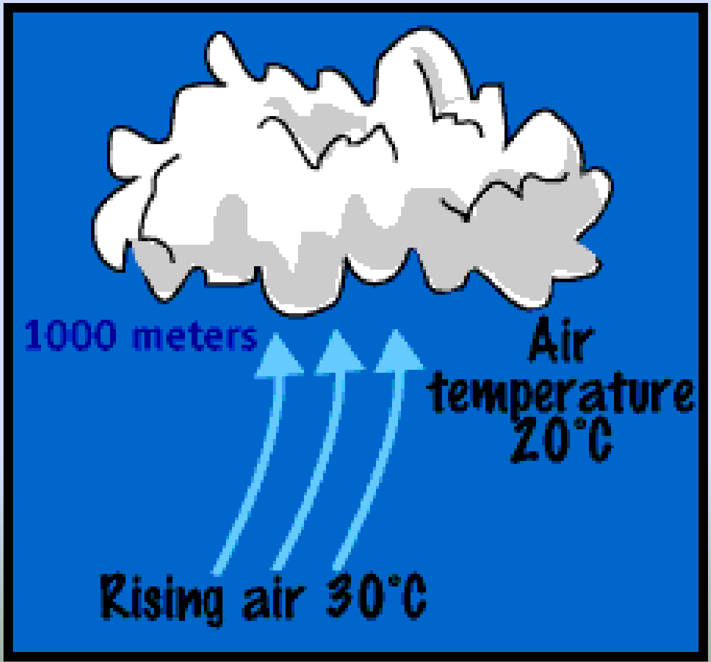
9.5 Diurnal temperature variation at (a) a continental and (b) a maritime station.

- Dry air (with no moisture) has a lapse time of 9°C/km.
- But, generally, as an air parcel cools it can hold less water vapor → Therefore an increase in altitude leads to cooling which may lead to precipitation since warm air can hold more water vapor than cold air.
  - At 30°C → 4% 40mb water vapor held.
  - At 10°C → 12mb water vapor held (factor of 3).

http://www.angliacampus.com/public/pri/geog/rivers/page05.htm

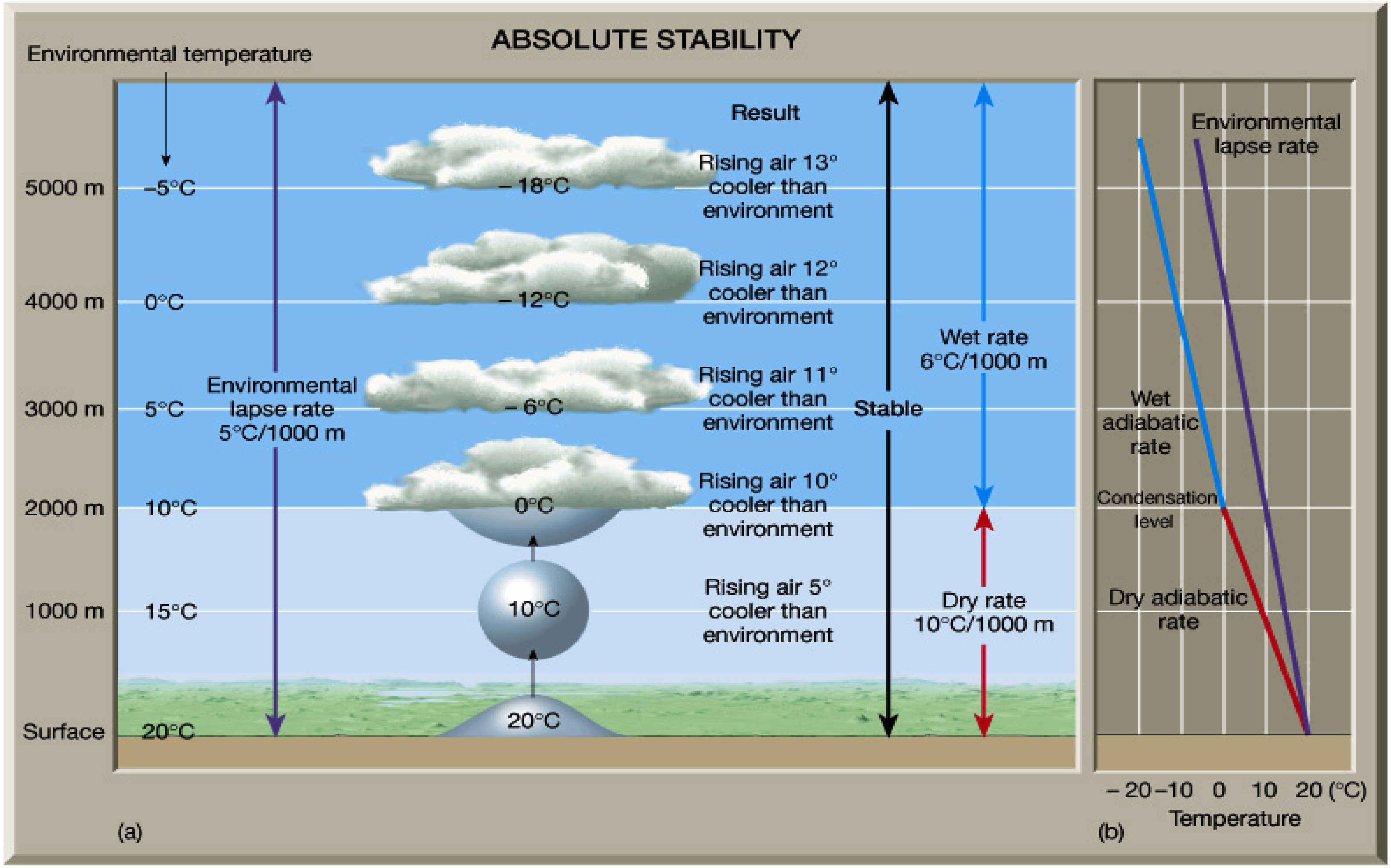
- As rise higher in the atmosphere, temperature decreases at a very constant rate (-6^{o} C/km) = lapse rate of atmosphere.
- There is a decrease in temperature because the air parcel expands → A parcel of air stays at the surface at a given volume due to pressure of the surrounding atmosphere. As the parcel rises, there is less pressure on it from its surroundings and it can expand; increasing volume and decreasing temperature.


http://whyfiles.org/174earth_observe/4.html



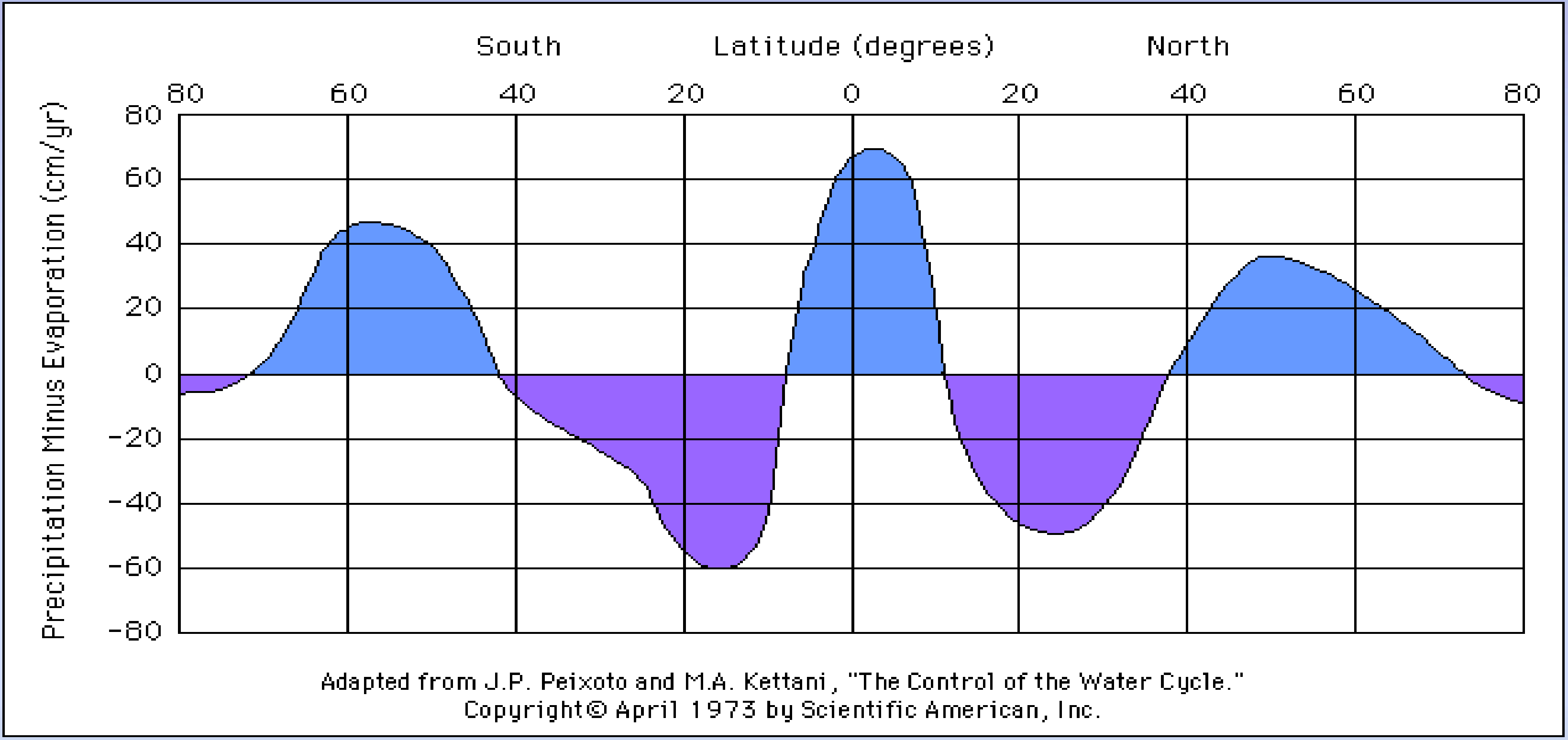
http://ivanova.gsfc.nasa.gov/outreach/EOSDIS_CD-03/docs/enso_troposph.htm

