WATER & the Biosphere, ESPM 2

Water

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ESPM 2, The Biosphere
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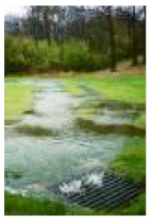

Liquid

Solid

Gaseous

Water exists in liquid, solid and gaseous forms.. All play roles in the biosphere.

Water, water, every where,
And all the boards did shrink ;
Water, water, every where,
Nor any drop to drink.

Rime of the Ancient Mariner, Samuel Coleridge

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British poet and philosopher, 1772-1834. Founder of the Romantic movement.

Why cant we drink sea water?

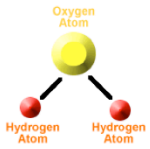
Outline

- Physical properties
- Water at cell level
  - Water potential
- Water at Plant level
  - Adhesion Cohesion theory
  - Transpiration
  - Hydraulic lift
- Water at Ecosystem/Watershed Level
  - Evaporation
- Water Balance at Continental/Global Level

Water, Life and the Biosphere

- Water is a highly effective solvent for salts, sugars, gases, acids and alkalis
- It is transport medium for nutrients to cells
- Provides turgidity for cell growth and expansion
- It provides electrons in photochemical reactions that lead to carbon reduction
- Plays role in weathering rock and forming soil

Reasons why water is important to life..and if we assume life evolved in the sea it is important for the origin of life, too.



Properties of Water

Property	Value
molecular weight	18 g $mole^{-1}$
melting point	273.15 K
boiling point	373.15 K
latent heat of vaporization	2.442 MJ kg^{-1} or 44.00 kJ mol^{-1} at 20 C
latent heat of sublimation	2.826 MJ kg^{-1} or 51.0 kJ mol^{-1} at 0 C
dialectric constant	80
thermal conductivity	0.599 W m^{-1} at 20 C
heat capacity of water	4182 J kg^{-1} at 20 C
molecular diffusivity, water in air	2.42 10^{-5} m^2 s^{-1} at 20 C
Density	1.000 kg m^{-3} at 4 C

Biometeorology, ESPM 129

Is water less or more dense at 0C. Key points include the facts that water can be in liquid, gas and solid forms across the range of climate conditions the biosphere experiences. The large latent heat of vaporization has major effects on weather, climate, rain and storms. Its high heat capacity gives water bodies much thermal inertia.

The dielectric constant of water is distinct. It enables us to use time domain reflectometers, essentially cable testers, to measure moisture as the time of flight is dependent on the dielectric constant and the value for dry soil is so much different.

Salvucci and latent heat exchange.

1 car 1000 kg lifted 1 m

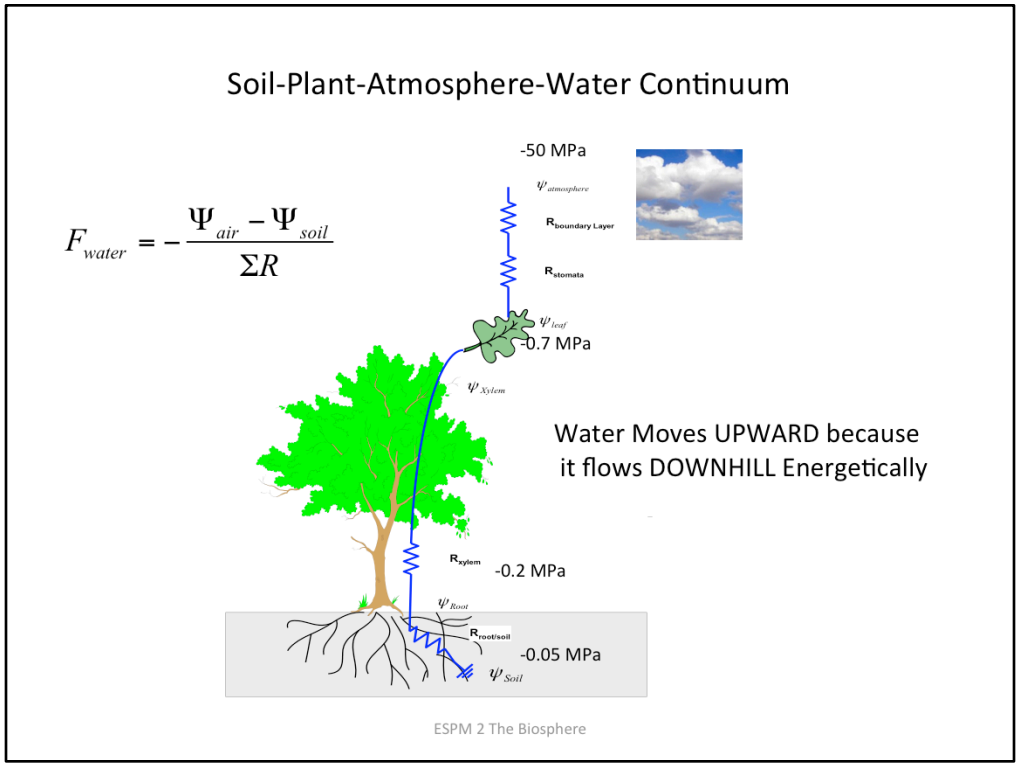
9.8 m s-2 * 1000 kg * 1 m = 9800 kg m2 s-2

Latent energy in 1 kg water, 2,442, 000 J (kg m2 s-2)

1 kg water is 10 cm by 10 cm by 10 cm

1 g water is 1 cm by 1 cm by 1 cm

It possesses 2,442 J of energy and can lift a car 0.4 m



Network of water transport through the soil-plant-atmosphere continuum. While it is conventional wisdom that water moves 'downhill' here is a case where it moves upward. The point is it moves down hill energetically. Hence it is important to consider the case of water potential.

In this SPAC the nodes are water in the soil, which is the least negative, towards nodes across resistors associated with the roots, xylem, stem, leaves and atmospheric boundary layer. The demand is set by the highly negative water potential of the atmosphere

It Takes Energy to Move Water, the Concept of Water Potential

- Water Potential is the Thermodynamic Capacity for a Unit of Water to do Work
- Work is Force times Distance
- It Takes Energy to do Work
- Water Potential has units of Pressure
  - Pressure is Energy per unit volume, or Force per unit Area

Unit, Pa: kg m^{-1} s^{-2}

It Takes Energy to Move Water, Water Potential

- The **total water potential** of a system consists of the sum of water potentials associated
  - **Pressure**
  - **Gravity**
  - **Solutes**
  - **Matric**

$$\psi = \psi_p + \psi_g + \psi_\pi + \psi_m$$

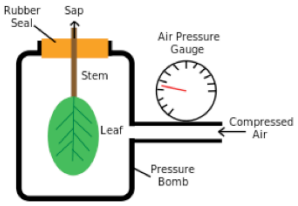
- Water Moves across Gradients in Water Potential
- Water Potential of Pure Water at Rest is Zero

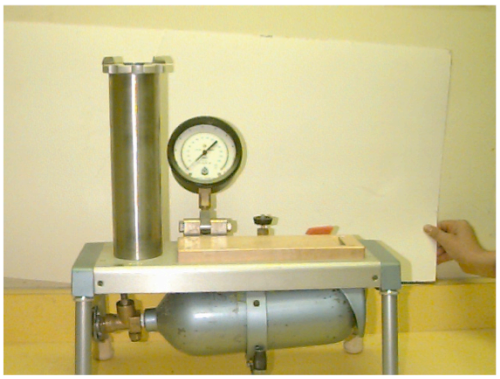
Unit, Pa: kg m^{-1} s^{-2}

ESPM 111 Ecosystem Ecology

The water potential of pure water is zero. It is important to know the various components of water potential. These are associated with Pressure, with Gravity, or head, that induced by solutes and that with the Matrix surrounding water molecules.

Measuring Water Potential





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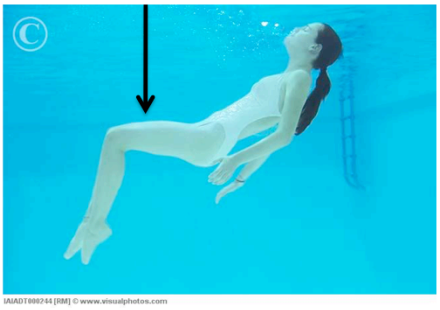
We use a Scholander pressure 'bomb' to measure total leaf water potential. The leaf is placed in a sturdy metal chamber and the pressure of air is increased. At equilibrium sap will start to exude out the cut petiole. Domestic plants tend to wilt when the water potential is below -1.5 MPa, or -15 atmospheres. Drought adapted oaks can function as low as -6.0 MPa.

Pressure, or Hydrostatic, Water Potential

Pressure exerted by an overlying water column on an infinitesimal cube of water

Force/Area



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Pressure potential can be positive or negative. Think of the case of the stomatal guard cells, the movement of water into these cells makes the turgid as pressure potential is positive. This leads to their opening. In the reverse case, they can experience negative pressure potential as they become water leaves and they become flaccid. The actual potential of a sample of pure water in water is defined as zero

Osmotic/Solute Water Potential

Change in Energy of Pure Water when Solutes are Added

Solutes reduce the free energy of water by reducing the mobility of water molecules as they are attracted to the charged or polar surfaces of the solutes

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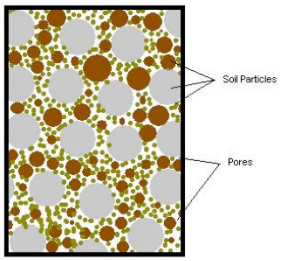
Solutes in water reduce its free energy and make its water potential more negative.

Matric Water Potential

Matric potential refers to the effect of a large polar or charged surface (e.g. soil matrix) on the water system



interactions between water and solid surfaces act to reduce the activity of water. Results from capillary and adsorptive (van der Waal's) forces

Matric effect reduces the free energy of water molecules through attractive forces that reduce their mobility

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Matric water potential is exerted on water in soils, as well as in cells and the plant xylem.

A Sponge is a Good Example, or Analog, for Matrix potential

It Takes Work, Energy, to squeeze the Sponge to Release Water

Gravity Potential
= Density of water times Acceleration of Gravity
times Head Differential

$$\psi_g = \rho_w g h$$

It takes Energy to Lift water Up Hill
Energy is Released when Water Flows Down Hill

Conveyance, Storage and Treatment of Water accounts for 19% of CA electricity use

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We are most associated with gravitational potential. Its value depends on the position relative to a reference, known as head

Lifting Water by Suction, 10.3 m at sea level

$$P_{atmos} = -\psi_g = \rho_w g h = 101300\,Pa$$

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How does a Straw work? Does Paris suck the water out of the glass?; The technical answer is no. Sucking evacuates the atmospheric pressure acting on the water column under the straw. With it evacuated of air pressure, the pressure on the water exposed in the glass pushes it up the straw to a new equilibrium.

What are the Limits on Pumping Water from a Well?
How deep can the Water Table Be?

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This is an important limit as it also establishes the limit of lifting ground water with a suction pump. If you are interested in doing work for the Peace corp and bring water to underserved people you should know this fact. It is a reason companies like Jacuzzi develop submersible pumps.

How do Redwood Trees get water up 100m?

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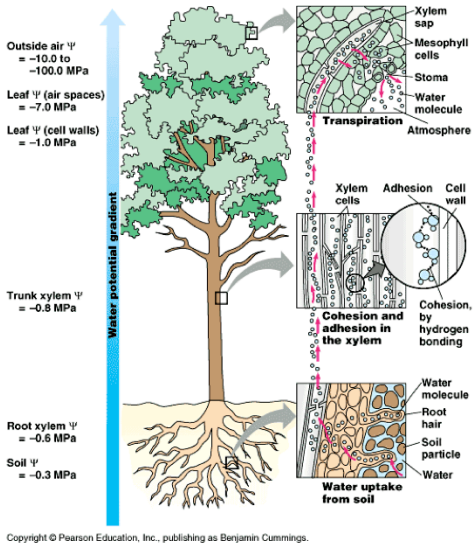
A redwood tree needs to lift water up 90 m or so, this imposes a negative water potential of about -0.88 MPa, or nearly 9 atmospheres of negative pressure. Remember by suction alone one can only lift a column of water 10.3 m. So how does this tree beat physical limits?

