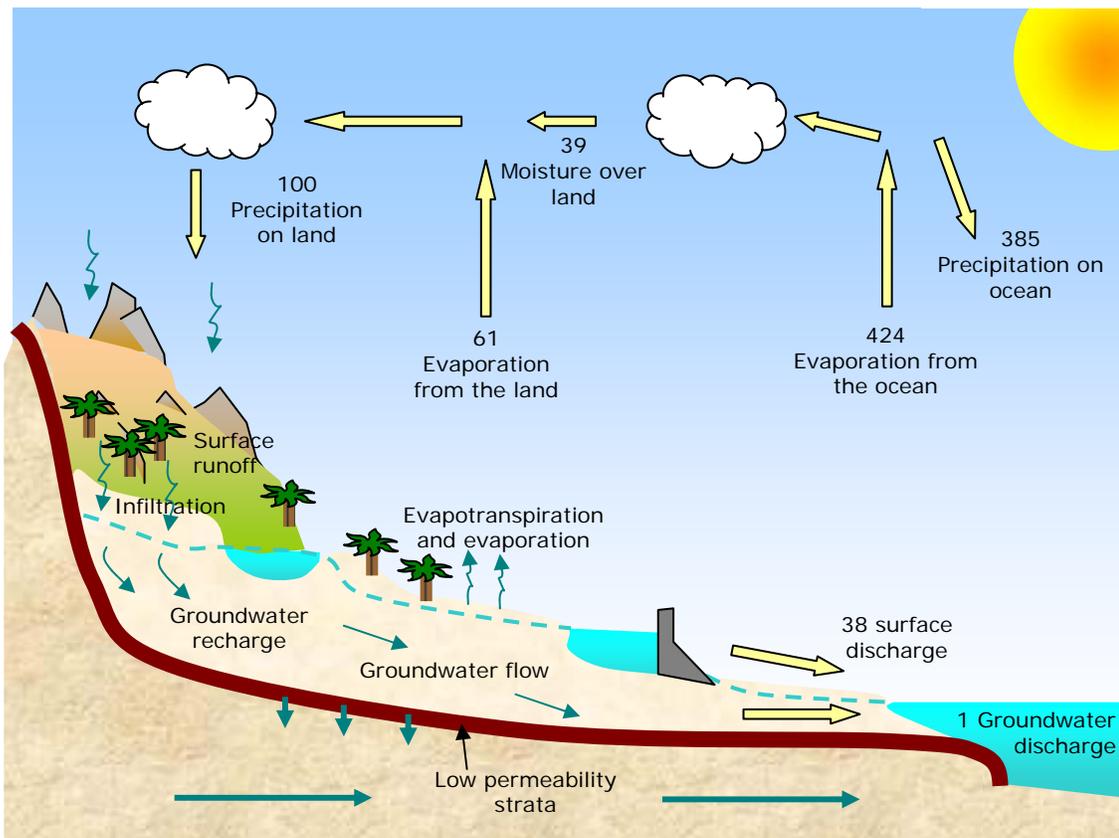


Lecture Packet #1: Course Introduction, Water Balance Equation

Where does water come from?

It cycles. The total supply doesn't change much.



Hydrologic cycle with yearly flow volumes based on annual surface precipitation on earth, ~119,000 km³/year.

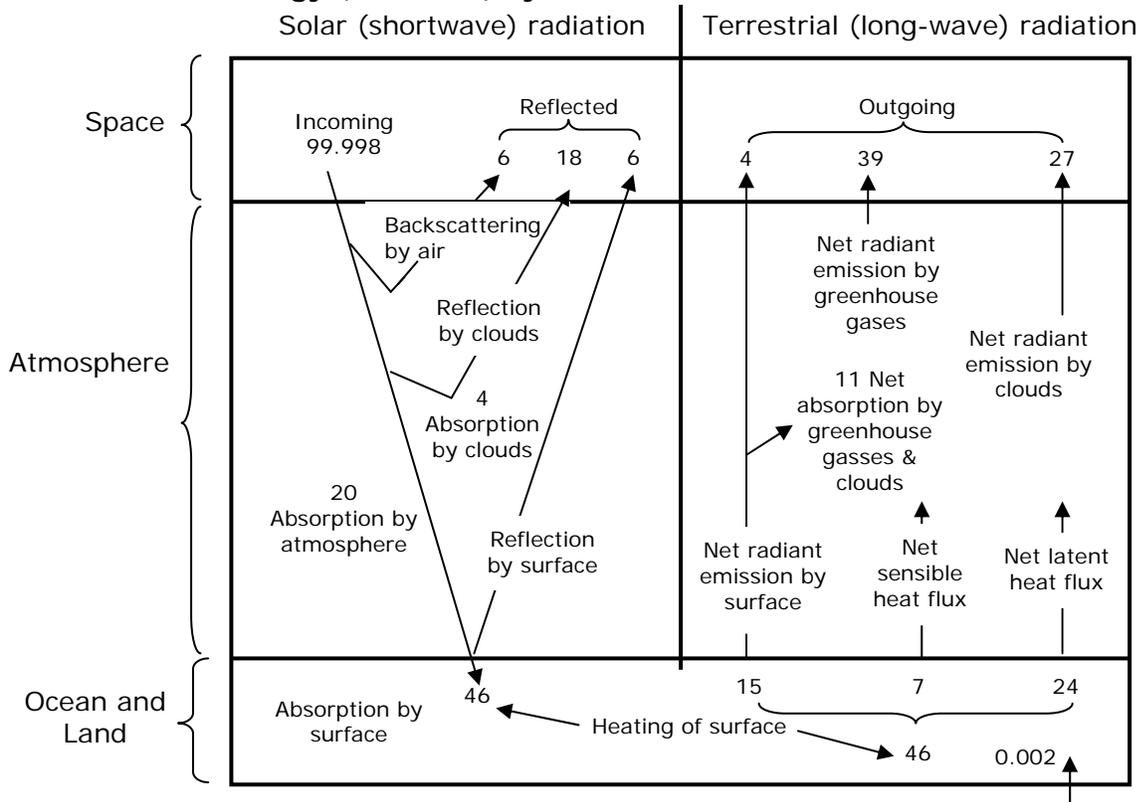
3000 BC – Ecclesiastes 1:7 (Solomon)