- Therefore, with the cooling of the air mass, water will condense and rain out → therefore energy is released back into the atmosphere and warms it (resulting in the -6°C/km rather than the -9°C/km)



http://rst.gsfc.nasa.gov/Sect14/Sect14_1b.html

- *Therefore, areas of excess precipitation occur in the tropics where rising air masses condense water. Sinking masses of cold dry air occur at 20 degrees latitude- no clouds and evaporation exceeds precipitation*

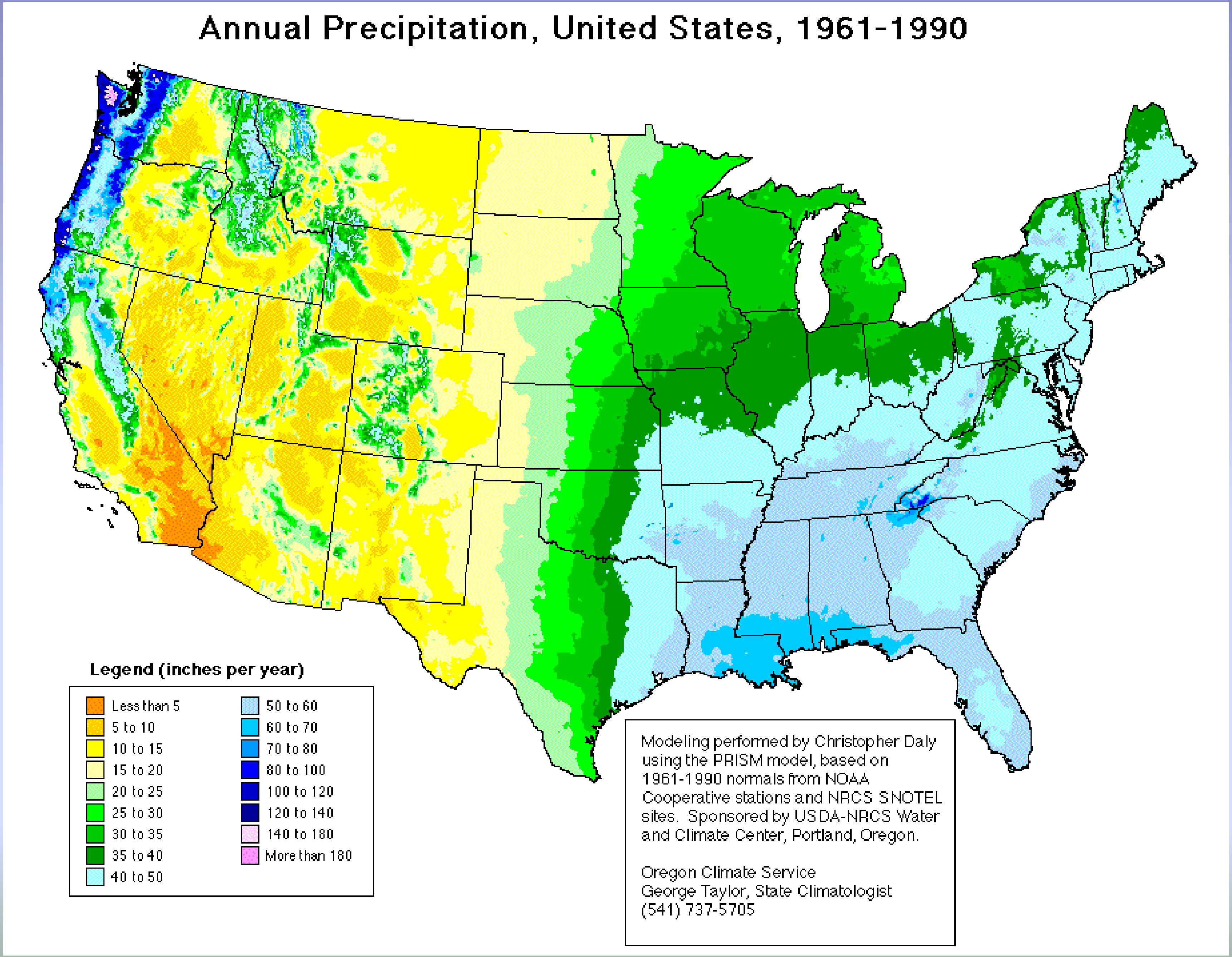


Adapted from J.P. Peixoto and M.A. Kettani, "The Control of the Water Cycle."
Copyright© April 1973 by Scientific American, Inc.

http://www.ldeo.columbia.edu/edu/

dees/ees/lithosphere/hays_tutorial_3/

figure4.GIF



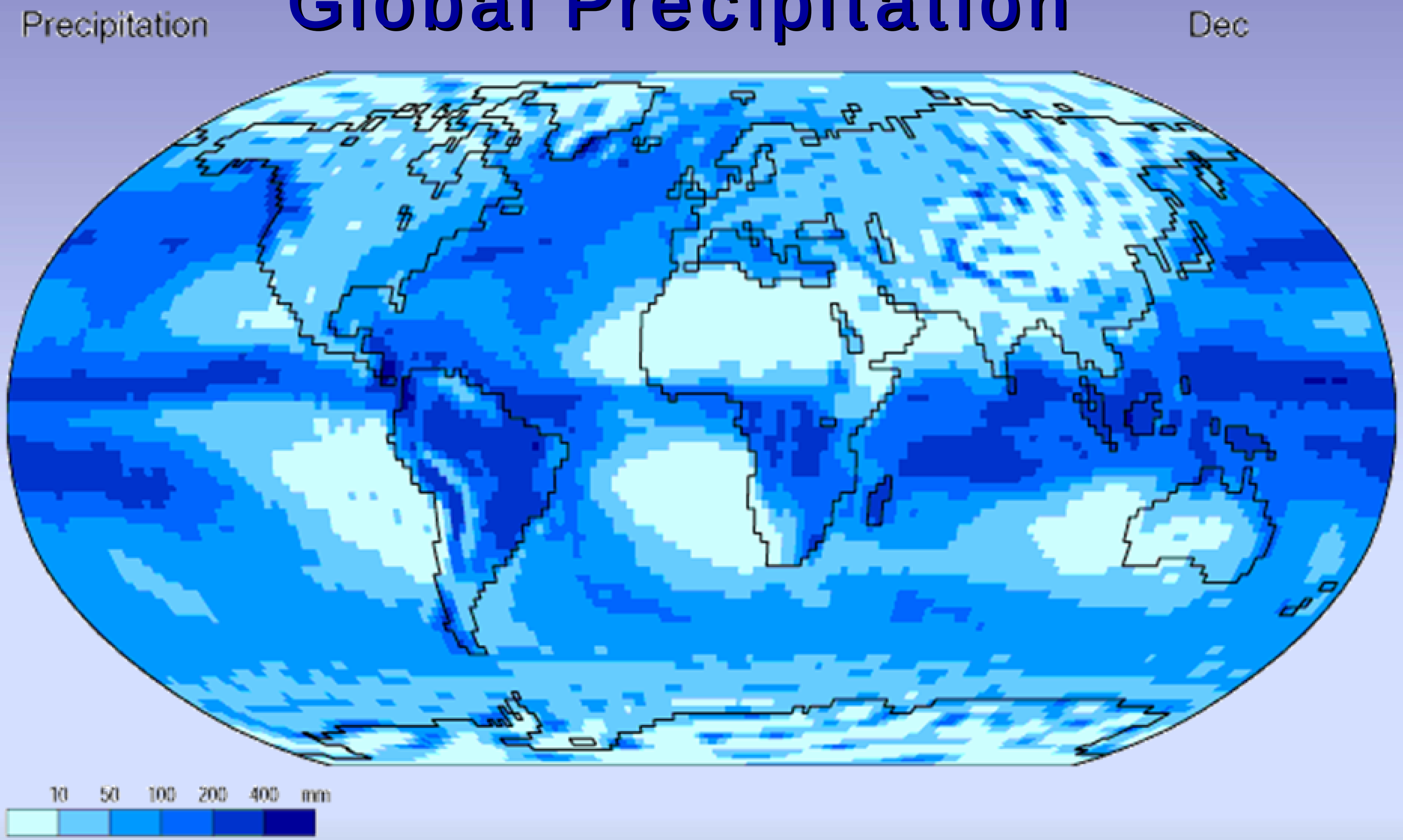
Annual Precipitation, United States, 1961-1990

Modeling performed by Christopher Daly using the PRISM model, based on 1961-1990 normals from NOAA Cooperative stations and NRCS SNOTEL sites. Sponsored by USDA-NRCS Water and Climate Center, Portland, Oregon.