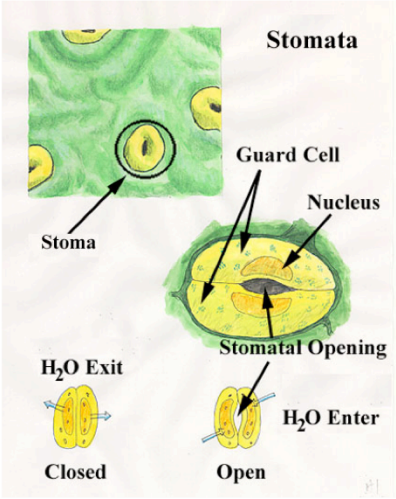
Adhesion-Cohesion Theory



http://www.uic.edu/classes/bios/bios100/lecturesf04am/model.gif

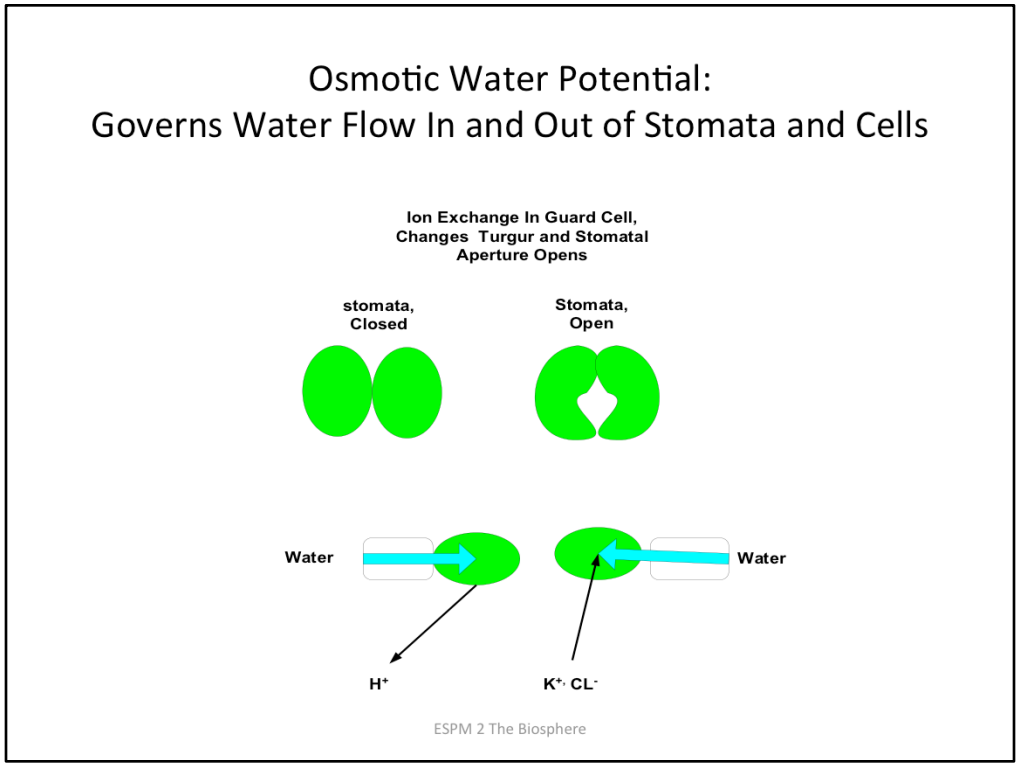
The idea of matric water potential enables the adhesion-cohesion theory to lift water up the column of xylem cells. Water is polar, so bonds allow adjacent water molecular cohesion with one another, tied together like a long string. Adhesion with the surface of vessels and tracheids in the xylem enable the string of water to work its way upward to the demand by the atmosphere.

Why Don't Leaves Dry Out?



http://www2.puc.edu/Faculty/Gilbert_Muth/art0077.jpg

Stomata are the gate keepers of water in the plant biosphere. The enable plants to not succumb to potential demand of evaporation by the atmosphere and regulate water use for carbon gain. No understanding of evaporation can proceed without due attention to stomata.



The movement of cations (K+) and anions (Cl-) with a charge balance of H+ out changes the solute water potential of guard cells. This promotes movement of water into those cells. It increases the turgor pressure, which bows the shape of the stomata and causes a pore to open.

Key Points

- Again We see the role of water potential for describing the movement of water.
- Water moves downhill Energetically, allowing it to move uphill Physically through the stem of plants
- We described the Soil-Water-Plant-Atmosphere Continuum, SPAC
- Stomata Play key role in regulating water loss by plants

Water in the Atmosphere

Saturation Vapor pressure
Dew point Temperature
Relative Humidity
Precipitation, dew, snow, frost

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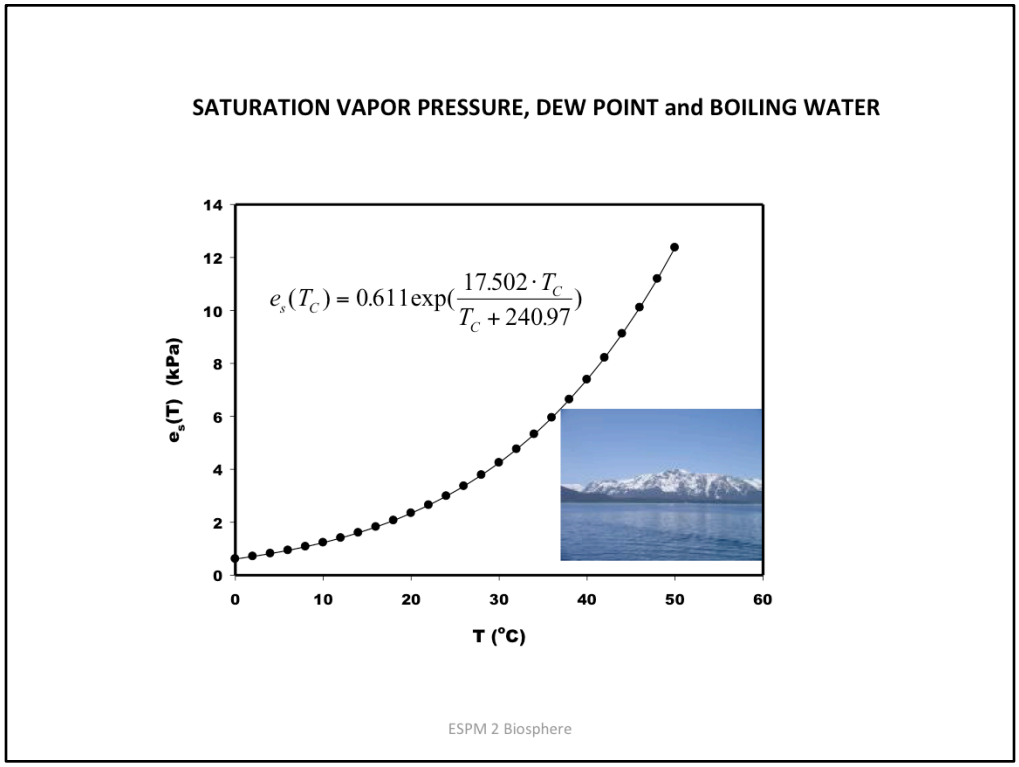
List of moisture variables of interest in studying the state of the atmosphere and weather. We show how much water the atmosphere is able to hold and how this holding capacity increases with Temperature

Saturation Vapor Pressure

- When a pool of water is at constant temperature in a closed container, some water molecules are leaving the liquid and others are condensing and returning to the liquid. Molecules in the head space exert a partial pressure on the system.
- The equilibrium vapor pressure that occurs is called the saturation vapor pressure.
- It is a function of temperature and is independent of pressure.

Saturation vapor pressure is one measure of humidity

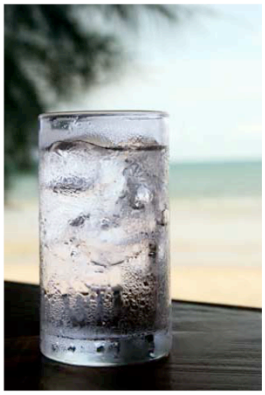


The saturation vapor pressure-temperature curve tells us how much water the atmosphere can hold. The vapor pressure is greater at high temperatures, associated with tropical forests, than cold temperatures associated with tundra. This plays a role why the hydrological cycle is intense in the warm and wet tropics and why rainfall in the tundra matches that of a desert.
If you know the saturated vapor pressure-temperature curve you can assess humidity by knowing the dew point temperature. It also tells you when water boils at a given altitude.

What is boiling? It is the temperature when the saturation vapor pressure equals atmospheric pressure. This is why water boils at lower temperatures in the high mountains than at sea level. By definition the saturation vapor pressure equals 101.3 kPa at 100 C

Relative Humidity

- RH = vapor pressure/saturation vapor pressure @ Tair



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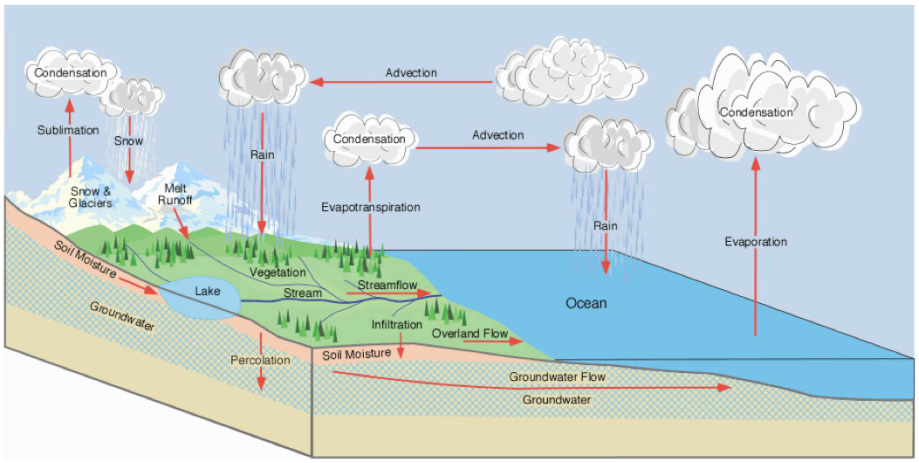
Simple definition. Estimate the vapor pressure from the dew point. Compute saturation vapor pressure for the air temperature. This is a way you can measure humidity in your kitchen.. All you need is a glass, ice, water and a thermometer. And patience. When humidity reaches 100% it condenses forming dew or water droplets. Latent heat is released by this phase change.

Simple Water Cycle



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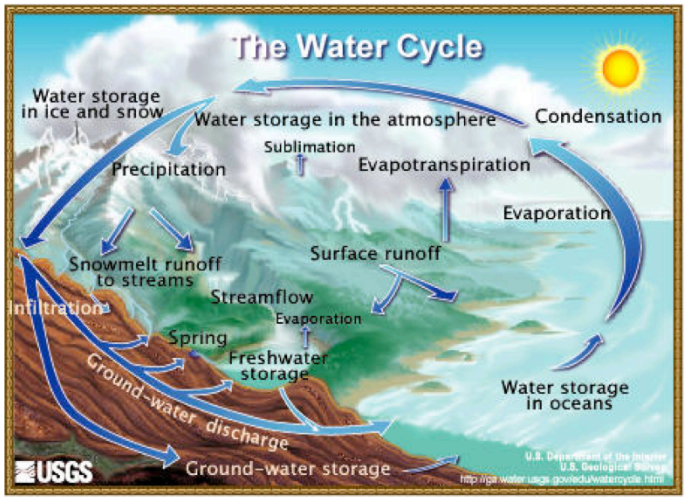
http://static.trunity.net/files/159101_159200/159153/hydrocycle-hires.jpg

Hydrological Cycle, USGS



Precipitation = Evaporation + Runoff + Storage

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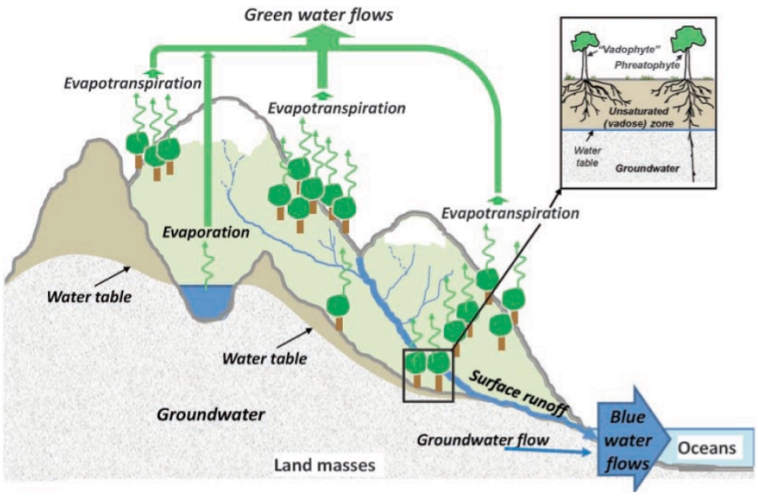
Here we will delve into the water cycle and focus on evaporation, rain, pools and stores of water, runoff, etc..