“All the rivers run into the sea; yet the sea is not full; unto the place from whence the rivers come, thither they return again.”

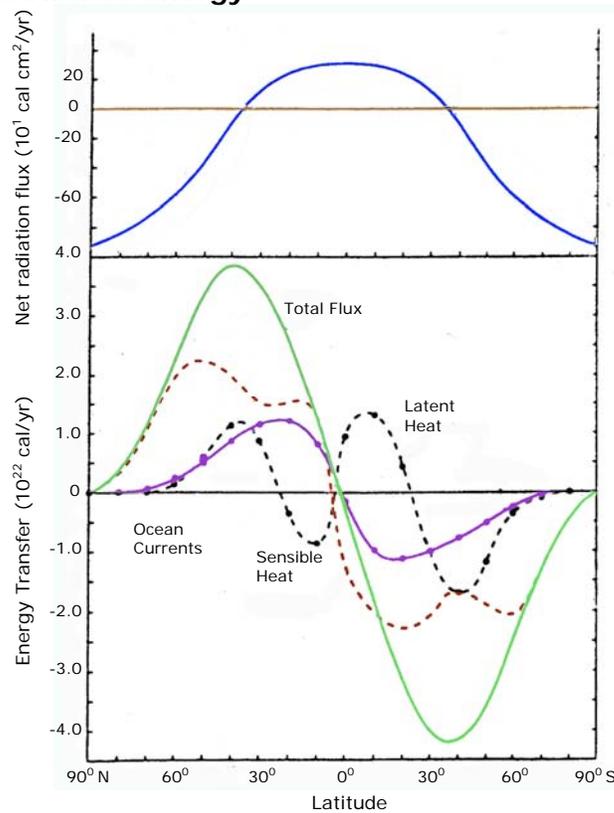
Greek Philosophers (Plato, Aristotle) embraced the concept, but mechanisms were not understood.

17th Century – Pierre Perrault showed that rainfall was sufficient to explain flow of the Seine.