Oregon Climate Service
George Taylor, State Climatologist
(541) 737-5705

http://www.ldeo.columbia.edu/~martins/climate_water/slides/US_precip_map.gif

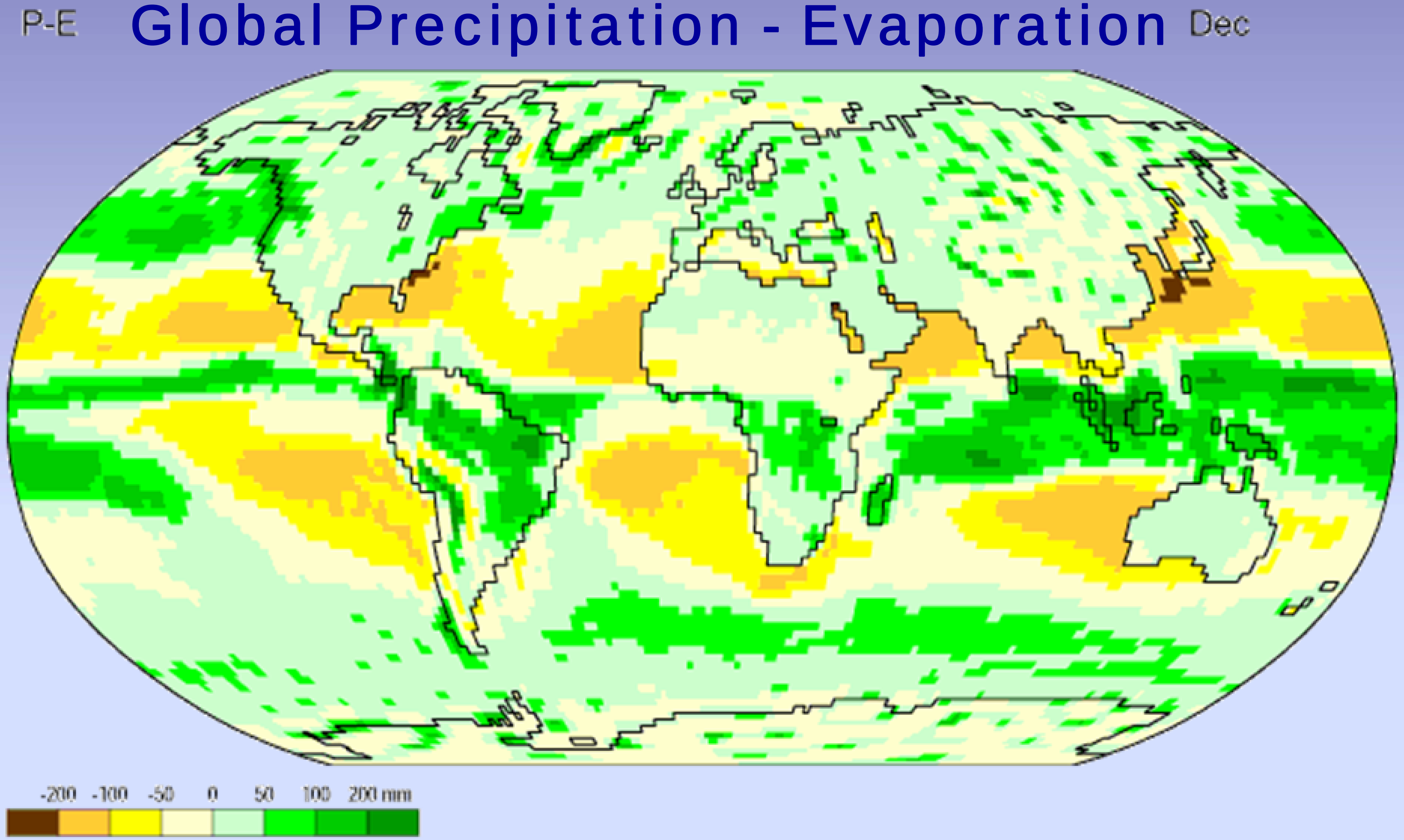
Global Precipitation



Data: NCEP/NCAR Reanalysis Project, 1959-1997 Climatologies
Animation: Department of Geography, University of Oregon, March 2000

http://geography.uoregon.edu/envchange/clim_animations/

Global Precipitation - Evaporation



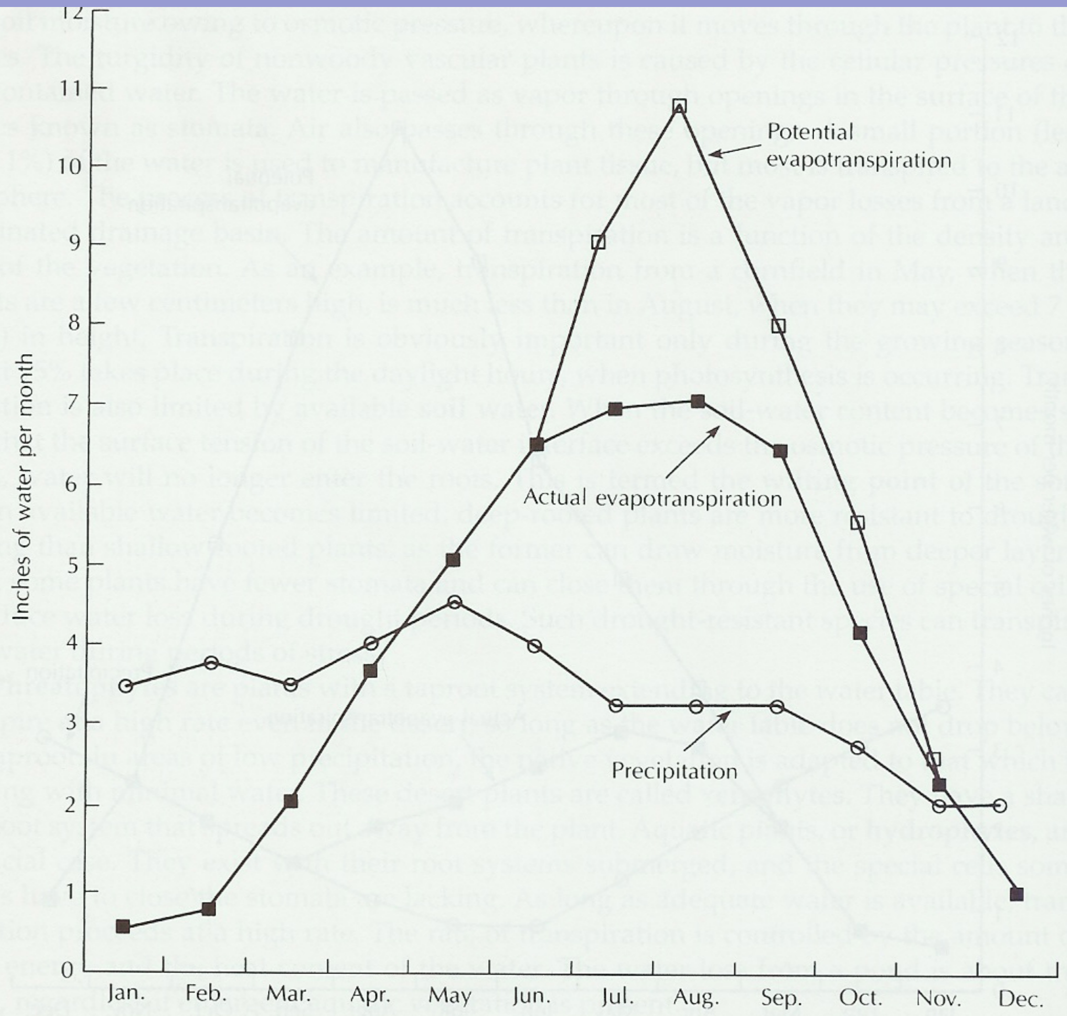
Data: NCEP/NCAR Reanalysis Project, 1959-1997 Climatologies
Animation: Department of Geography, University of Oregon, March 2000

http://geography.uoregon.edu/envchange/clim_animations/

Transpiration - the ability of living plants to transfer water from their roots to their leaves where it escapes to the atmosphere as water vapor.

http://www.floridasprings.org/anatomy/jow/text/assets/03_transpiration_thmb.jpg

Potential and Actual Evapo-transpiration



▲ FIGURE 2.3

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

Fetter, *Applied Hydrogeology 4th Edition*

Transpiration: 20-30% of total precipitation in grasslands
80% of total precipitation in forest regimes.

Evaporation: 100% in desert

Whatever is left (20-80%) contributes to the base flow and percolates down to the water table.