At global scales we close the water budget by defining precipitation as the sum of evaporation, runoff and storage

Green Water vs Blue Water



D'Odorico et al. 2010 Bioscience

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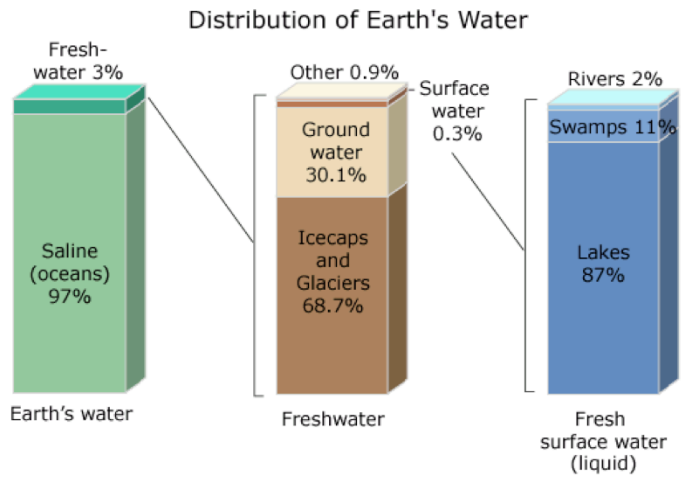
Water can be divided into blue water, that we don't access and which flows into the ocean, vs green water, that which cycles through plants and produces ecological and human services, like food and fiber.

Green water stocks and flows are controlled by biological processes.



A small Fraction is Fresh Water and much smaller fraction is drinkable, or accessible

http://ga.water.usgs.gov/edu/watercyclesummary.html#global

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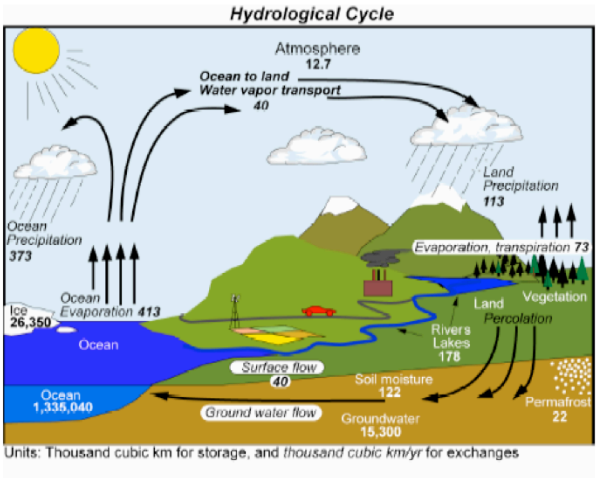
Fresh water is a scarce commodity. It is only 3% of the Earth's water. The water we drink is even scarcer..Of freshwater, only 30% is in ground water or surface water. Of freshwater, only about 0.3% is surface water, in lakes, swamps and rivers.

Global Water Pools and Fluxes

Key Fluxes

Land Precip: 113k km^3
Runoff: 40k km^3
Evaporation: 73k km^3

Ocean Precip: 373k km^3
Ocean ET: 413k km^3



Trenberth et al 2007 J Hydromet

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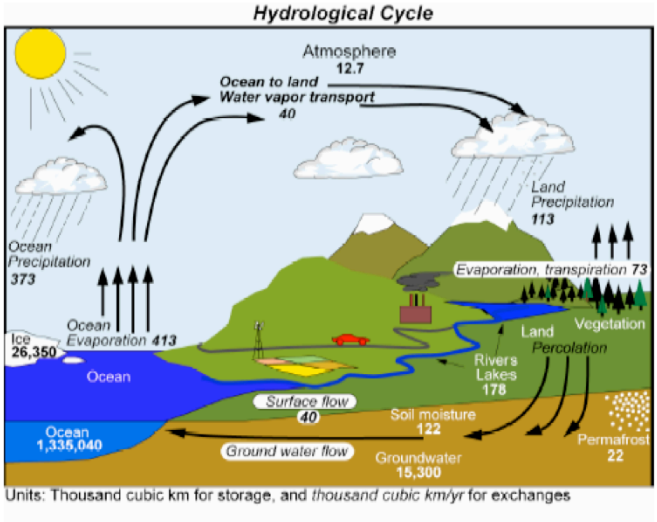
Flows and pools of water…113k km3 of precipitation leads to about 753 mm of rain on land;
373k km3 of precipitation over oceans leads to about 1036 mm of rain over sea

Why are Oceans Salty?



Trenberth et al 2007 J Hydromet

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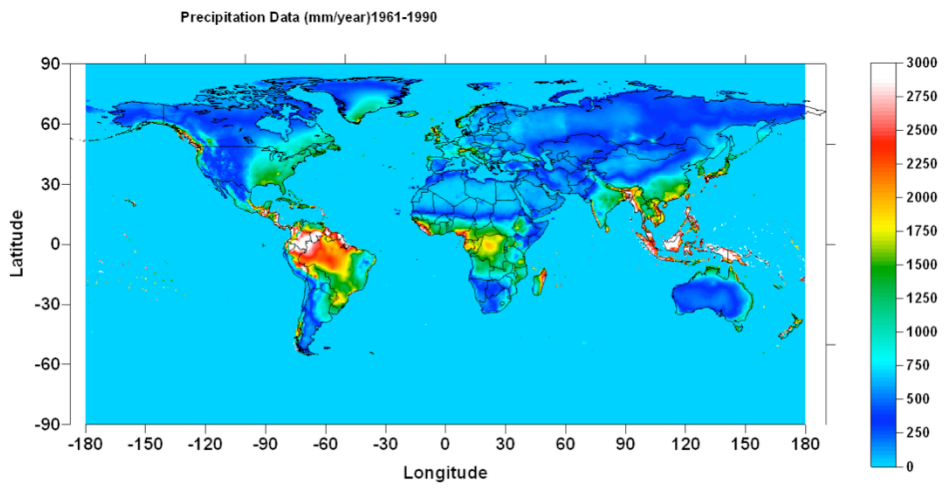
Ocean precipitation is less than evaporation, and this imbalance is met with runoff. Hence, salts build up in the oceans was fresh water readily evaporates and as air masses move fro sea to land, much of this water is deposited over land. The runoff of water from land to sea carries minerals and increases and reinforces the sea's saltiness.



Tropics: > 2000 mm; Eastern US > 1000 mm; Western US < 500 mm;
Pacific Northwest > 2000 mm; Deserts < 300 mm; Polar Regions < 300 mm

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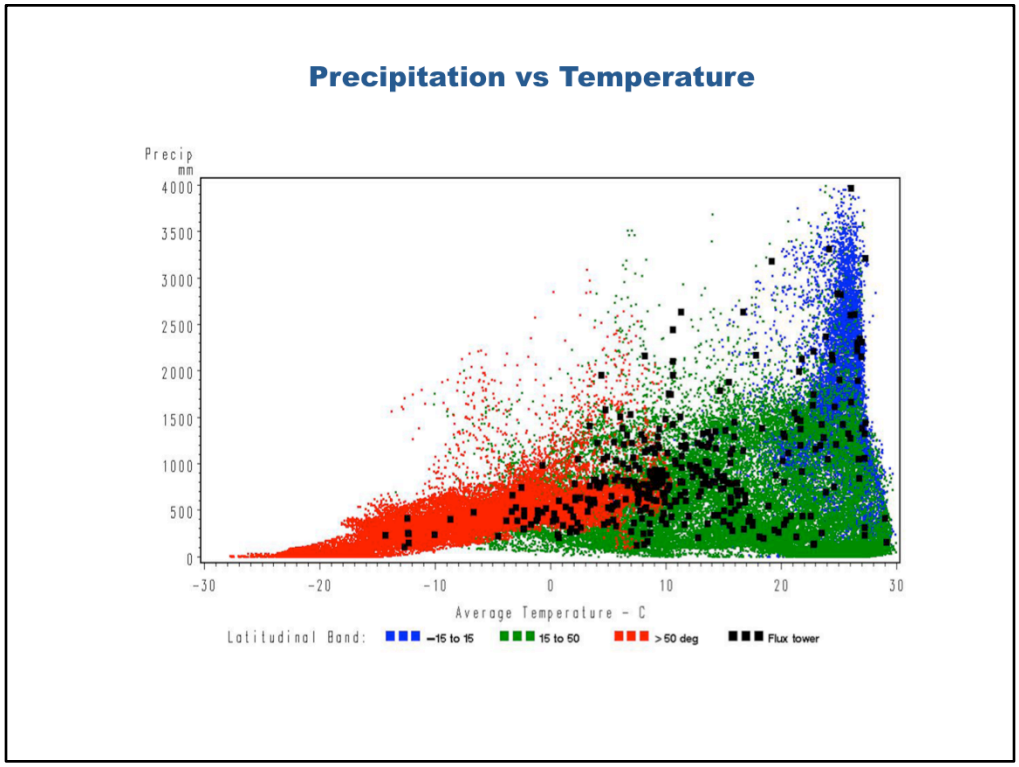
Get a sense of the amount of annual precipitation in major geographical regions..It may come in handy when you travel overseas and decide to bring a rain coat, or not.



Coldest regions are driest. Hottest regions can be both wet or dry. Upper limits of rainfall exceed 4000 mm.

Places in Hawaii, New Zealand and India receive over 450 inches, rain > 11 m; > 38 feet

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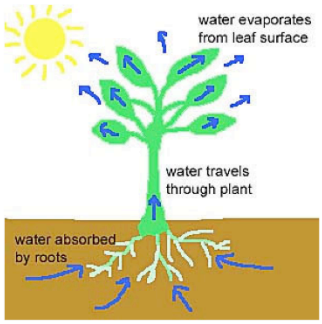
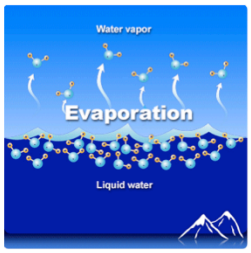
Fun fact on the wettest places and amounts on earth, over 11 meters.

How the Biosphere Uses Water



Evaporation

- Evaporation is the "physical process by which a liquid or solid is converted to a gaseous state" (Glossary of Meteorology).
- Plant canopies introduce water vapor into the atmosphere via **transpiration** and the **evaporation** of water from the soil and free water on the leaves and stems.



Measuring Evaporation

- Pan
- Eddy Covariance
- Sap Flow
- Lysimeter

Measuring Evaporation

Is evaporation greater from a Pan of Open Water or a well-Irrigated grass?

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The most obvious would seem to measure evaporation from a pond or pan. Sounds simple enough, but it is not the right metric. Evaporation from a well-irrigated grass is greater than an open pan. Sounds counter-intuitive? First, the grass has a leaf area index > 3, so there may be more than 3 meters of evaporation leaf area per meter of ground. In contrast, the surface area of the pan is 1 meter squared per meter squared. Second the leaf is moist. We assume the vapor pressure at the leaf is equal to its saturation vapor pressure at its surface temperature, the same as for a pan. Third, the water is transparent, so the water body may absorb less energy than a thick vegetated canopy. Finally the grass is aerodynamically rougher than a smooth water body, so its boundary layer resistance is less

USGS Primer on Water (Leopold and Langbein, 1960) Says:
a Large Oak Tree can Transpire 40,000 gallons.

Can we Believe this number?

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One aspect of this class is to have basic fundamentals to challenge conventional wisdom with back of the envelop calculations. Search the web, check a textbook and you will find that a tree may evaporation 40,000 gallons of water. As someone who measures evaporation, but uses different units, I had to test this idea. First was where the data came from? The citations are from 1960, but my colleagues and I were not even measuring forest evaporation until the 1980s. So this number had to have some flaws as being derived from the residual of the water balance, evaporation ~ precipitation minus runoff.

Leopold

Inspecting The Claim that
a Large Oak Tree can Transpire 40,000 gallons.

Langbein

40,000 gallons = 151 m^3

Assume Tree Crown is 10 m by 10 m

This Tree Must Transpire 1510 mm/y

Average Forest Evaporation is: 495 mm/y

Potential Evaporation for Flooded Rice in Sunny CA ~ 900 mm/y

Only Evergreen Broadleaved Tropical Forests Evaporate ~ 1400 mm/y

Oaks are Deciduous so they will not Transpire Year Round

Some loss is re-evaporation by interception and soil evaporation

What is Your Conclusion?

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So let's convert gallons to metric volume, and assuming the size of a tree covert to the depth of water evaporated. This yields over 1500 mm of evaporation. We just saw in previous slides that an upper limit of 1400 mm may be plausible in only the wettest and warmest regions, if there is enough sunlight, and that these systems become energy limited because clouds limit sunlight. And we find most temperate forests evaporate < 500 mm/year

How Much Water Does a Tree Evaporate?:
Case Study at Tonzi Ranch

Stand Transpiration: 230 mm/y = 2300 m^3/ha-y

Trees Density: 144 #/ha

Evaporation ~ 15.9 m^3/tree-year = 4216 gallons per tree-year

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Using data from annual evaporation measurements and tree density at our savanna site, we come up with about ~4000 gallons per tree. Granted this is a water limited system.