The earth's energy (radiation) cycle

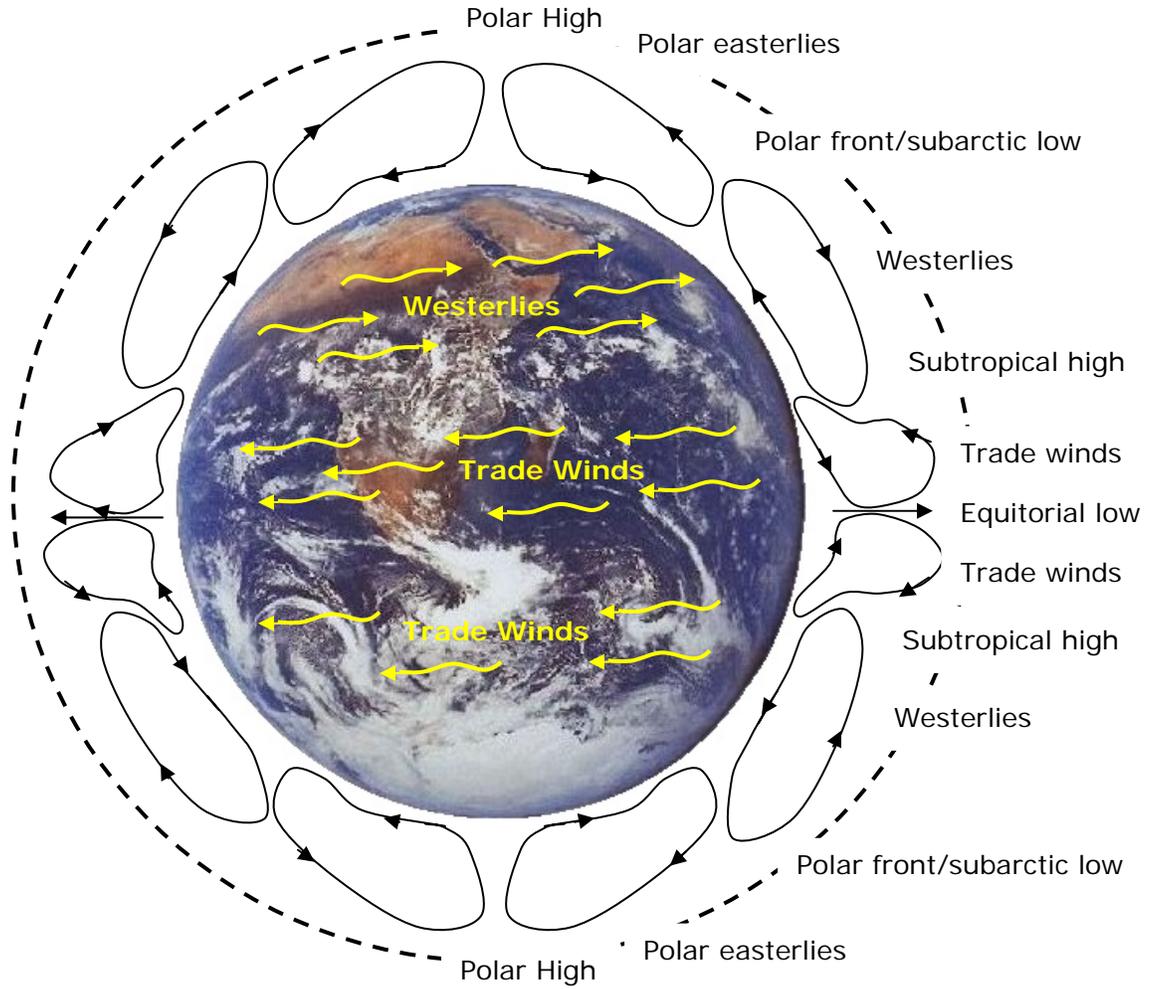


Circulation redistributes energy

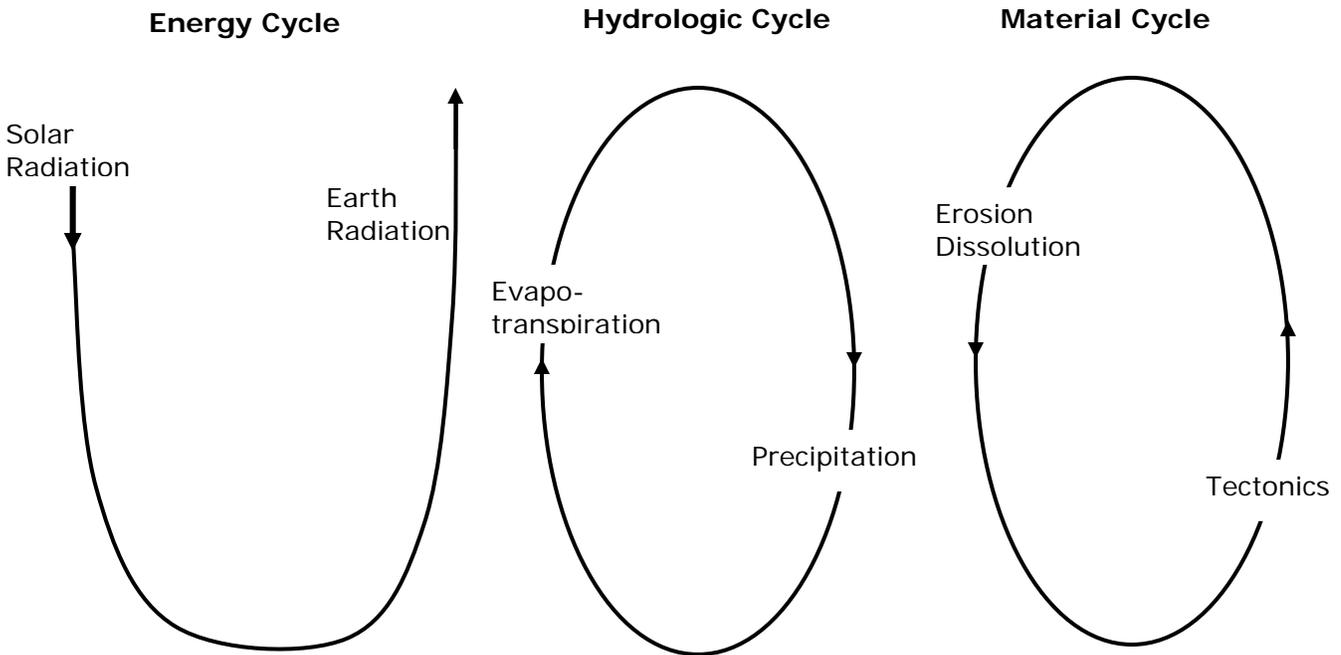


The Earth's Energy (Radiation) Cycle:

Spatial distribution of energy and temperature drives circulation – both global and local:



Coupled Earth Cycles

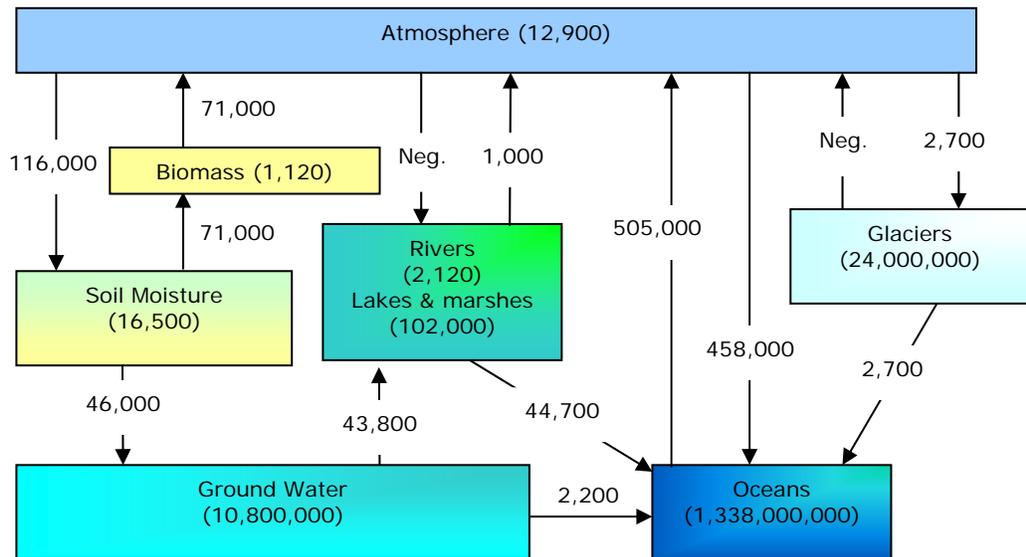


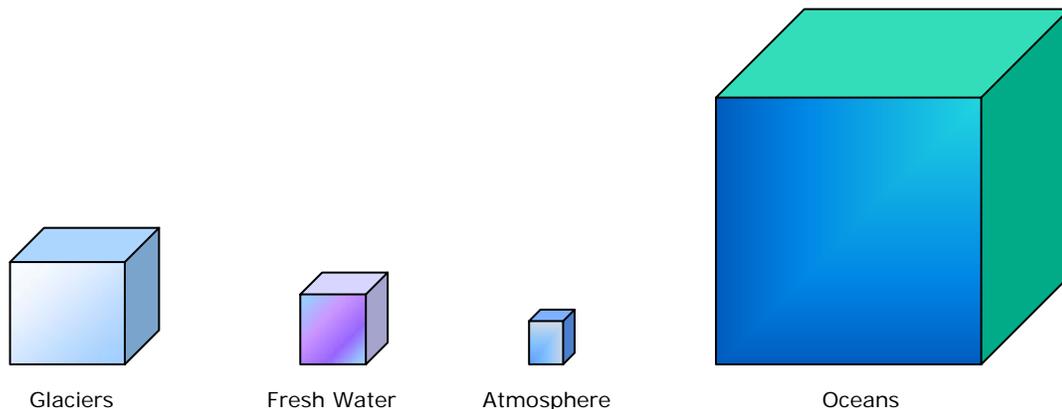
Estimates from river outflows indicate 17×10^9 Tons/Year of material is transported into the Ocean. Another 2 or 3×10^9 Tons/Year is trapped in reservoirs.

80% of material transported is particulate
20% is dissolved

0.05 mm/yr (may have been accelerated by man, and actual rates may be much larger)

Local rates depend on relief, precipitation, and rock type.





Relative volumes of water in glaciers, fresh water, atmosphere and oceans.

Estimate of the World Water Balance

Parameter	Surface area (km ²) X 10 ⁶	Volume (km ³) X 10 ⁶	Volume %	Equivalent depth (m)	Residence Time
Oceans and seas	361	1370	94	2500	~4000 years
Lakes and reservoirs	1.55	0.13	<0.01	0.25	~10 years
Swamps	<0.1	<0.01	<0.01	0.007	1-10 years
River channels	<0.1	<0.01	<0.01	0.003	~2 weeks
Soil moisture	130	0.07	<0.01	0.13	2 weeks – 1 year
Groundwater	130	60	4	120	2 weeks – 10,000 years
Icecaps and glaciers	17.8	30	2	60	10-1000 years
Atmospheric water	504	0.01	<0.01	0.025	~10 days
Biospheric water	<0.1	<0.01	<0.01	0.001	~1 week

Amazon is 6,000 km³/yr (~5x more than Zaire-Congo)
0.0003% is potable and available.

What are water needs for humans?

Primitive conditions – 3 to 5 gallons/day
Urban use – 150 gallons/day
US Fresh Water Use – 1,340 gallons/day

Where does the water go? To make things...to clean things....