- Hydrologic cycle can get out of balance by small perturbations to the system
  - e.g.. The removal of plants (rain forests)affects the amount of water transferred by transpiration and hence can greatly change the water balance.

Deforestation in the Myanmar Himalayas

http://www.hsdejong.nl/burma/putao/target_pages/deforestation.html

Groundwater Hydrology

Rain: Falls on and enters land surface.

- Some will flow over land surface as runoff- relatively common- important when the ground is frozen.
- Some will enter as interflow- just below the surface of the land- a very porous horizon (shallow flow system).
- The rest percolates into the soil

  → A high percentage of that is transferred back into the vapor phase through evaporation and transpiration (in temperate climates).

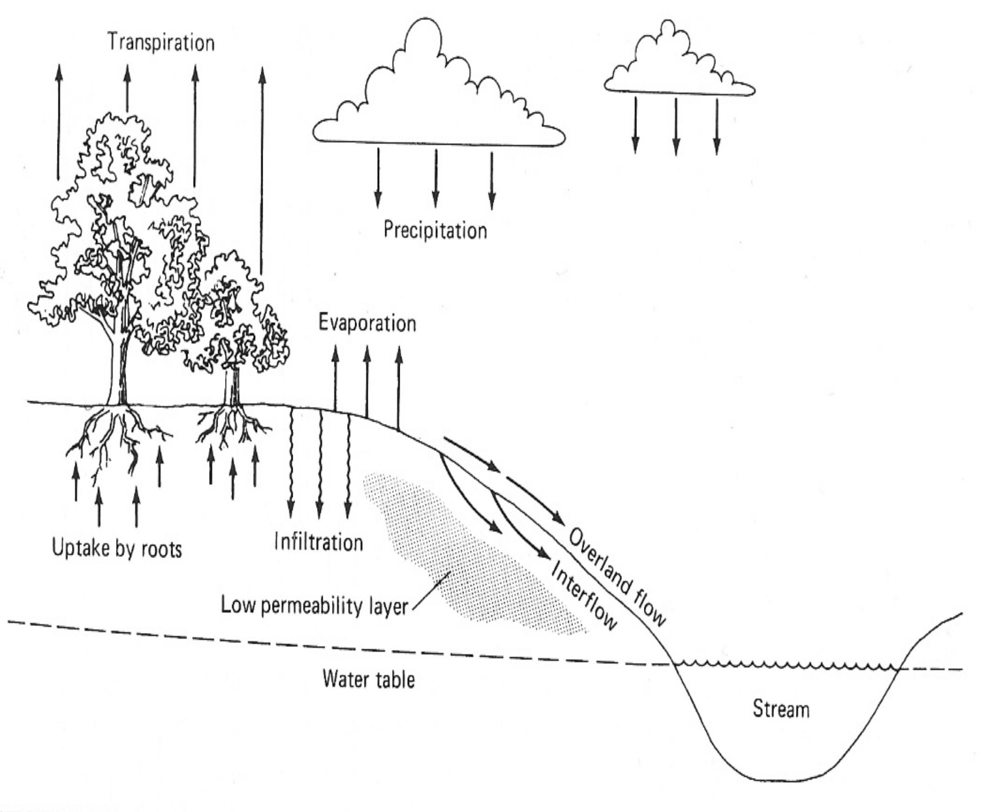


FIGURE 1-6 Near-surface hydrologic processes.

- When it rains, the water table can change dramatically.
- The flow of a stream will increase during/after a storm even though there is little runoff.
  - In this model, the stream represents area where the land is below the water table.
  - Increased stream discharge- should be intuitively obvious why...
    - Rain percolates down and raises the level of the water table.
    - 2 cm rainfall may percolate quickly and dramatically change the level of the water table by about 50 cm! This is because the zone above the saturated zone is not totally devoid of water- only some of the void spaces have to be filled in (ie capillary fringe may be 90% full).

http://www.largest.org/c0d3/image_gimme.cgi?i=968

Change in the water table → increase in the flow of the stream.

- Therefore, the slope of the water table has a direct effect on flow of water.
  - In a flat water table the water wouldn't flow, so must have some gradient to drive the flow therefore need slope.

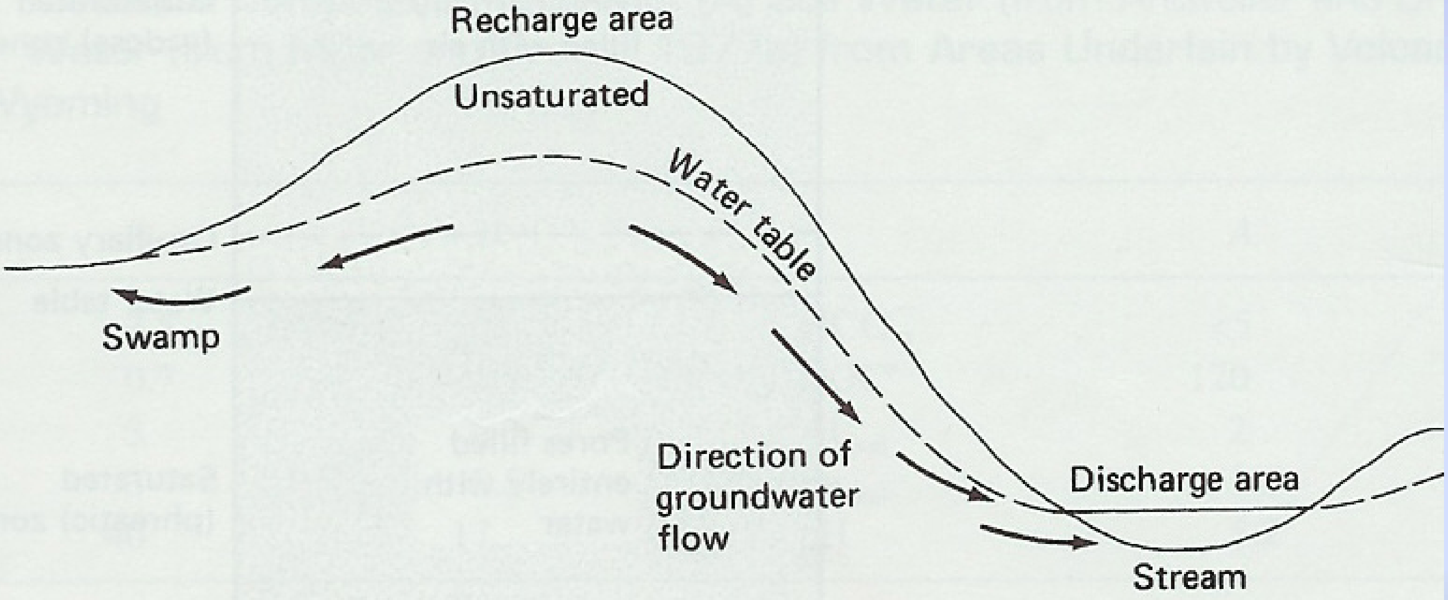


FIGURE 1-9 Groundwater system in a uniform, permeable rock.

Drever, *The Geochemistry of Natural Waters*

Water 'box'(Weir) constructed to monitor flow.

- During rain events, the flow increases.
- But the water transported is not just the water from the precipitation event but rather water in the subsurface.

→ How does the water flow through the subsurface?

* Need to look at tools to measure flow and factors controlling flow.

- Flow is driven by gradient : height /length ($\Delta h/\Delta l$) of the water table
- The medium the water flows through also has an effect on the flow.

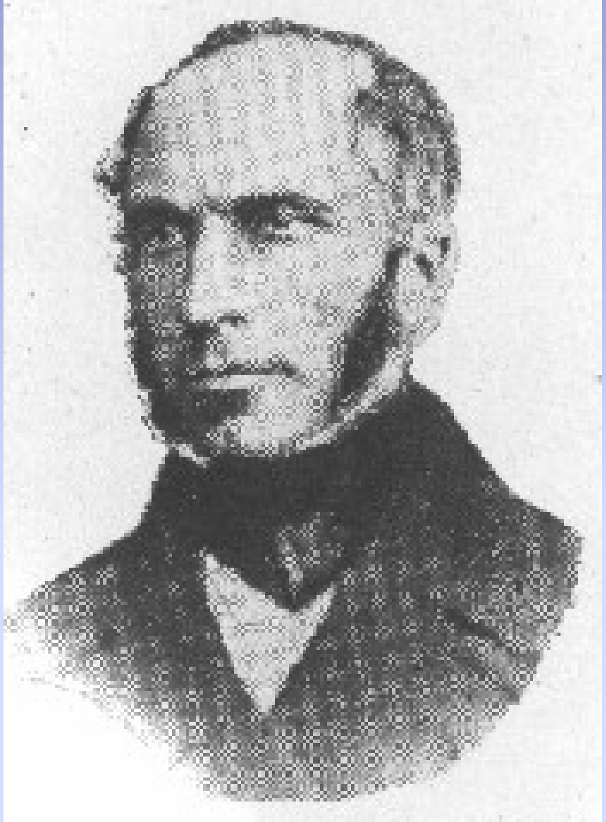
➔ The implications of these observations lead to…

DARCY’S LAW

Background

In 1856, Darcy was the 1st to do experiments with water flow through a tube to see how rapidly it flowed & what the controlling factors were.