Walker Branch Watershed, TN

1628 Trees/ha (site survey)

100 Trees/ha (overstory)

Annual ET = 485 mm

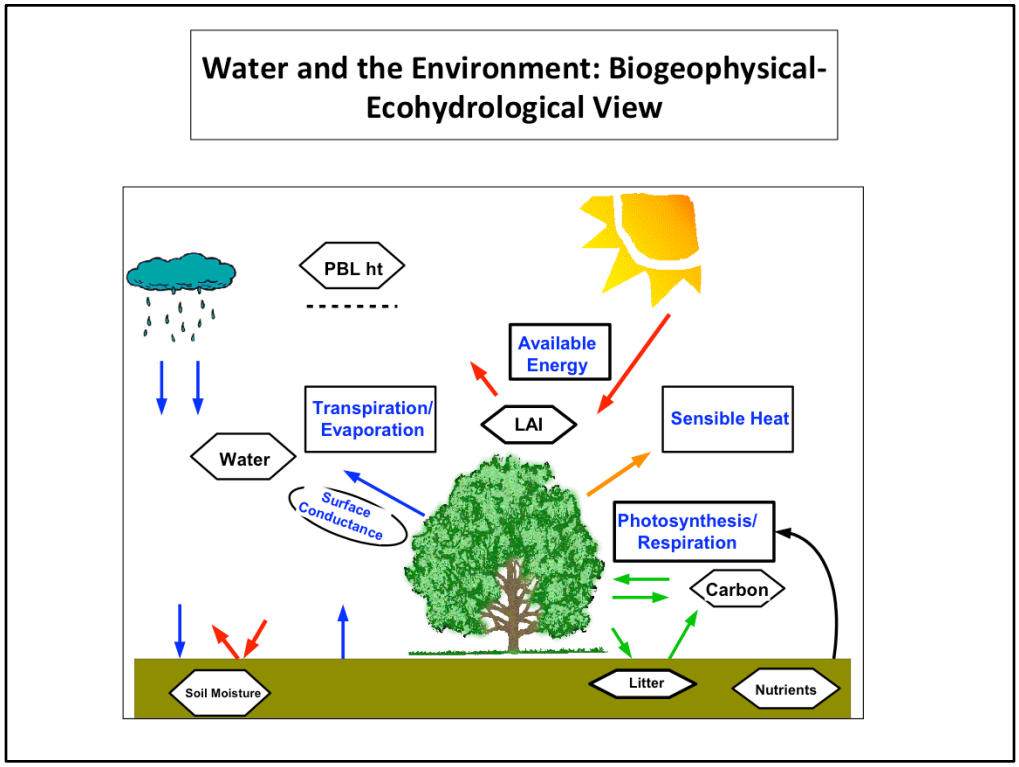
Soil ET: 86 mm

Tree Transpiration: 399 mm = 3990 m3/y-ha

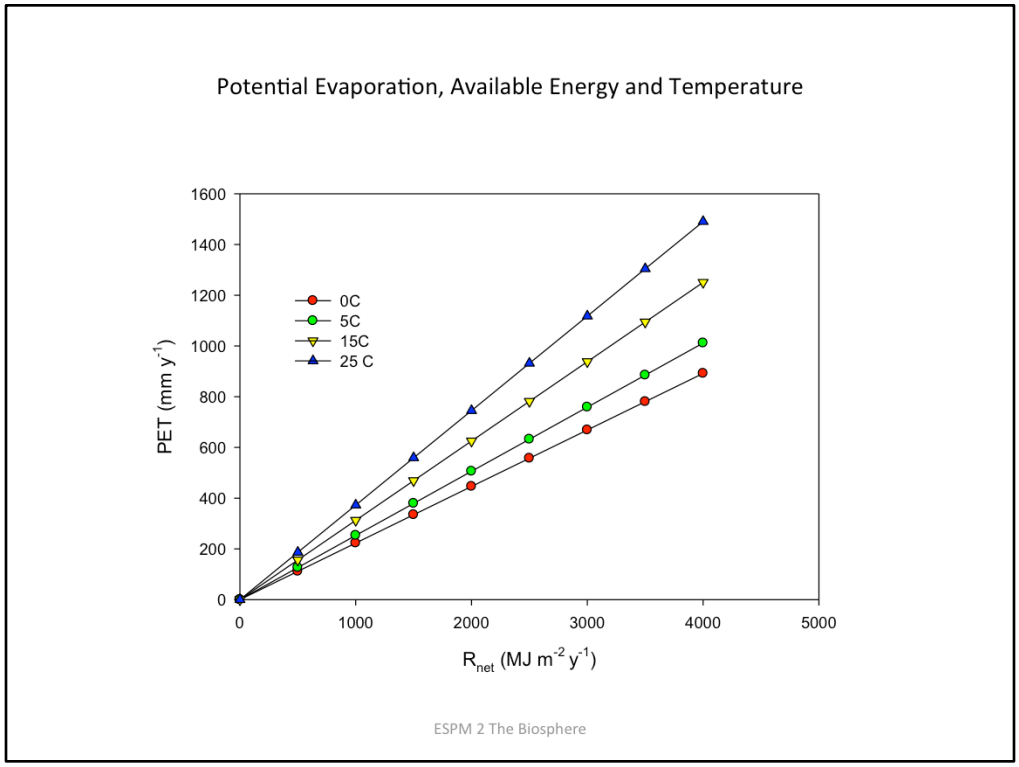
Evaporation per tree: 2.45 m^3/y-tree= 646 gallon/y-tree

Evaporation per Overstory Trees: 39.9 m^3/y-tree = 10533 gallon/y-tree

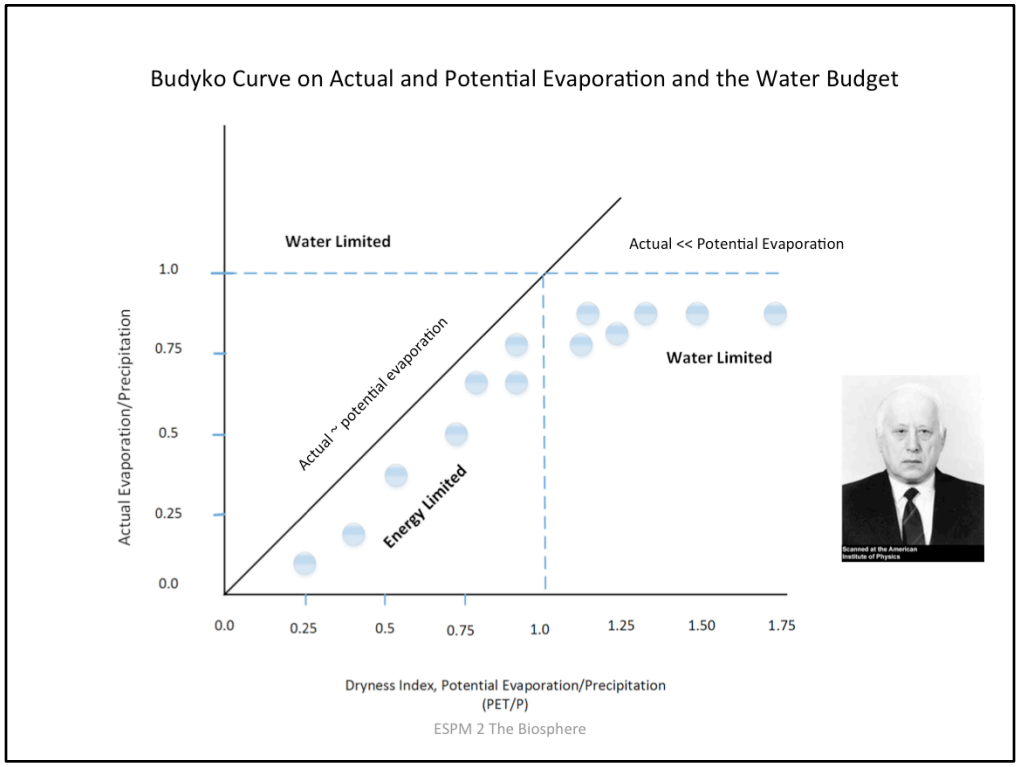
So let's consider a forest in Tennessee that is not water limited..Here, the tree density is greater. And we come up with less than 10,000 gallons per tree if we focus only on the upper storey emergent trees. We obtain a number about ¼ the classic, conventional wisdom



The is an ecosystem view on evaporation and transpiration. You are starting to see connections between previous lectures on carbon cycle, energy balance, structure and function and biosphere-atmosphere interactions come together to provide a more mechanistic understanding of evaporation. Many of these processes are indeed coupled. Here the amount of evaporation will depend on leaf area index, which affects light interception and the amount of available light energy. LAI determines the surface area of transpiring leaves. Stomatal conductance depends on factors like photosynthetic pathway, soil moisture and the nitrogen status of leaves.



The relationship between potential evaporation, temperature and available energy helps us understand better the slow water cycling of the tundra vs the tropics. It also helps us understand that the highest rates can only be achieved with evergreen forests, not deciduous ones.



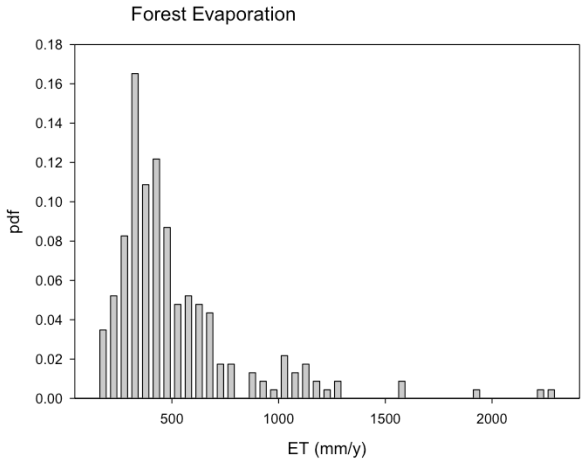
When potential evaporation (f(Rnet) is less than precipitation (PET/P) is less than one, evaporation is energy limited, as in tropical forests; not during the 'dry' season daily evaporation can increase due to fewer clouds and more sunlight. When potential evaporation is less preciptation actual evaporation is water limited, and reaches an asymptote

Budyko Distilled

- Water Limited
- Hot Dry, Sunny California
- Potential Evaporation ~ 1200 mm/y
- Rainfall ~ 500 mm/y
- Actual Evaporation < Rainfall (~300 mm/y) << Potential Evaporation

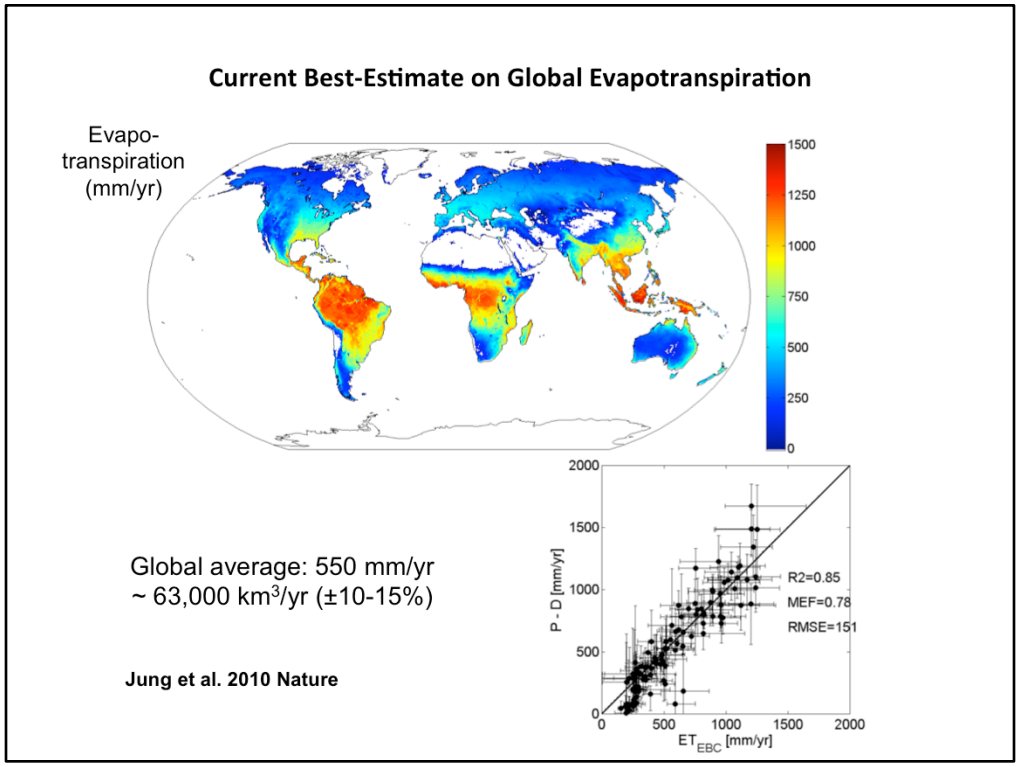
- Energy Limited
- Rainy, Cloudy Tennessee
- Potential Evaporation, 1050 mm/y
- Rainfall, 1400 mm/y
- Actual evaporation 550 mm/y

How Much Water Do Forests Evaporate?