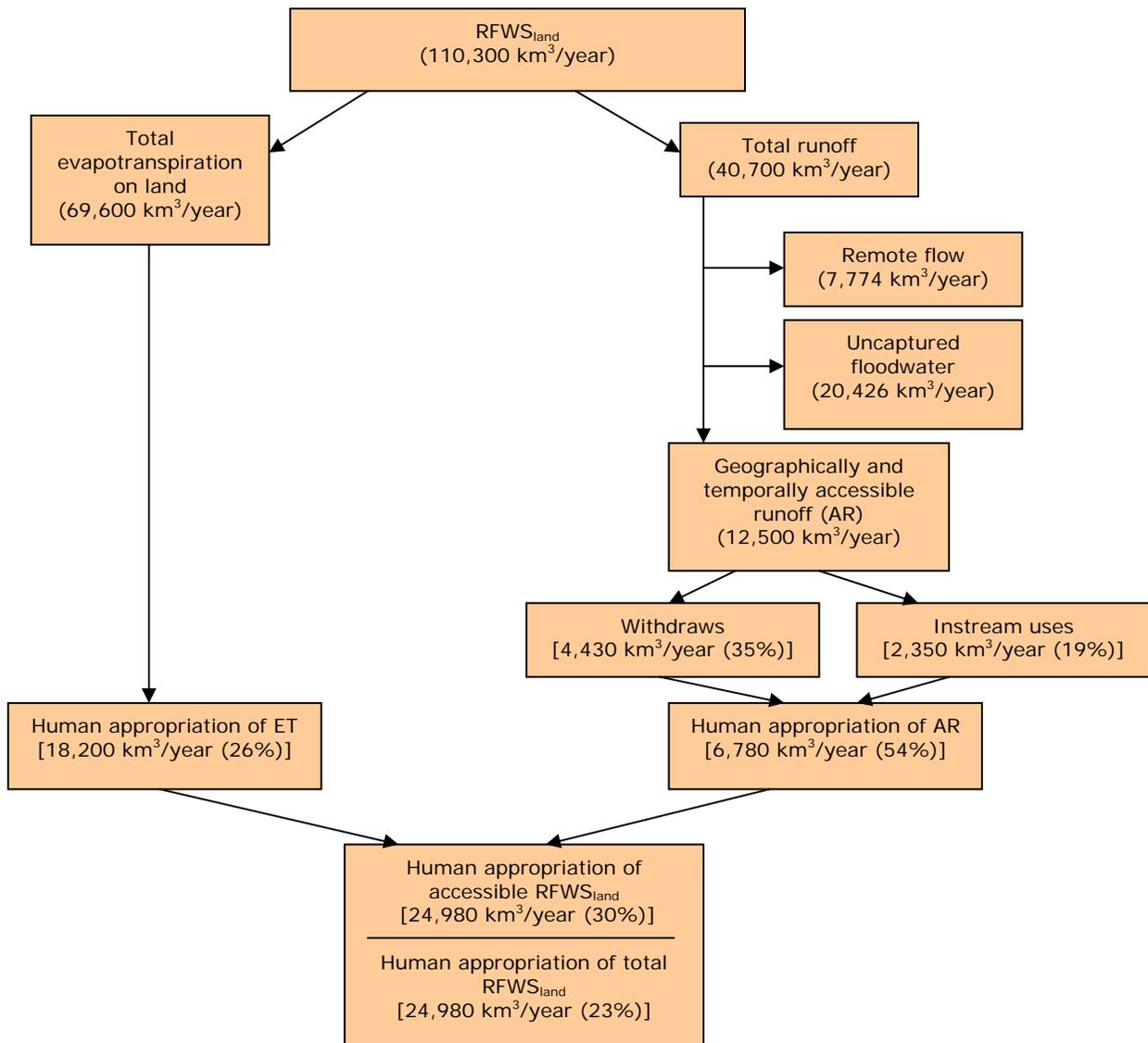
Item	Gallons
1 pound of cotton	2,000
1 pound of grain-fed beef	800
1 loaf of bread	150
1 car	100,000
1 kilowatt of electricity	80
1 pound of rubber	100
1 pound of steel	25
1 gallon of gasoline	10
1 load of laundry	60
1 ten-minute shower	25-50

Some points:

- A lot of water is used for agriculture
 - 56% (76 BGD) is consumptive use
 - 20% (28 BGD) is lost in conveyance
 - 24% (33 BGD) is return flow
- A lot of water is used for thermoelectric power generation
 - 87% of all industrial water use
- A small savings in either of these categories would free up significant quantities for public supplies

Water Use in the US in 1990

Fresh Water Use 1990 Total 339 BGD	
California	35.1
Texas	20.1
Idaho	19.7
Illinois	18.0
Colorado	12.7
Louisiana	11.7
Michigan	11.6
New York	10.5
Pennsylvania	9.8
Indiana	9.4
Montana	9.3
Four states account for 27%	
11 states account for 50%	



Analysis of human appropriation of renewable freshwater supply (RFSW) on land. *Figure adapted from Postel et al., Science, (271) p. 758, Feb. 9, 1996*

Postel et al.'s Calculations

- 1) Calculation of appropriated ET – indirect
 - 132 billion tons of biomass produced a year (Vitousek, 1992).
 - 30% used by people.
 - Approximate people's use of ET from the proportion of biomass – 30%.
 - Subtract agricultural irrigation (2,000 km³/year) and assume half the water from parks and lawns is irrigation (80 km³/year).
- 2) Inaccessible runoff
 - 95 of the Amazon, Half of the Zaire-Congo and all of the Polar rivers 7774 .km³/year (did not consider other northern rivers – conservative?).
 - Flood water. 11,100 km³/year of runoff is base flow (6).
 - Capacity of man-made reservoirs is 5,500 km³/year.
 - Accessible runoff = Baseflow + reservoir capacity = 12,500.