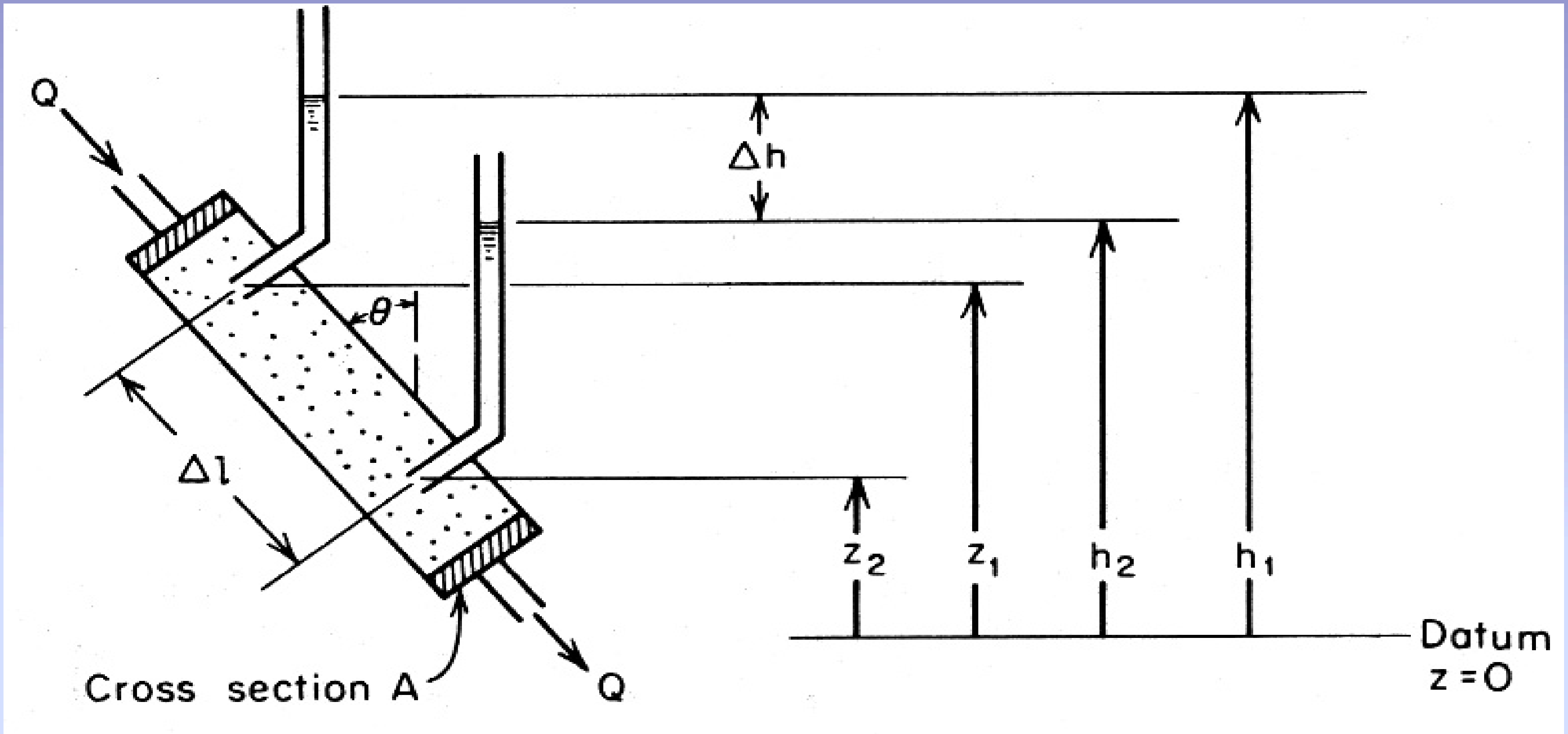
Question of interest: What determines the rate of discharge?



Henry Darcy (1803-1858)

http://www.edge.ou.edu/hydrogeology/page8.html

Experimental Apparatus for illustrating Darcy’s Law



$Q = -KA((h_1-h_2)/L)$,where:

Q = volumetric discharge rate (L^3/T)
K = proportionality constant = hydraulic conductivity (L/T)
A = cross sectional area through which flow occurs (L^2)
h_1-h_2 = difference in hydraulic head over the flow distance (L)
L = distance through which flow occurs (L)

http://www.rses.anu.edu.au/~uli/Teaching/Hydro/Berno_Darcy.html

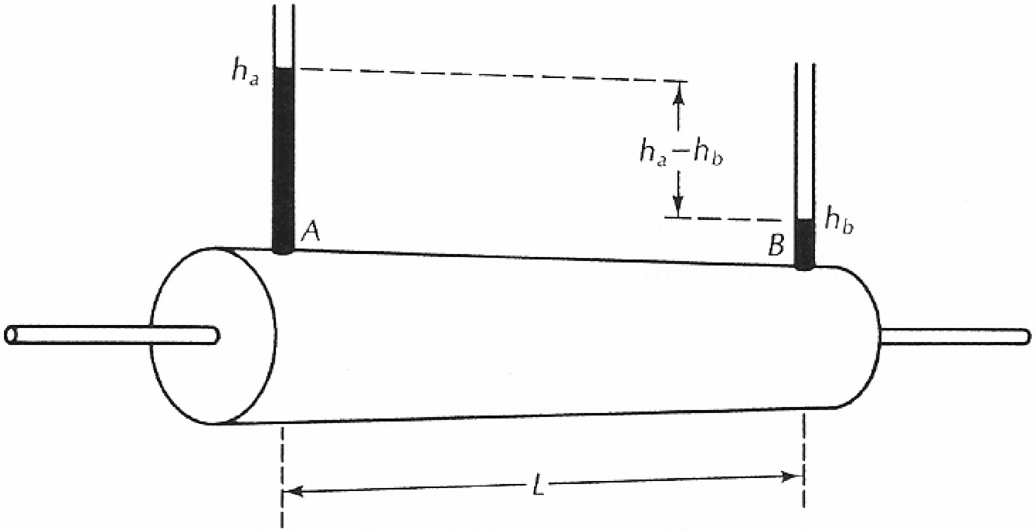
Darcy's Findings

A. rate of discharge (Q) was:

1. proportional to change in height **Δh and change in length Δl.**

→ **therefore, Q is proportional to the gradient Δh/ Δl**

2. **a function of the cross-sectional area (A).**
3. **a function of the constant hydraulic conductivity (K) which varied with the medium.**



▲ FIGURE 3.12
Horizontal pipe filled with sand to demonstrate Darcy's experiment. (Darcy's original equipment was actually vertically oriented.)

Fetter, *Applied Hydrogeology 4th Edition*

Darcy's Law

***B. Formula*:**

Q (flux) = $-K_iA(dh/dl) = K*A*(l_1-l_0)/x$ for a pipe

1. Q is negative because we're going from a higher to lower potential → (dh is negative ∴ Q is negative).

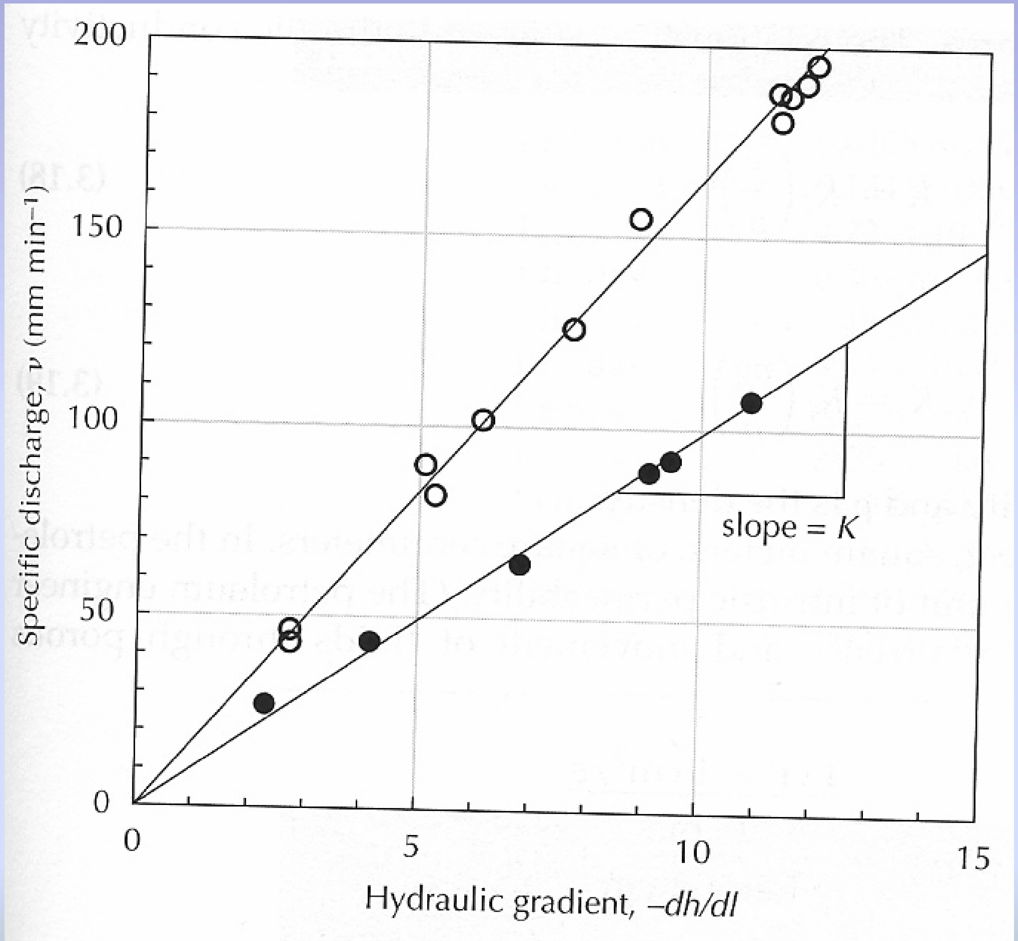


Figure 3.13 Original data from Darcy's 1856 experiments that show a linear relationship between specific discharge and hydraulic gradient for two different sands.