Baldocchi and Ryu, 2011 in Forest Hydrology and Biogeochemistry

This histogram gives you a clue on the amount of water that is evaporated from forests. Most are below 1000 mm/y

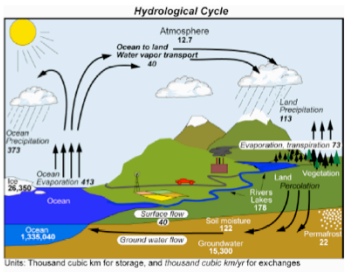


Newer estimates of global ET put it at 63,000 km3/y rather than 73,000 km3/y, 14% difference
Areas of highest evaporation are in the tropics. Amazon, Congo, Southeast Asia

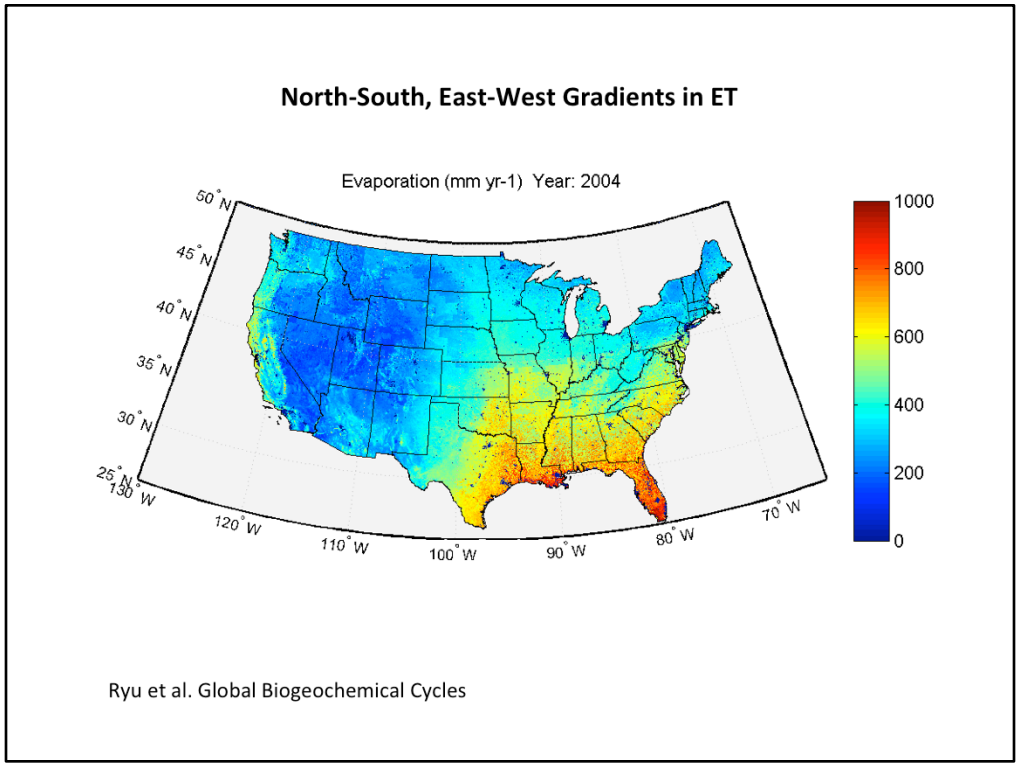
How Accurate is the Global Estimate of Land Evaporation?

Budget reports: 73,000 km^3

ET tends to be deduced by Residual, the Difference between Precipitation (113k km^3) and Runoff (40k km^3) using 'Back of Envelope' calculations

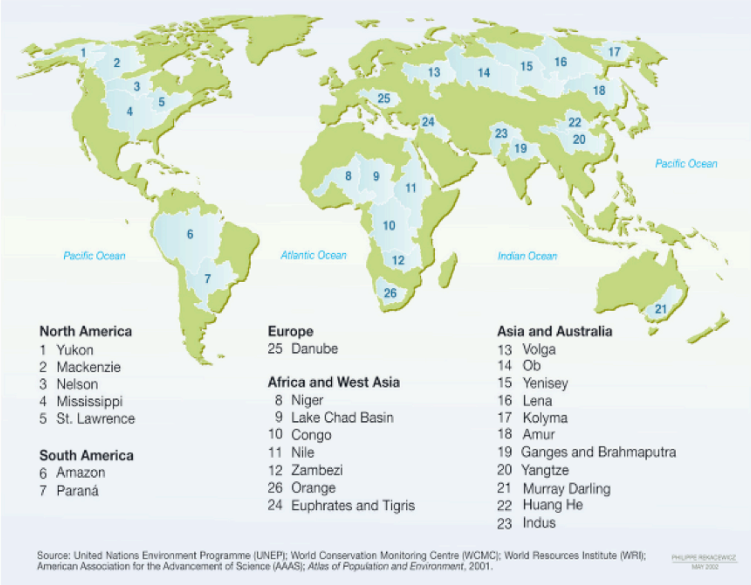


Textbook estimates of global evaporation, determined by residual of the water budget, are being challenged with newer bottom up integration of measurements and Earth system models



Map showing the spread of evaporation rates across the US. The Southeast is hot and humid with highest evaporation rates. Range of evaporation is from about 100 mm to 1000 mm per year..

Major River Basins of the World



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All that rain has to go somewhere, hence the key rivers of the world. The Amazon, Mississippi, Nile, Ganges, Indus, Yangtze, Congo are among the largest and Iconic. What Rivers drain the Sierra Nevada in California?

California Rivers

Sacramento
- Mokelomne
- Feather
- American
- Consumnes

San Joaquin
- Merced
- Stanislaus
- Kern
- King

Eel
Klamath
Russian
Salinas

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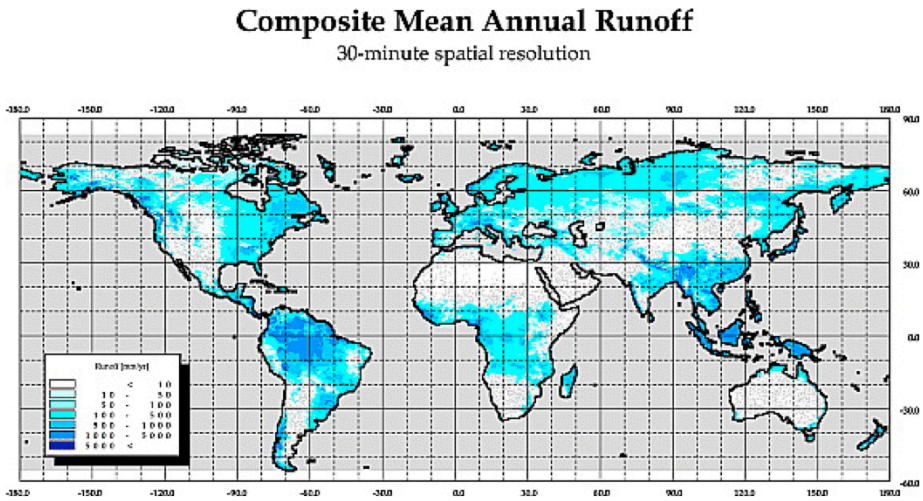
For those of you new to California, here are our major rivers.

High-resolution fields of global runoff combining observed river discharge and simulated water balances



Global Biogeochemical Cycles
Volume 16, Issue 3, pages 15-1-15-10, 7 AUG 2002 DOI: 10.1029/1999GB001254
http://onlinelibrary.wiley.com/doi/10.1029/1999GB001254/full#gbc768-fig-0008

Map gives a sense where runoff is greatest, or nil. What is the runoff of the Great Basin of North America?

Mean annual combined runoff field.

Key Pints

- Evaporation and Transpiration vary with Temperature, Available Energy and Available Soil Moisture
- New Earth Observation Systems enable us to measure and synthesize local to global evaporation and runoff.

Human Water Use

Global Water Use

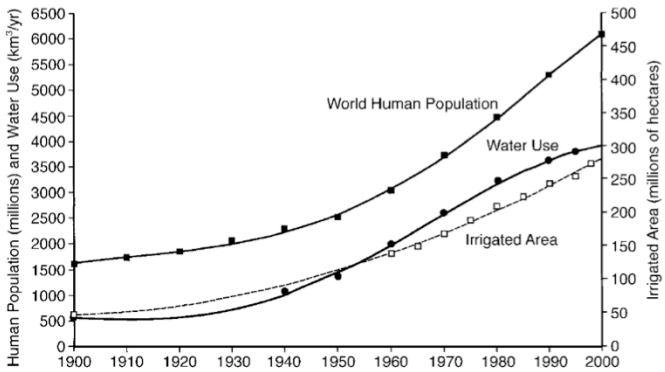


FIG. 1. Global data for human population, water withdrawals, and irrigated land area from 1900 to 2000 (redrawn and updated from Gleick [1998*b*]).

'Few Civilizations, dependent upon Irrigated Agriculture
have Sustained themselves Indefinitely', Various UC Davis Water Science Professors

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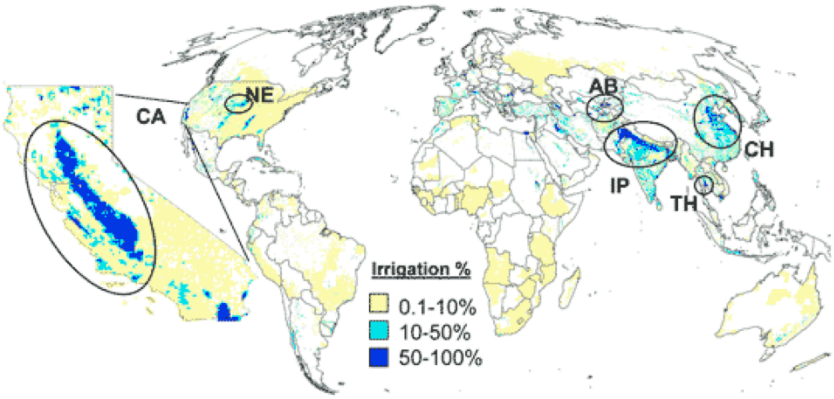
Irrigation is rising with human population. Yet there are questions to the sustainability of irrigation, especially when and where it mines ground water and when and where salts build up. Agriculture accounts for over 80 of consumptive water use, globally (Gleick, + Field and Michalak

Agricultural water use accounts for about 75% of total global Human consumption



https://www.llnl.gov/news/newsreleases/2007/NR-07-08-02.html

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Rivers and ground water provide water for irrigations to many of the world's bread baskets. 33% of crop production comes from 25% of land that is irricated

Global irrigation map..where are the hot spots? Central Valley of California, Nile Delta, Aral Sea, Great Plains, middle East, Northern India, Po Valley Italy, Spain/Portugal, eastern China

Water, Climate, Energy, Food: Inseparable & Indispensable

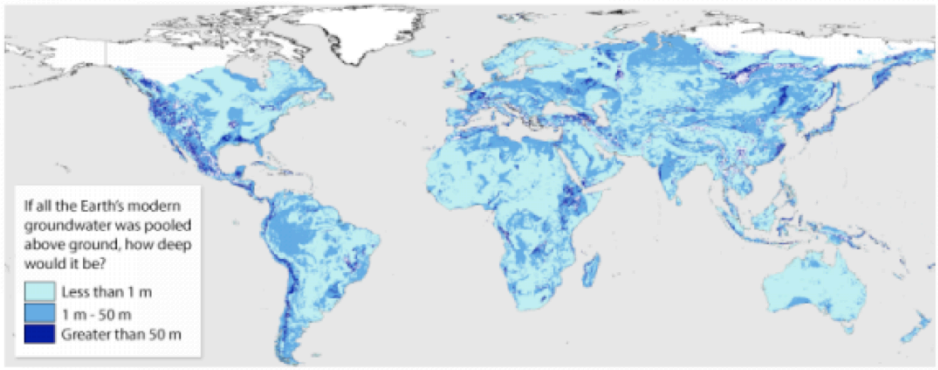
Table 1

Average Water Consumption for Producing Food Products

Food product	Water consumption (gal/lb)
Rice	356
Wheat	160
Corn	109
Soybeans	214
Sugar cane	21
Eggs	400
Milk	119
Cheese	589
Beef	1857
Pork	582
Sheep	736
Chicken	469

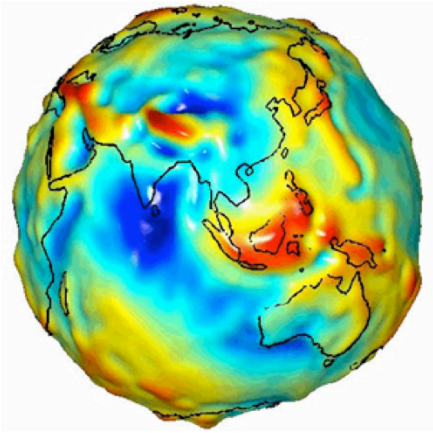
Average consumption incorporates often substantial regional differences due to climate and management. Source: Arjen Y. Hoekstra and Ashok K. Chapagain, "Water Footprints of Nations: Water Use by People as a Function of Their Consumption Pattern," *Water Resources Management* 21 (2007): 35 – 48.