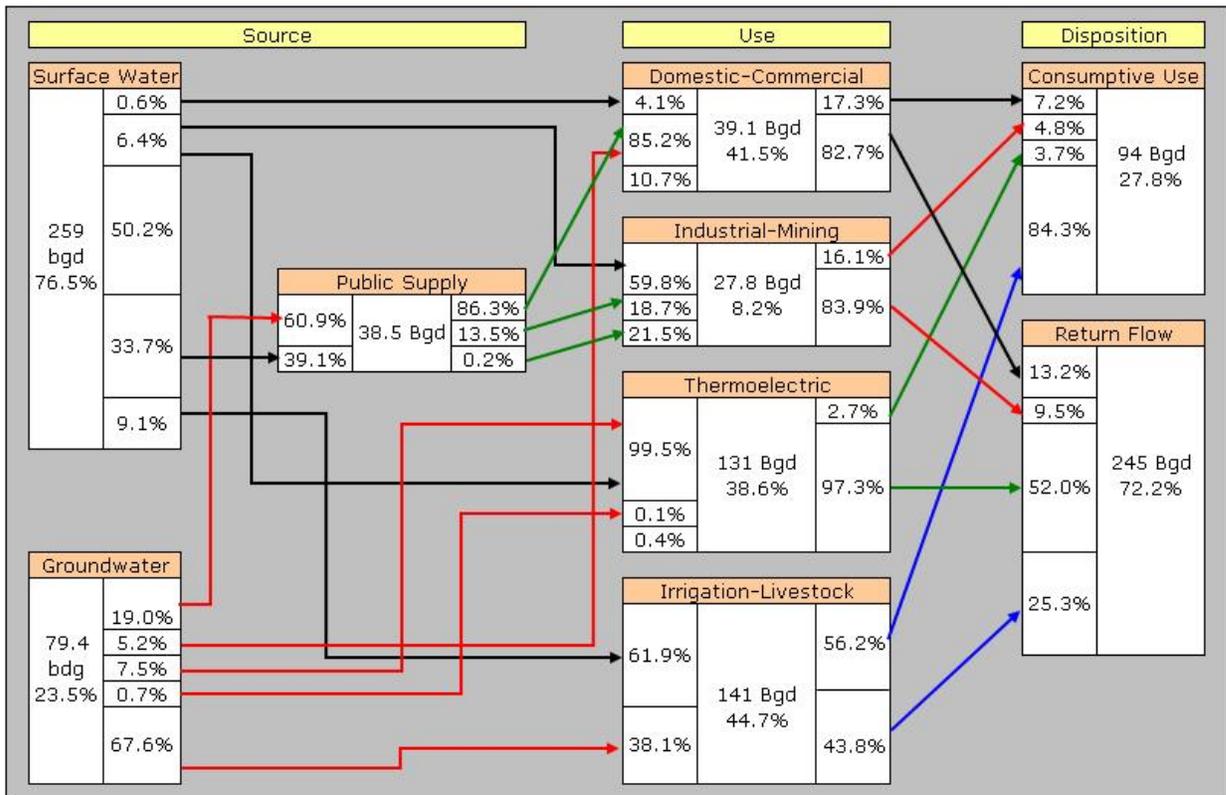
← adjusted for accessible

3) Withdrawals (consumed)

- 12,000 m³/ha average irrigation water application.
- 240,000,000 ha of world irrigated area.
- 2,880 km³/year.
- 65% consumed = 1,870 km³/year.
- Industrial use: 975 km³/year, 9% consumed, 90 km³/year.
- Municipal use: 300 km³/year, 17% consumed, 50 km³/year.
- Reservoir losses – 5% loss, 275 km³/year.
- Total consumed = 2,285 km³/year.

4) Instream use

- 28.3 L/s per 1,000 population, applied to 1990 population, 4,700 km³/year.
- Assuming 50% of waste gets treatment – 2,350 km³/year.
- Neglects dispersed pollution (agricultural) and flood waters.



Estimated water use in the United States, billion gallons per day (bgd), for domestic and commercial purposes. Adapted from Solley, Pierce, and Perlman, 1993.

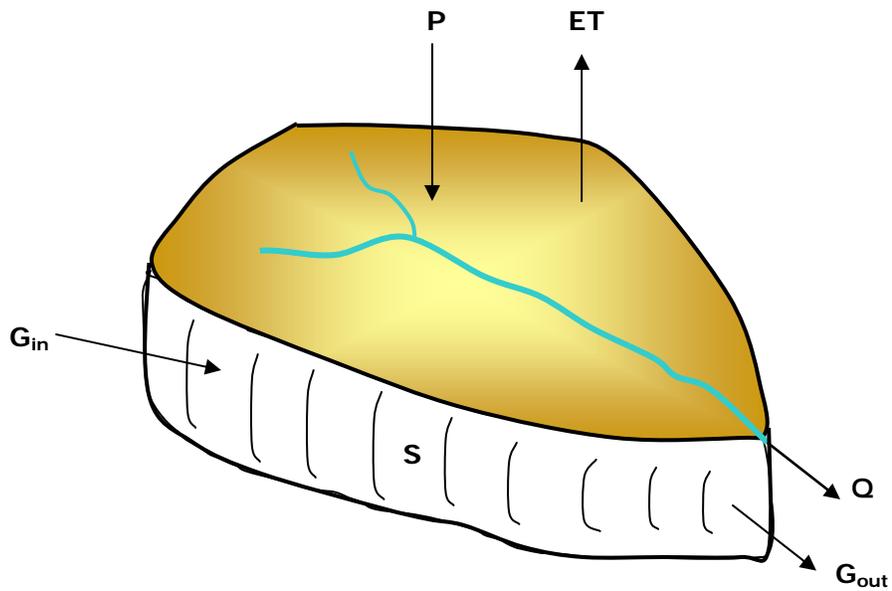
Relative Merits of Surface and Subsurface Reservoirs

Surface Reservoirs	Subsurface Reservoirs
Disadvantages	Advantages
Few new sites free (in USA)	Many large-capacity sites available
High evaporative loss, even where humid climate prevails	Practically no evaporative loss
Need large areas of land	Need very small areas of land
May fail catastrophically	Practically no danger of failure
Varying water temperature	Water temperature uniform
Easily polluted	Usually high biological purity, although pollution can occur
Easily contaminated by radioactive fallout	Not rapidly contaminated by radioactive fallout
Water must be conveyed	Act as conveyance systems, thus obviating the need for pipes or canals

Watershed Hydrologic Budgets

Delineation of a watershed (drainage basin, river basin, catchment)

- Area that topographically appears to contribute all the water that flows through a given cross section of a stream. In other words, the area over which water flowing along the surface will eventually reach the stream, upstream of the cross-section.
- Horizontal projection of this area is the drainage area.
- The boundaries of a watershed are called a divide, and can be traced on a topographic map by starting at the location of the stream cross-section then drawing a line away from the stream that intersects all contour lines at right angles. If you do this right, the lines drawn from both sides of the stream should intersect. Moving to either side



Water Balance Equation

$$\frac{\partial S}{\partial t} = P + G_{in} - (Q + ET + G_{out})$$

At steady-state: $\frac{\partial S}{\partial t} = 0$

$$P + G_{in} = (Q + ET + G_{out})$$

↑
↑

Hydrologic Production
Runoff, or Hydrologic Circulation

Q and P are the only quantities that we can try to measure directly. If steady state is assumed, these measurements can be used to calibrate models of evapotranspiration and groundwater flow.