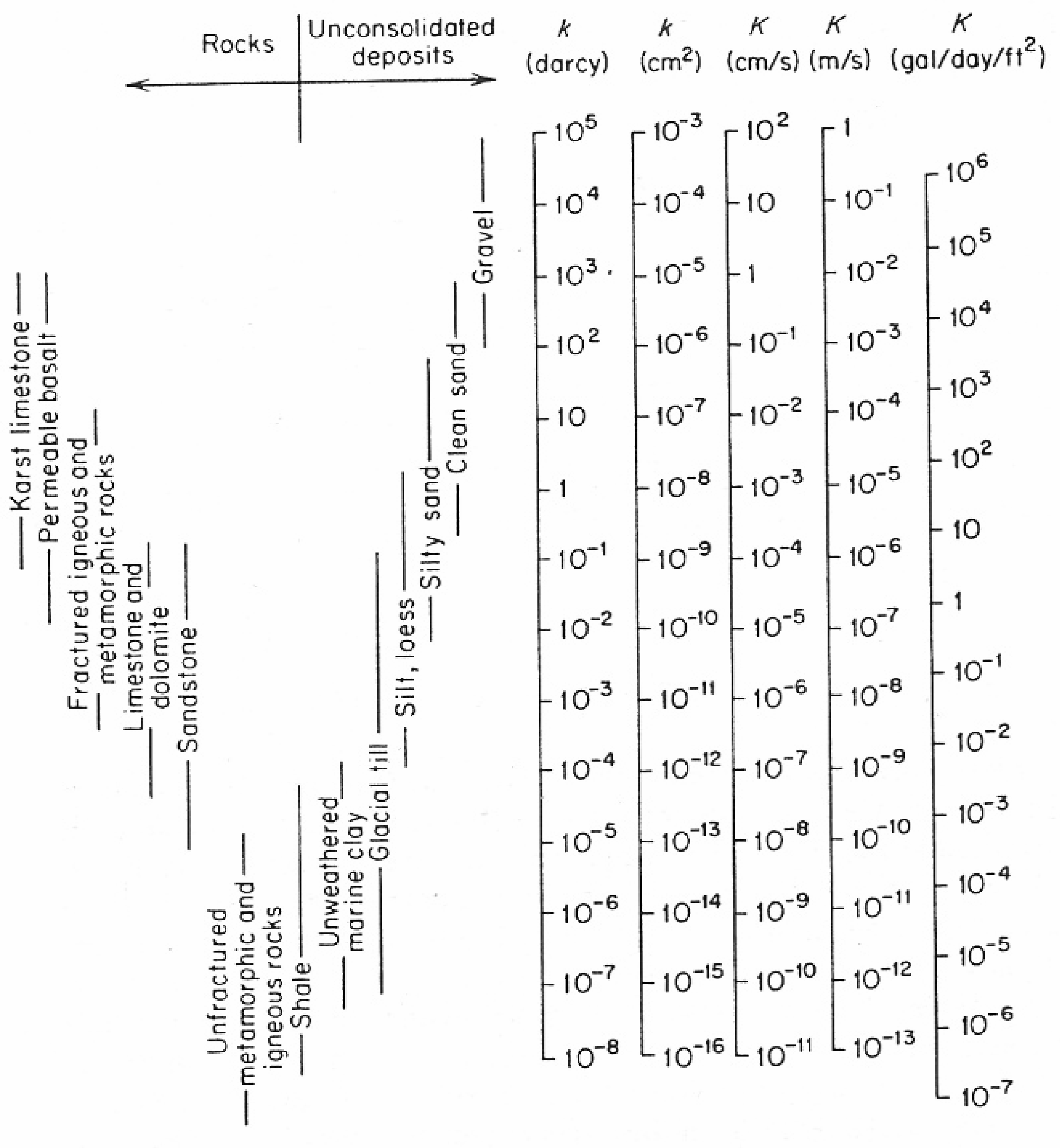
Fetter, *Applied Hydrogeology 4th Edition*

2. **K typically equals the hydraulic conductivity of the medium**(cm/sec), as given in Fetter for sand, silt, & clay

→There is a huge range in how rapidly a certain medium will conduct water – by ≈ 5 orders of magnitude!

http://fbe.uwe.ac.uk/public/geocal/SoilMech/water/water.htm#>PERMSTRAT

Range of Values of Hydraulic Conductivity and Permeability



Freeze and Cherry, *Groundwater,* Ch. 2, Table 2.2

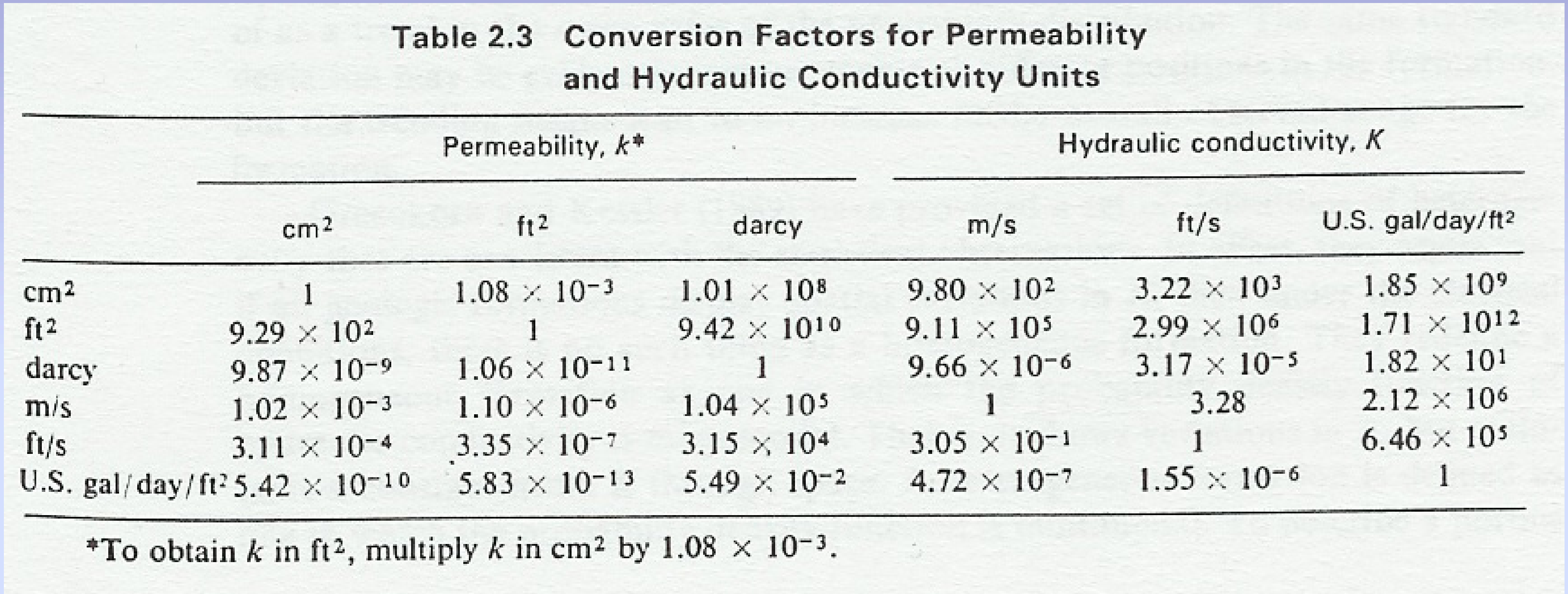


Table 2.3 Conversion Factors for Permeability and Hydraulic Conductivity Units

	Permeability, k*			Hydraulic conductivity, K		
	cm^2	ft^2	darcy	m/s	ft/s	U.S. gal/day/ft^2
cm^2	1	1.08×10^{-3}	1.01×10^{8}	9.80×10^{2}	3.22×10^{3}	1.85×10^{9}
ft^2	9.29×10^{2}	1	9.42×10^{10}	9.11×10^{5}	2.99×10^{6}	1.71×10^{12}
darcy	9.87×10^{-9}	1.06×10^{-11}	1	9.66×10^{-6}	3.17×10^{-5}	1.82×10^{1}
m/s	1.02×10^{-3}	1.10×10^{-6}	1.04×10^{5}	1	3.28	2.12×10^{6}
ft/s	3.11×10^{-4}	3.35×10^{-7}	3.15×10^{4}	3.05×10^{-1}	1	6.46×10^{5}
U.S. gal/day/ft^2	5.42×10^{-10}	5.83×10^{-13}	5.49×10^{-2}	4.72×10^{-7}	1.55×10^{-6}	1

*To obtain k in ft^2, multiply k in cm^2 by 1.08×10^{-3}.