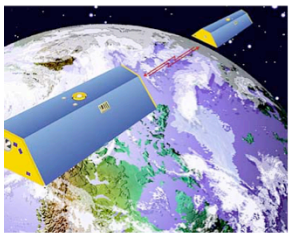
Field and Michalak 2015 Daedelas



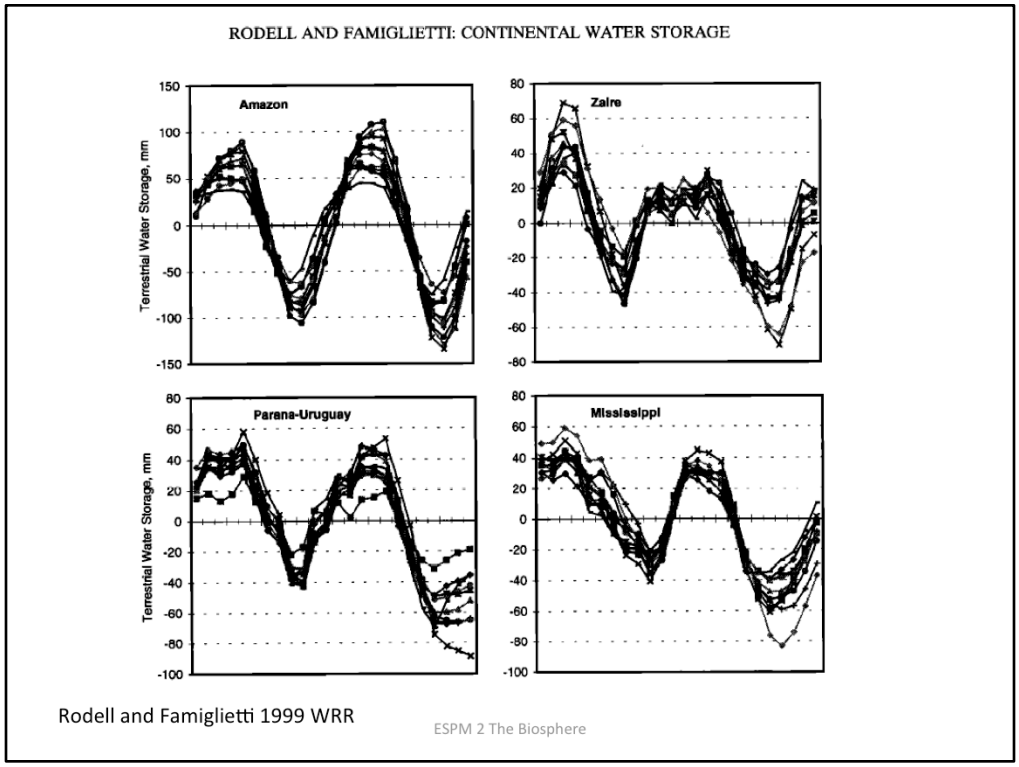
Tom Gleeson, Kevin M. Befus, Scott Jasechko, Elco Luijendijk and M. Bayani Cardenas (2015). *Nature Geoscience*, DOI: 10.1038/NGEO2590.

Measuring Storage of Water Basins with GRACE Satellite
Gravity Recovery And Climate Experiment



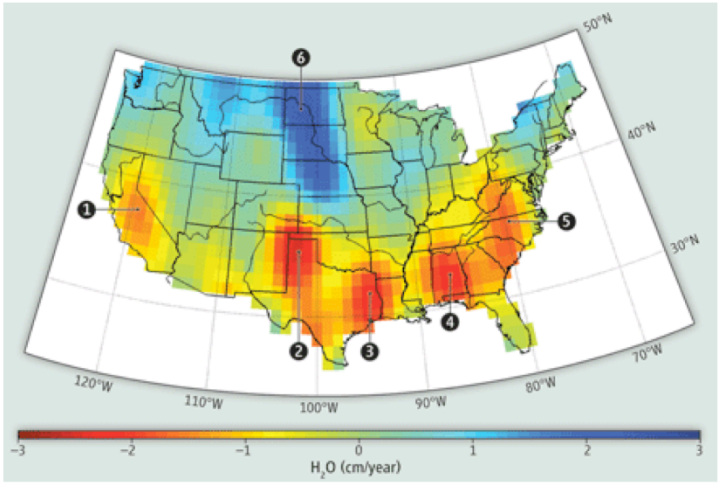


GRACE involves a pair of satellites, whose gravitational attraction varies with mass of the earth, which can vary with stored water



Data from GRACE Satellite…It shows the year to year variation in stored water in major river basins. What do you distill from this figure? Is Storage Nill, or trending??

Change in Water, detected by GRACE, 2003-2012



Famiglietti and Rodell, 2013 Science

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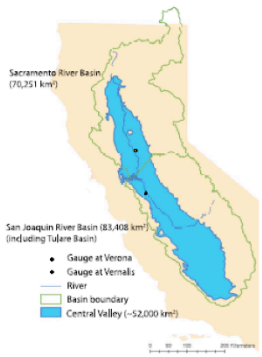
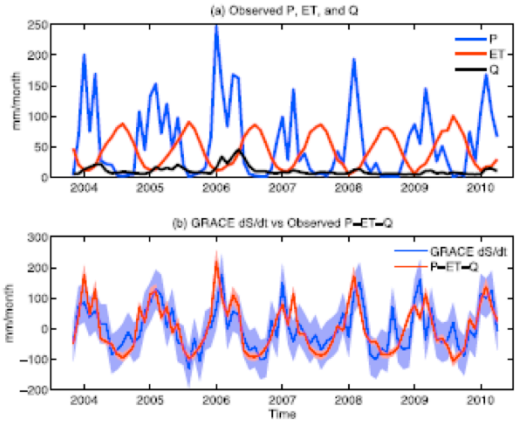
Mixed picture. Between 2003 and 2012, GRACE data show water losses in agricultural regions such as California's Central Valley (**1**) (−1.5 ± 0.1 cm/year) and the Southern High Plains Aquifer (**2**) (−2.5 ± 0.2 cm/year), caused by overreliance on groundwater to supply irrigation water. Regions where groundwater is being depleted as a result of prolonged drought include Houston (**3**) (−2.3 ± 0.6 cm/year), Alabama (**4**) (−2.1 ± 0.8 cm/year), and the Mid-Atlantic states (**5**) (−1.8 ± 0.6 cm/year). Water storage is increasing in the flood-prone Upper Missouri River basin (**6**) (2.5 ± 0.2 cm/year). See fig. S1 for monthly time series for all hot spots. Data from (*15*) and from GRACE data release CSR RL05.

What is Happening in California, with Groundwater?





Famiglietti et al. 2011 GRL

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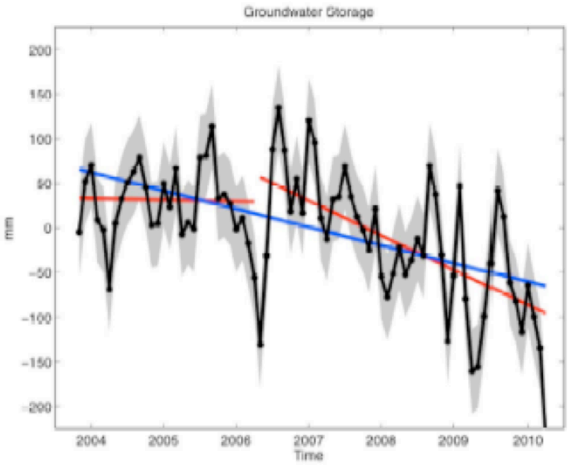
GRACE is being used to study ground water in California

Irrigation is Mining Groundwater from the Central Valley
at a rate of 20.4 +/- 3.9 mm/y



Famiglietti et al. 2011 GRL

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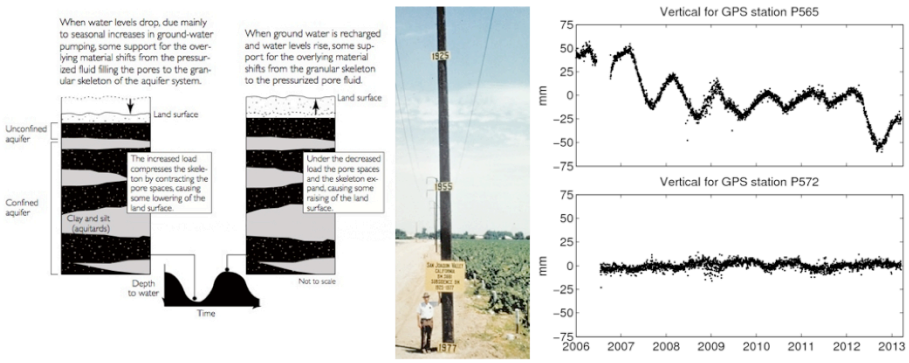
Groundwater is the source of irrigation water for many of the fruits, nuts and vegetables you like to eat. Ground water storage is declining and soils in the San Joaquin Valley are subsiding

Land Subsidence in the San Joaquin Valley



In 50 years Aquifer Depletion has cause the ground to settle by 9 meters

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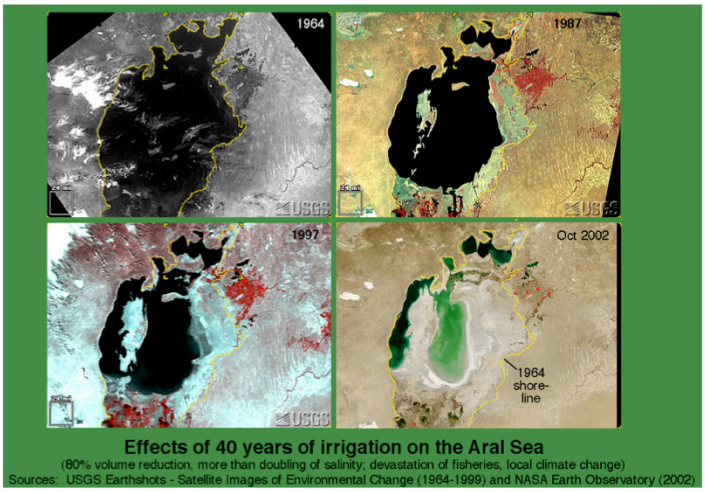
Evidence of land subsidence in the San Joaquin Valley…Lesson: We cannot mine our ground water indefinitely.

Loss of the Aral Sea by Intense Irrigation



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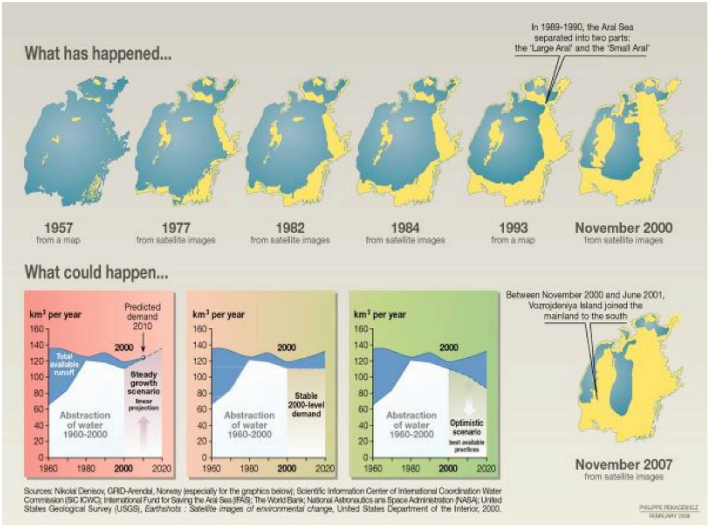
Irrigation of the Aral Sea for cotton to support the Soviet era agricultural economy has led to its immense shrinkage

Disappearance of Aral Sea to Supply Soviet Irrigated-Cotton Fields



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I first became aware of the Aral Sea reading National Geographic at home. It is an issue that resonated with me, so I show you what is happening

Aral Sea 2013, Google Earth

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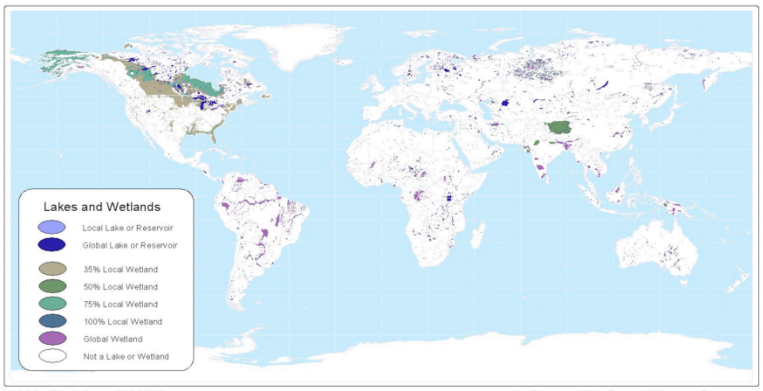
Picture of the Aral Sea today..