From an engineering point of view we are interested in understanding what controls Q.

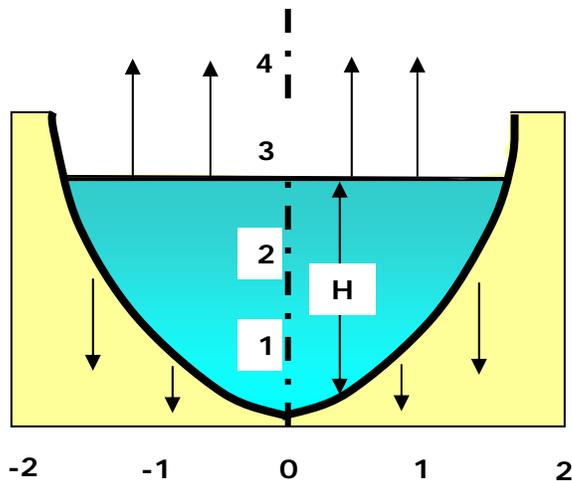
$$Q = P + (G_{in} - G_{out}) - ET$$

How much of Q is available to human use?

How can we increase Q?

Lake Parabola

(A simple quadratic model of the cross section of a circular lake)



$$H = cr^2$$

$$A = \pi r^2 = \frac{\pi}{c} H$$

$$V(H) = \int_0^H A(h) dh = \int_0^H \frac{\pi}{c} H dh = \frac{\pi}{2c} H^2$$

Discharge into Lake Parabola

If there is constant volume flux Q m³/day into the lake, how does the depth depend on time? (At time 0, the depth is H_o m)

Since there is no outflow, the change in storage must equal the inflow

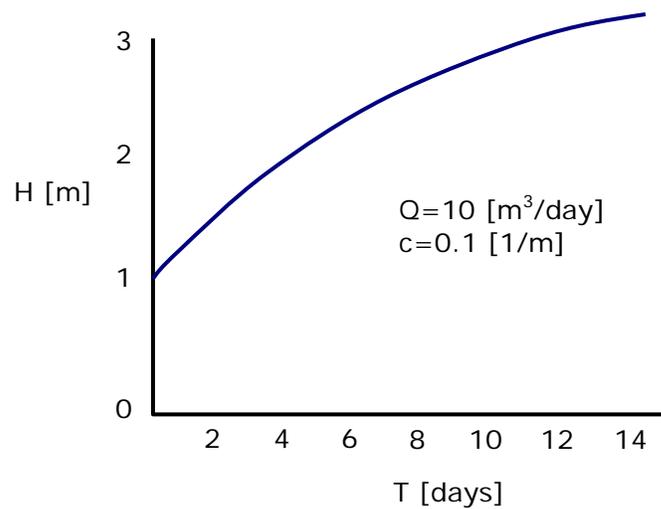
Mass-balance (water balance) equation

$$Q = \frac{dV(H)}{dt} = \frac{\pi}{2c} \frac{d(H^2)}{dt} = \frac{\pi}{c} H \frac{dH}{dt}$$

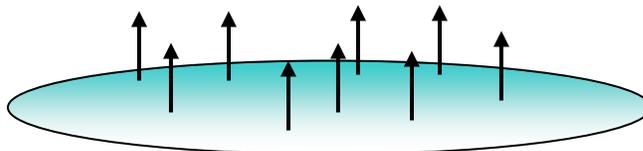
This differential equation can be solved by separation of variables

$$\int_0^T \frac{cQ}{\pi} dt = \int_{H_o}^H h dh$$

$$\frac{cQ}{\pi} T = \frac{H^2}{2} - \frac{H_o^2}{2} \qquad H = \sqrt{\frac{2cQ}{\pi} T + H_o^2}$$



Discharge into and Evaporation out of Lake Parabola

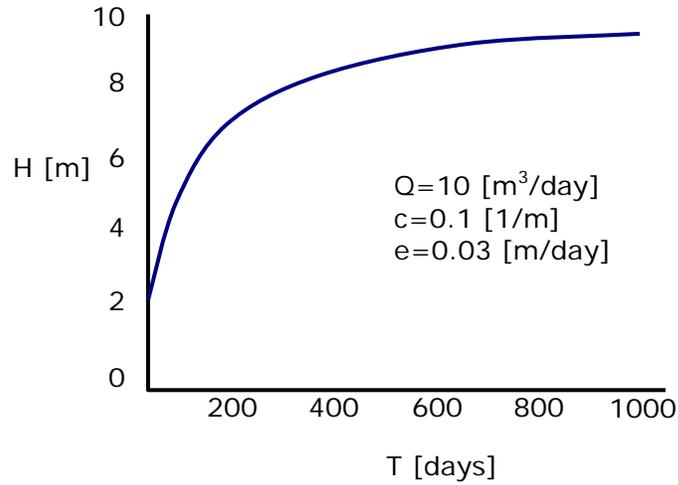


e = rate of evaporation [L/T]