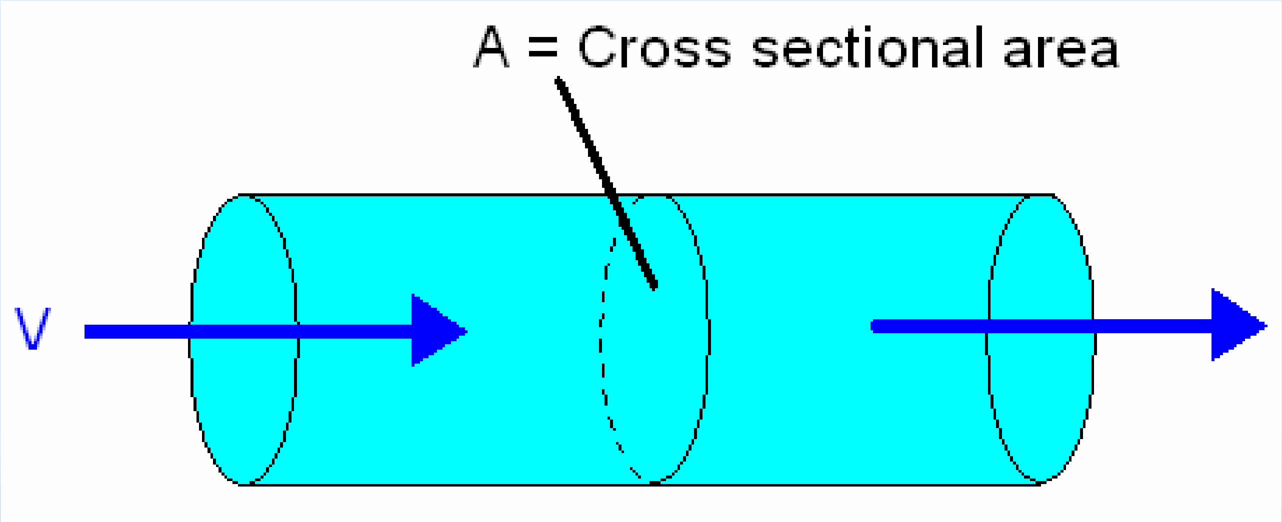
Freeze and Cherry, *Groundwater,* Ch. 2

FLOW:

In a pipe:

$Q = VA \rightarrow V = Q/A$

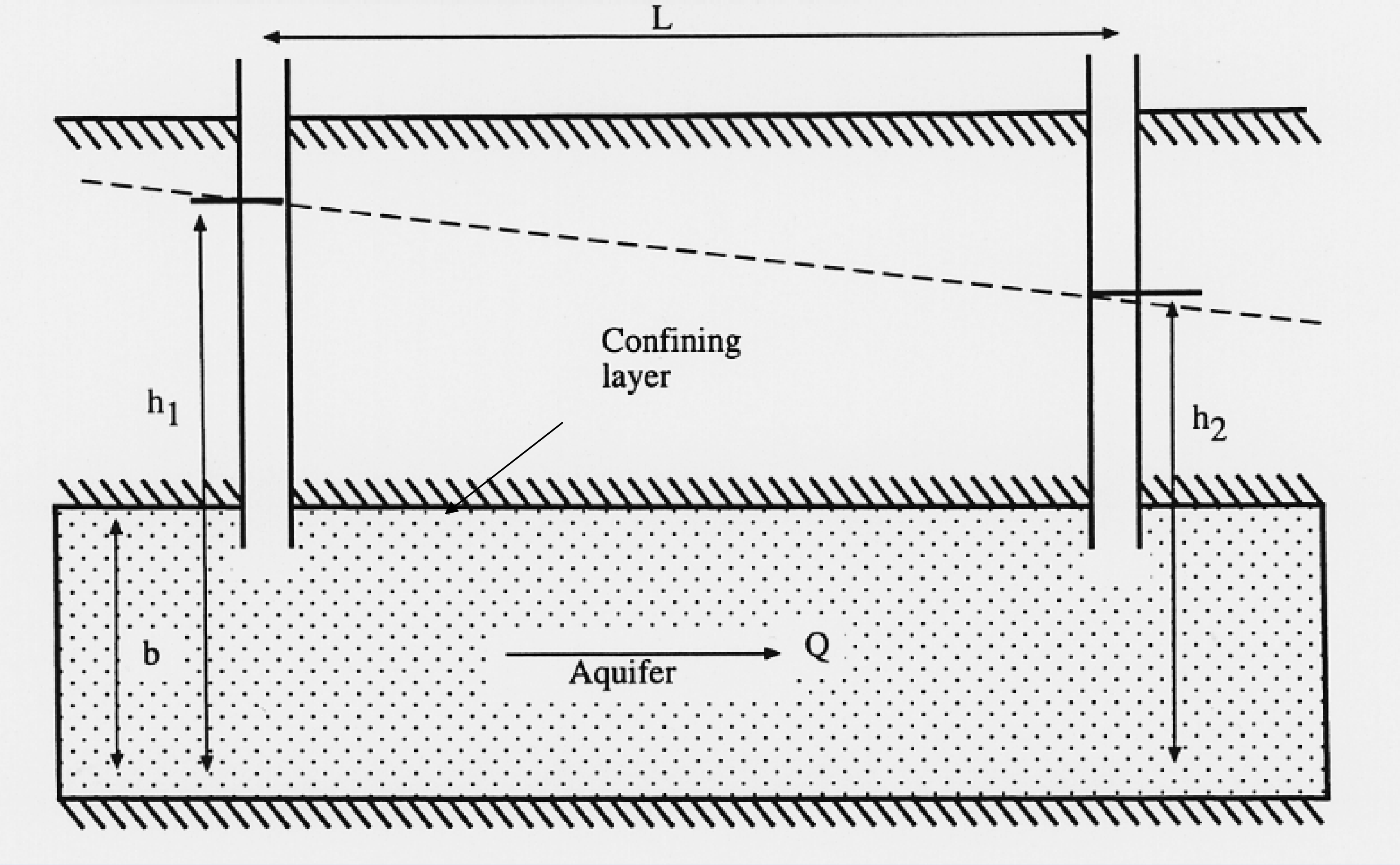
V = Velocity   A = Cross Section



In the ground:

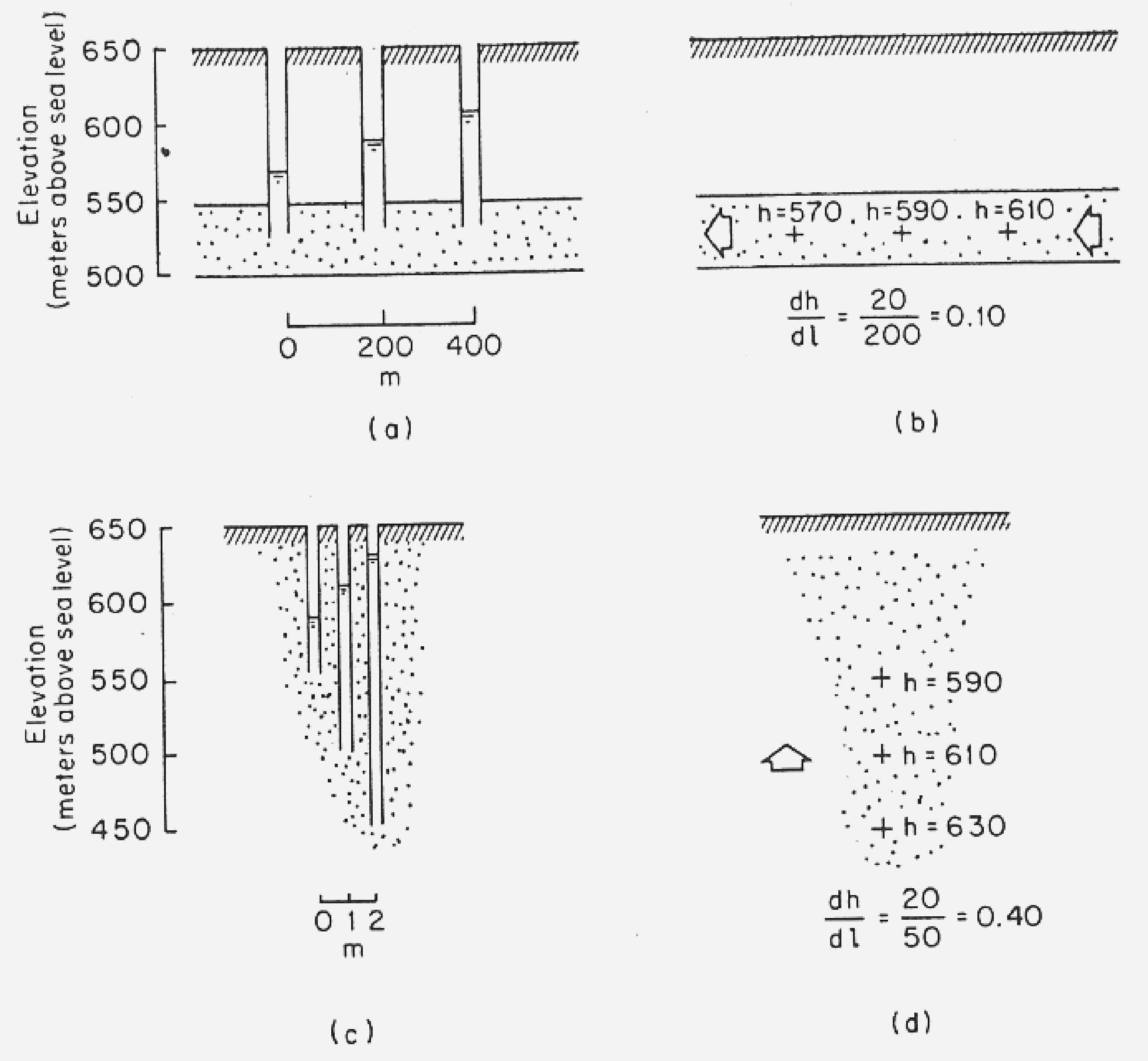
$$V_x = \frac{Q}{A*R} = (k/\eta)\frac{\Delta h}{\Delta l}$$