Lakes and Wetlands



Data taken from: Lehner and Doll (2001)

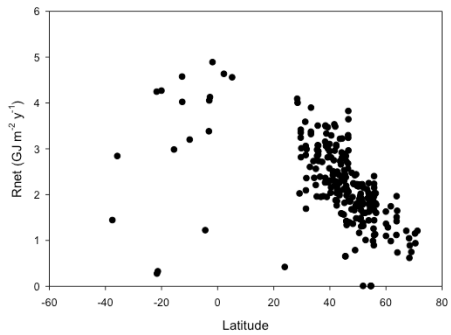
Atlas of the Biosphere
Center for Sustainability and the Global Environment
University of Wisconsin - Madison

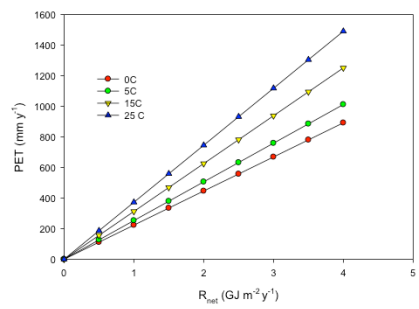
Why are most of the Wetlands in the Sub Arctic?:
Isn't it a Desert?

At High Latitudes Potential Evaporation (PET) < 200 mm for Available Energy …

ET < Less than Precipitation

FLUXNET Database





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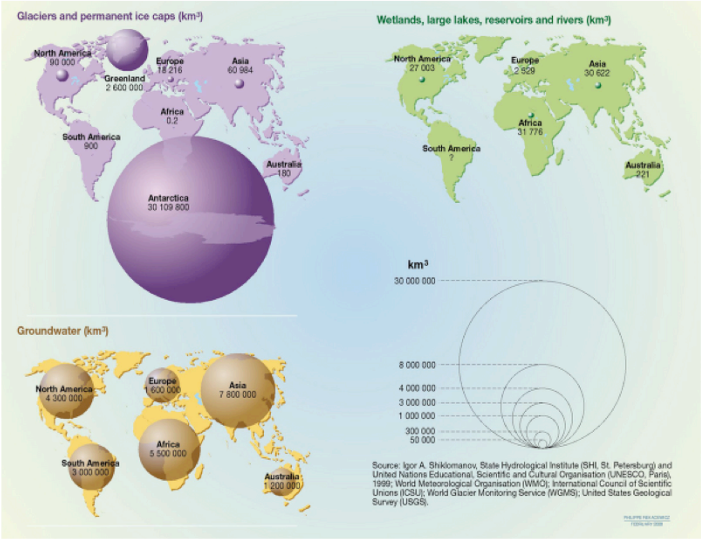
Reinforces why evaporation near the poles is so low.. despite long summer days with 24 hours of sunlight

Glaciers and Groundwater



Rapid and Recent Melting of Himalaya Glaciers,
Source of Water for over 2 Billion People

1950s

Notice lake

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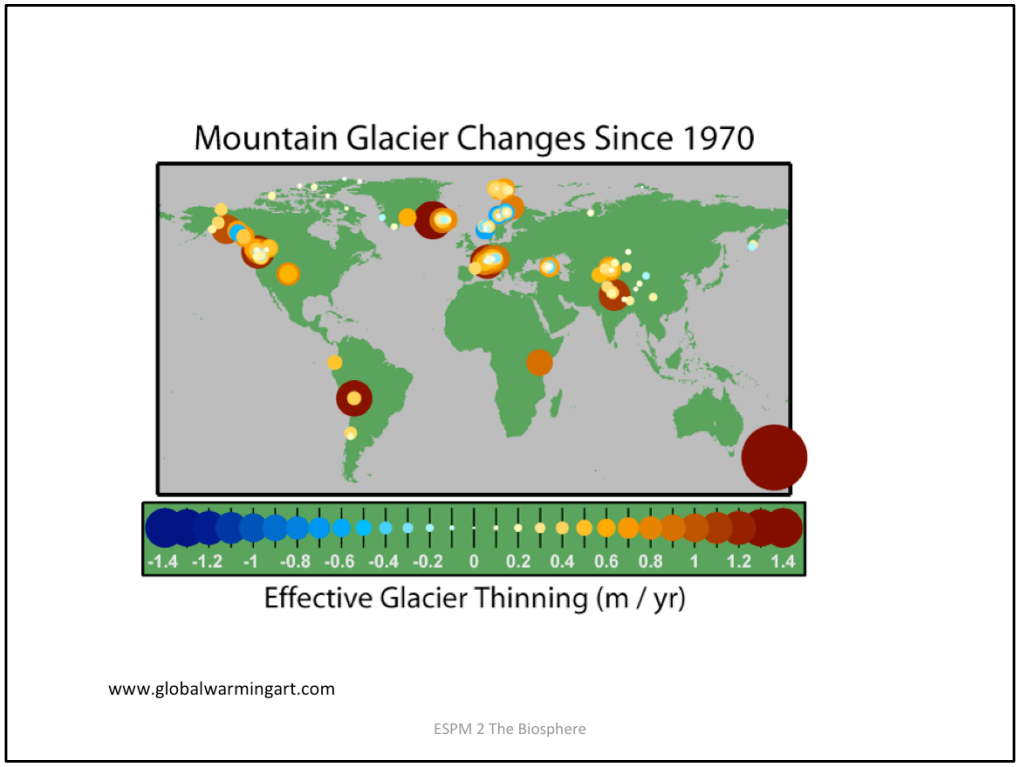
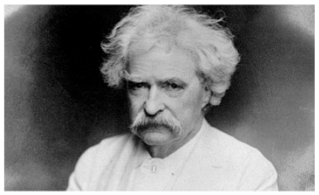
Water from Himalaya glaciers are critical for feeding the rivers that are the source of water for over 2 billion people in southern Asia

Oliver Schell's editorial NY Times



Mountain glaciers are shrinking with warming

Whiskey is for Drinking; Water is for fighting over



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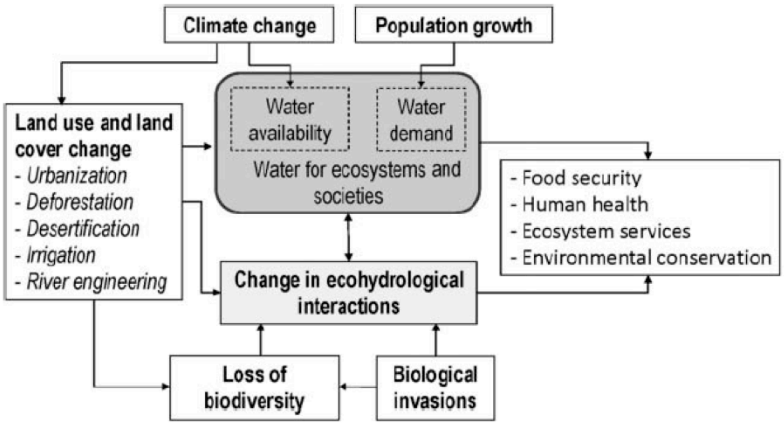
Quote attributed to Mark Twain, but not proven

Water Scarcity can be a source of Conflict
To manage the Biosphere We have to Disperse Water Fairly



D'Ordorico et al Bioscience

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Water has multiple stakeholders, many with divergent interests. How do we share water? Part of the problem is our water laws were based on English Law and ideas like Riparian rights were given during years of ample rain, low populations and water demand.

Take Home Points

- Water Flows Down Hill Energetically
- The Global Water Balance, Precipitation is balanced by evaporation, runoff and storage
- Clean, Fresh Drinking Water is Extremely Scarce
  - Only 3% of the World's Water is Fresh
  - Only 0.3% of Fresh Water is Surface Water
- 30% of Freshwater is Groundwater, but it is being rapidly depleted in an unsustainable manner.

Discussion Topics

- What are some Solutions to Stop and Reverse the loss of Ground Water in California?

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Mean Global Mixing Ratio of Humidity of the Atmosphere

Mass Atmosphere: 5.28 10^{18} kg

Volume of Water in Atmosphere: 12,900 km^3

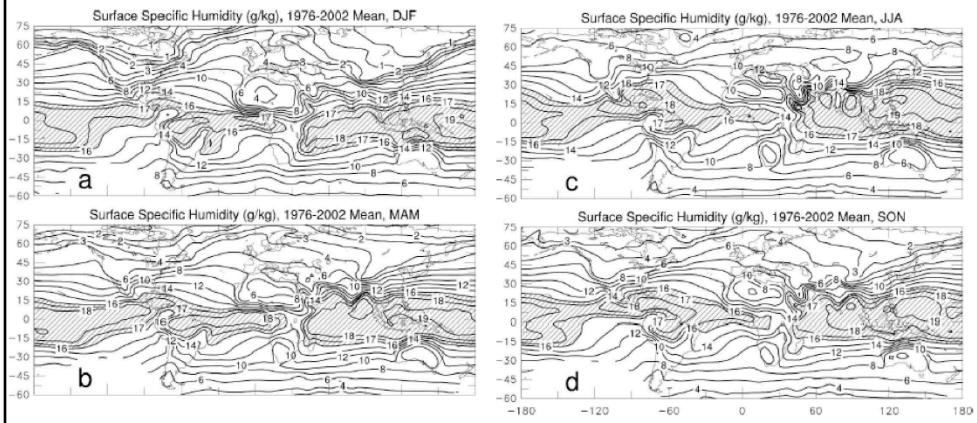
Density of Water: 1000 kg m^{-3}

Mass of Water: 1.29 10^{16} kg

Mean Global Mixing Ratio: 2.44 g/kg == 0.244%

May n

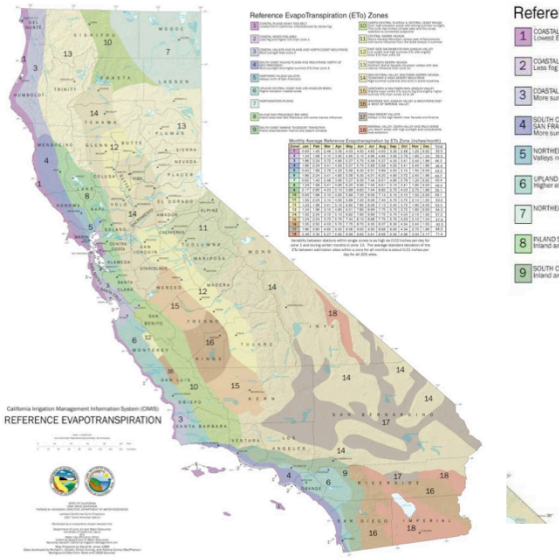
Specific Humidity near the Surface



Dai, 2006 J Climate

Values near the surface may not reflect the integrated atmosphere

Managing Water in California
CIMIS ET Map



Reference EvapoTranspiration (ETo) Zones

1. COASTAL PLAINS HEAVY FOG BELT — Lowest ETo in California. Characterized by dense fog
2. COASTAL MIXED FOG AREA — Less fog and higher ETo than zone 1
3. COASTAL VALLEYS AND PLAINS AND NORTH COAST MOUNTAINS — More sunlight than zone 2
4. SOUTH COAST INLAND PLAINS AND MOUNTAINS NORTH OF SAN FRANCISCO — More sunlight and higher summer ETo than zone 3
5. NORTHERN INLAND VALLEYS — Valleys north of San Francisco
6. UPLAND CENTRAL COAST AND LOS ANGELES BASIN — Higher elevation coastal areas
7. NORTHEASTERN PLAINS
8. INLAND SAN FRANCISCO BAY AREA — Inland area near San Francisco with some marine influence
9. SOUTH COAST MARINE TO DESERT TRANSITION — Inland area between marine and desert climates
10. NORTH CENTRAL PLATEAU & CENTRAL COAST RANGE — Cool, high elevation areas with strong summer sunlight. This zone has limited climate data and the zones selection is somewhat subjective
11. CENTRAL SIERRA NEVADA — Sierra Nevada Mountain valleys east of Sacramento with some influence from the delta breeze in summer
12. EAST SIDE SACRAMENTO-SAN JOAQUIN VALLEY — Low winter and high summer ETo with slightly lower ETo than zone 14
13. NORTHERN SIERRA NEVADA — Northern Sierra Nevada mountain valleys with less marine influence than zone 11
14. MID-CENTRAL VALLEY, SOUTHERN SIERRA NEVADA, TEHACHAPI & HIGH DESERT MOUNTAINS — High summer sunshine and wind in some locations.
15. NORTHERN & SOUTHERN SAN JOAQUIN VALLEY — Slightly lower winter ETo due to fog and slightly higher summer ETo than zones 12 & 14
16. WESTSIDE SAN JOAQUIN VALLEY & MOUNTAINS EAST & WEST OF IMPERIAL VALLEY
17. HIGH DESERT VALLEYS — Valleys in the high desert near Nevada and Arizona
18. IMPERIAL VALLEY, DEATH VALLEY AND PALO VERDE — Low desert areas with high sunlight and considerable heat advection