$$\frac{dV(H)}{dt} = Q - Ae = Q - \frac{\pi}{c} He$$

$$\frac{\pi}{c} H \frac{dH}{dt} = Q - \frac{\pi}{c} He$$

$$\frac{dH}{dt} = \frac{Qc}{\pi H} - e$$

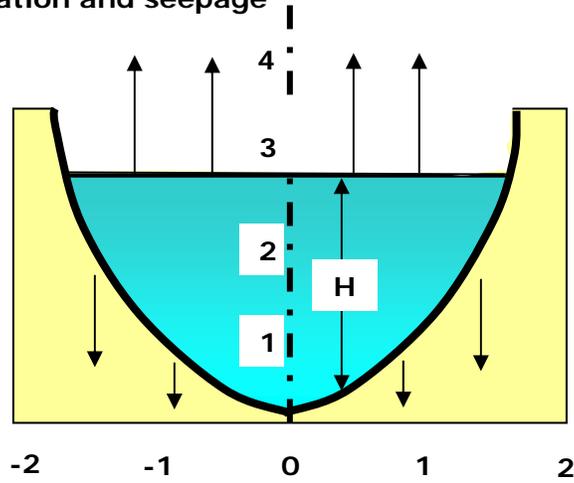


Steady State Solution

~~$$\frac{dH}{dt} = \frac{Qc}{\pi H} - e$$~~

$$H = \frac{Qc}{\pi e} = \frac{(10)(0.1)}{\pi(0.03)} = 10.6 \text{ m}$$

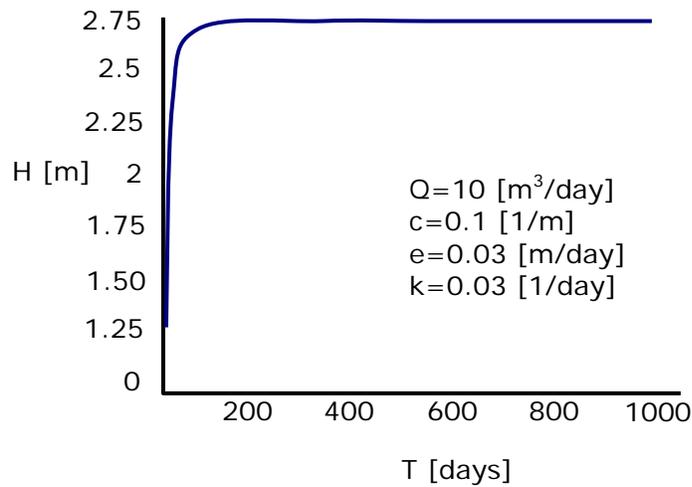
Discharge, evaporation and seepage



$$\frac{dV(H)}{dt} = Q - eA - kHA = Q - \frac{e\pi}{c}H - \frac{k\pi}{c}H^2$$

$$\frac{\pi}{c}H \frac{dh}{dt} = Q - \frac{e\pi}{c}H - \frac{k\pi}{c}H^2$$

$$\frac{dh}{dt} = \frac{Qc}{\pi H} - e - kH$$



Steady State Solution

~~$$\frac{dh}{dt} = \frac{Qc}{\pi H} - e - kH$$~~

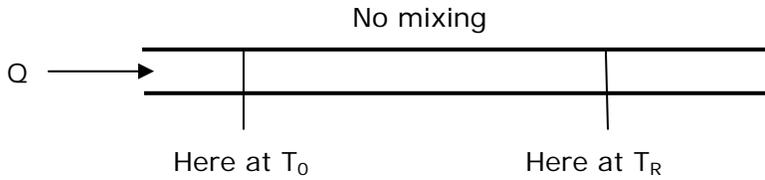
$$\frac{Qc}{\pi} - eH - kH^2 = 0$$

Quadratic formula:

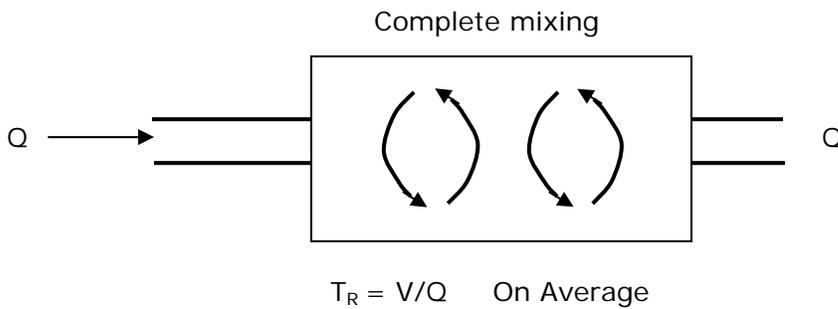
$$H = \frac{-e\pi \pm \sqrt{(e\pi)^2 - 4ck\pi Q}}{2k\pi} = -3.8 \text{ m}, 2.8 \text{ m}$$

Residence Time (steady state, complete mixing)

Very useful concept for degradation and chemical reactions



$$V = QT_R \quad T_R = V/Q \quad \text{Exactly}$$



For this problem:

Consider discharge and evaporation out of Lake Parabola. Assume no seepage.

$$Q = \text{input} = \text{output} = 10 \text{ [m}^3/\text{day]}$$

$$V(H) = \frac{\pi}{2c} H^2 = \frac{\pi}{2(0.1)} 10.6^2 = 1,765 \text{ m}^3$$

$$T_R = V/Q = \frac{1,765 \text{ m}^3}{10 \text{ m}^3/\text{day}} = 176.5 \text{ days}$$

Consider yourself:

Quantity	Men	Women
Water weight [Kg]	60	50
Average Intake [Kg/day]	3	2.1
Residence Time [day]	14	14