- where η = porosity
- k is the conductivity
- gradients ($\Delta h/\Delta l$) are typically .0001 → .01(max)



http://jan.ucc.nau.edu/~doetqp-p/courses/env302/lec16/16fig2.gif

Determination of hydraulic gradients from piezometer installations.



$$\frac{dh}{dl} = \frac{20}{200} = 0.10$$

$$\frac{dh}{dl} = \frac{20}{50} = 0.40$$

Freeze and Cherry, Figure 2.6

Steady flow through an unconfined aquifer resting on a horizontal impervious surface

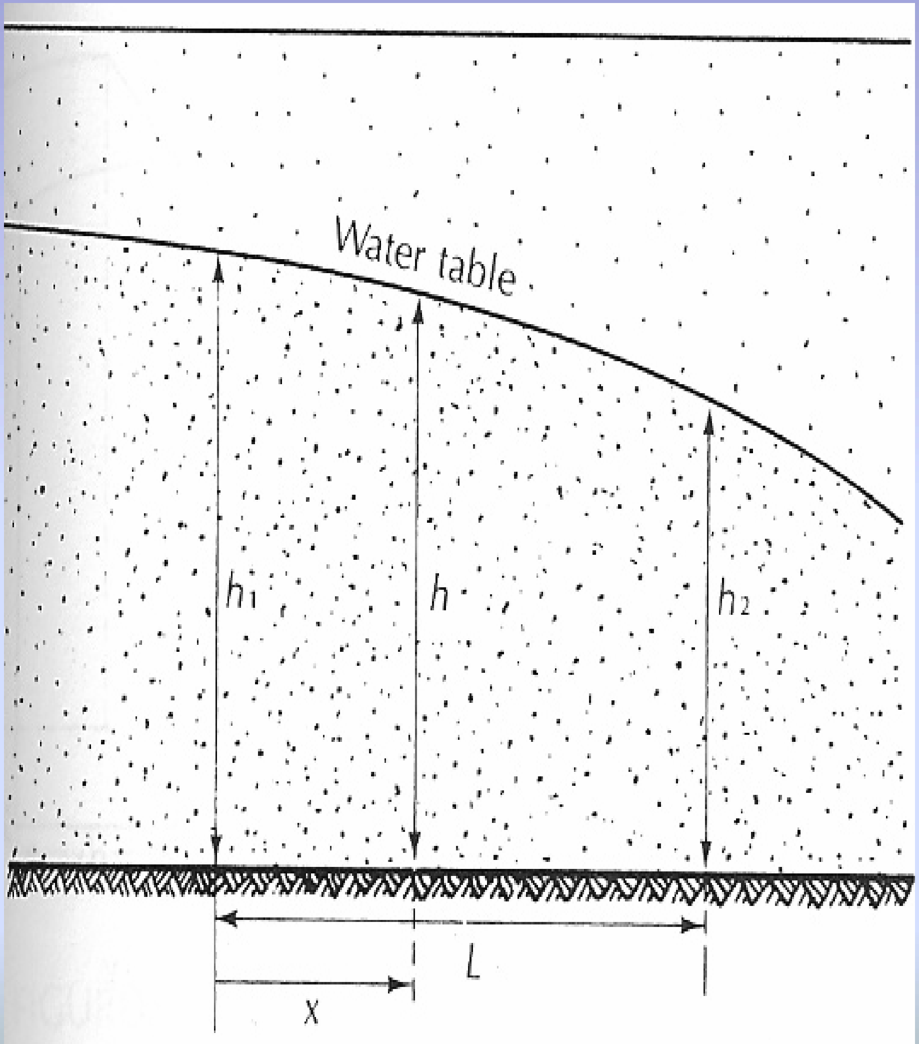


Figure 4.17. Fetter, *Applied Hydrogeology 4th Edition*

Steady flow through a confined aquifer of uniform thickness

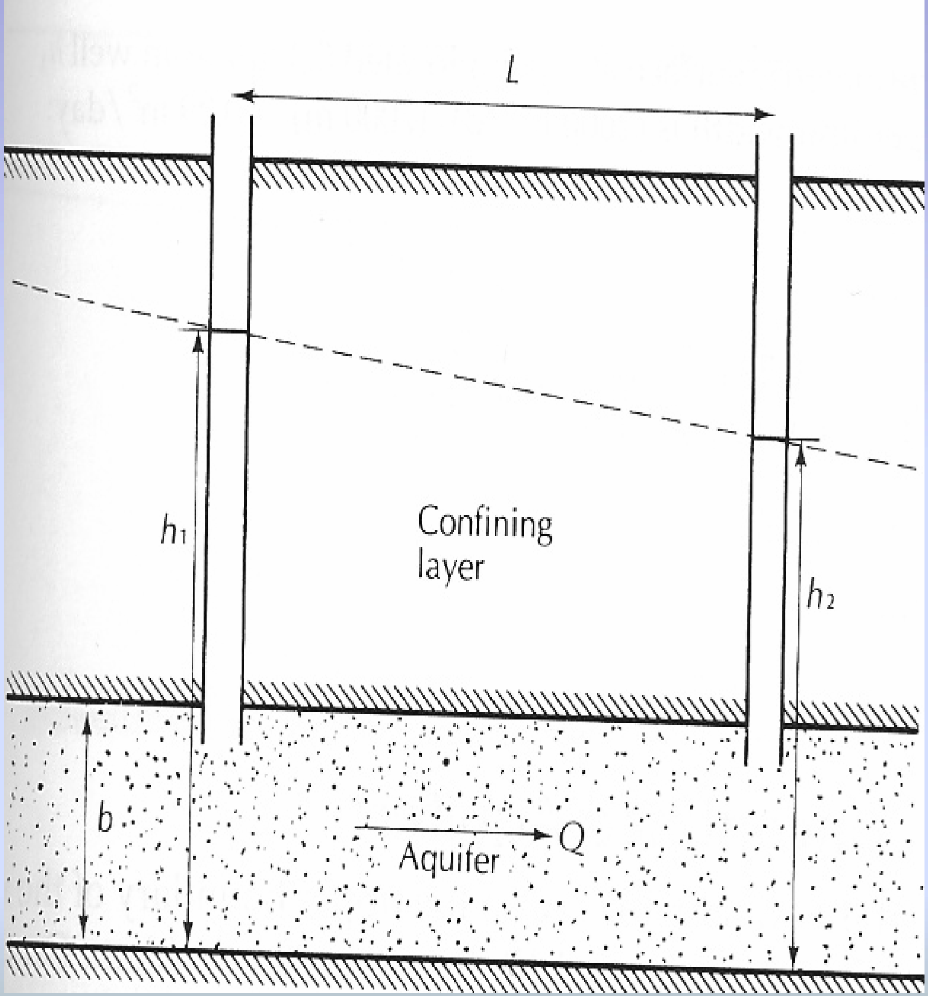


Figure 4.16. Fetter, *Applied Hydrogeology 4th Edition*

→Equation that governs fluid flows are fairly straight forward. Only rigorous in interpretation and when in 3 dimensions.

→Essentially, the velocity will depend on the hydraulic conductivity; therefore need to establish the hydraulic conductivity of the medium which is typically performed with a variety of aquifer testing (e.g. slug tests) or laboratory testing (permeameter)

→Transport will depend on the hydraulic gradient – established from well observations