Monthly Average Reference Evapotranspiration by ETo Zone (inches/month)

Zone	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1	0.93	1.40	2.48	3.30	4.03	4.50	4.65	4.03	3.30	2.48	1.20	0.62	33.0
2	1.24	1.68	3.10	3.90	4.65	5.10	4.96	4.65	3.90	2.79	1.80	1.24	39.0
3	1.86	2.24	3.72	4.80	5.27	5.70	5.58	5.27	4.20	3.41	2.40	1.86	46.3
4	1.86	2.24	3.41	4.50	5.27	5.70	5.89	5.58	4.50	3.41	2.40	1.86	46.8
5	0.93	1.68	2.79	4.20	5.58	6.30	6.51	5.89	4.50	3.10	1.50	0.93	43.9
6	1.86	2.24	3.41	4.80	5.58	6.30	6.51	6.20	4.80	3.72	2.40	1.86	49.7
7	0.62	1.40	2.48	3.90	5.27	6.30	7.44	6.51	4.80	2.79	1.20	0.62	43.4
8	1.24	1.68	3.41	4.80	6.20	6.90	7.44	6.51	5.10	3.41	1.80	0.93	49.4
9	2.17	2.80	4.03	5.10	5.89	6.60	7.44	6.82	5.70	4.03	2.70	1.86	55.1
10	0.93	1.68	3.10	4.50	5.89	7.20	8.06	7.13	5.10	3.10	1.50	0.93	49.1
11	1.55	2.24	3.10	4.50	5.89	7.20	8.06	7.44	5.70	3.72	2.10	1.55	53.0
12	1.24	1.96	3.41	5.10	6.82	7.80	8.06	7.13	5.40	3.72	1.80	0.93	53.3
13	1.24	1.96	3.10	4.80	6.51	7.80	8.99	7.75	5.70	3.72	1.80	0.93	54.3
14	1.55	2.24	3.72	5.10	6.82	7.80	8.68	7.75	5.70	4.03	2.10	1.55	57.0
15	1.24	2.24	3.72	5.70	7.44	8.10	8.68	7.75	5.70	4.03	2.10	1.24	57.9
16	1.55	2.52	4.03	5.70	7.75	8.70	9.30	8.37	6.30	4.34	2.40	1.55	62.5
17	1.86	2.80	4.65	6.00	8.06	9.00	9.92	8.68	6.60	4.34	2.70	1.86	66.5
18	2.48	3.36	5.27	6.90	8.68	9.60	9.61	8.68	6.90	4.96	3.00	2.17	71.6

Global Water Pools

Water source	Water volume, in cubic kilometers	Percent of freshwater	Percent of total water
Oceans	**1,338,000k**	--	**96.5**
Ice caps Glaciers	**24,064k**	68.7	**1.74**
Groundwater	**23,400k**	--	**1.7**
Fresh	10,530k	30.1	0.76
Saline	12,870k	--	0.94
Soil Moisture	16.5k	0.05	0.001
Ground Ice & Permafrost	300k	0.86	0.022
Lakes	176.4k	--	**0.013**
Fresh	91k	0.26	0.007
Saline	85.4k	--	0.006
Atmosphere	**12.9k**	0.04	**0.001**
Swamp Water	11.,47k	0.03	0.0008
Rivers	2.120k	0.006	0.0002
Biological Water	1.120k	0.003	0.0001
Total	1,386,000k	-	100

http://ga.water.usgs.gov/edu/watercyclesummary.html#global

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Green water is a much, much smaller fraction of blue water.. Many wars and regional disputes tend to be over resources like available water and more will occur in the future.

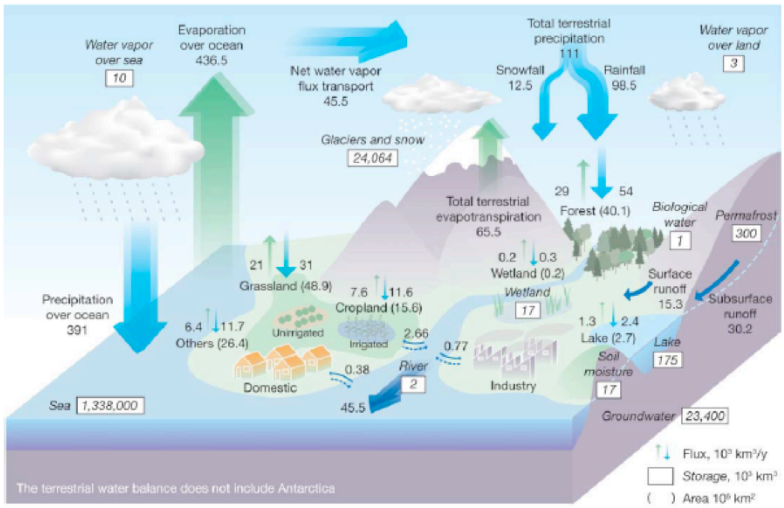
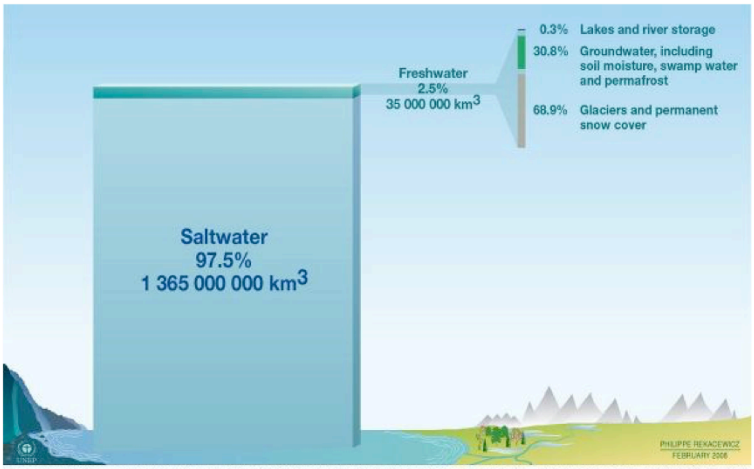
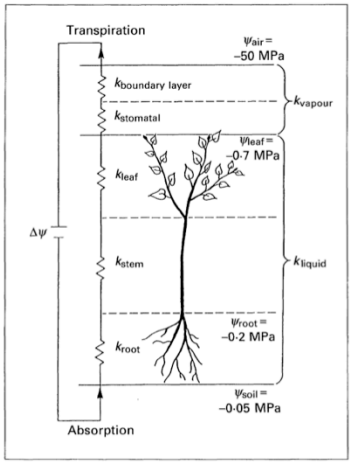


Fig. 1. Global hydrological fluxes (1000 km³/year) and storages (1000 km³) with natural and anthropogenic cycles are synthesized from various sources (*1*, *3*–*5*). Big vertical arrows show total annual precipitation and evapotranspiration over land and ocean (1000 km³/year), which include annual precipitation and evapotranspiration in major landscapes (1000 km³/year) presented by small vertical arrows; parentheses indicate area (million km²). The direct groundwater discharge, which is estimated to be about 10% of total river discharge globally (*6*), is included in river discharge.

Oki and Kanae 2006 Science



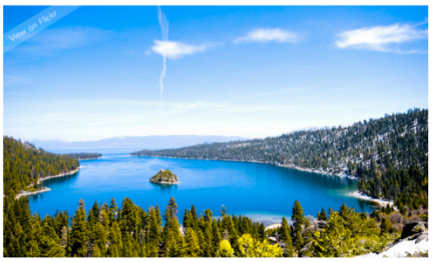
Source: Igor A. Shiklomanov, State Hydrological Institute (SHI, St. Petersburg) and United Nations Educational, Scientific and Cultural Organisation (UNESCO, Paris), 1999.



Tyree and Ewers, New Phytologist

Water on Earth

- Earth Area: 5.1 10^{14} m^2
- Ocean Area: 3.6 10^{14} m^2 (70%)
- Land Area: 1.5 10^{14} m^2 (30%)



This section is on the Earth's water budget and pools

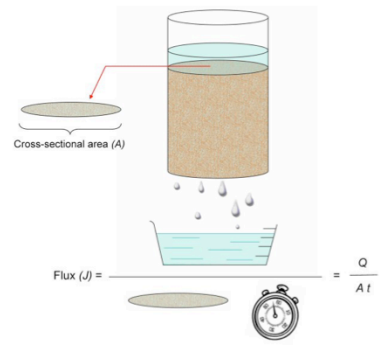
Water Movement through Soils, Darcy's Law

Henry Darcy

The volume of water, V, passing through a bed of sand per unit time is a function of the cross-sectional area, A, the thickness of the bed, L, the depth of water on top of the bed, Δh, and the hydraulic conductivity of the sand, K:

$$\frac{V}{t} = K\frac{A\Delta h}{L}$$

$$J = \frac{V}{At} = K\frac{\Delta h}{L}$$



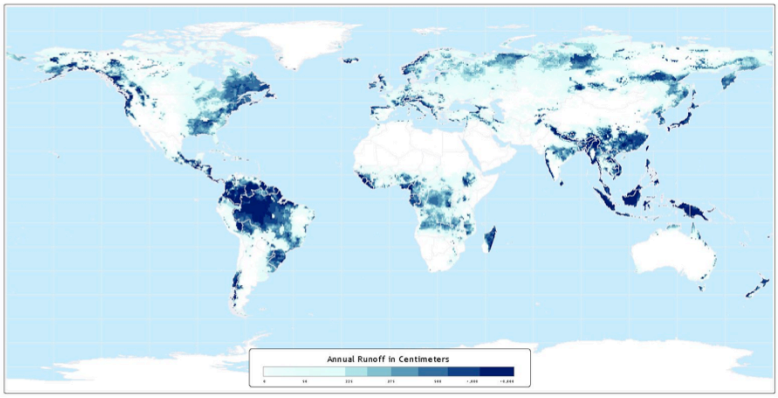
soils.usda.gov/.../note6fig2_lowres.jpg

ESPM 2

Note on water movement through soils. Flux rates of saturated flow depend upon the head and the hydraulic conductivity of the soil. Sand is more conductive than clays.

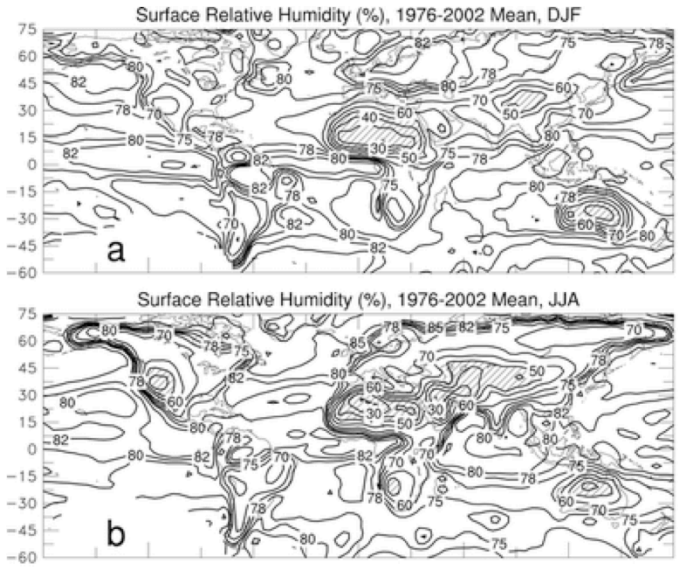
Precipitation = Evaporation + Runoff + Storage

Annual Runoff



Data taken from: UNH-GRDC Composite Runoff Fields v1.0

Atlas of the Biosphere
Center for Sustainability and the Global Environment
University of Wisconsin - Madison



NH Winter:

RH: ~80% over oceans

RH: 30-80% over land

NH Summer:

RH: ~80% over oceans

RH: 30-80% over land

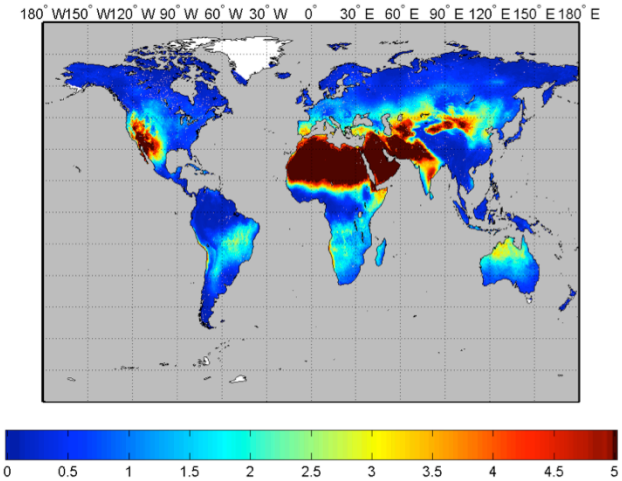
Dai, 2006 J Climate

ESPM 2, The Biosphere

How humid is the atmosphere and where is it humid?

Vapor Pressure Deficit Map

Midday VPD (kPa) Year: 2003Mon: 6



ESPM 2, The Biosphere