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*"We forget that the water cycle and life cycle are one"*

Jacques Cousteau



Water Balance (Law of Conservation of Mass ...for water)

$$P - ET - Q \pm \Delta S = 0$$

P = precipitation (rain and snow)

ET = evapotranspiration

Q = water yield (streamflow + groundwater)

S = storage

$$P - (E + T + I) - (Q_{OF} + Q_{SSF} + Q_{GW}) \pm \Delta (S_{SNOW} + S_{SOIL} + S_{WETLANDS} + S_{LAKES} + S_{STREAMS} + S_{VEG.}) = 0$$

P = precipitation (rain and snow)

E = evaporation (...from soil and water features)

T = transpiration (water use by plants)

I = interception (...of water on plant surfaces, usually followed by evaporation)

$Q_{OF}$  = overland flow

$Q_{SSF}$  = shallow subsurface flow (through the root zone)

$Q_{GW}$  = groundwater flow (deeper flow paths, below the influence of evaporation and plants)

S = storage (...throughout the watershed ...some tightly held ...some in transit)

Water Balance =  $f$ (Energy Balance, climate, time, geologic history, terrain features, soil and vegetation characteristics, current land use, land use history and legacy effects, etc.)

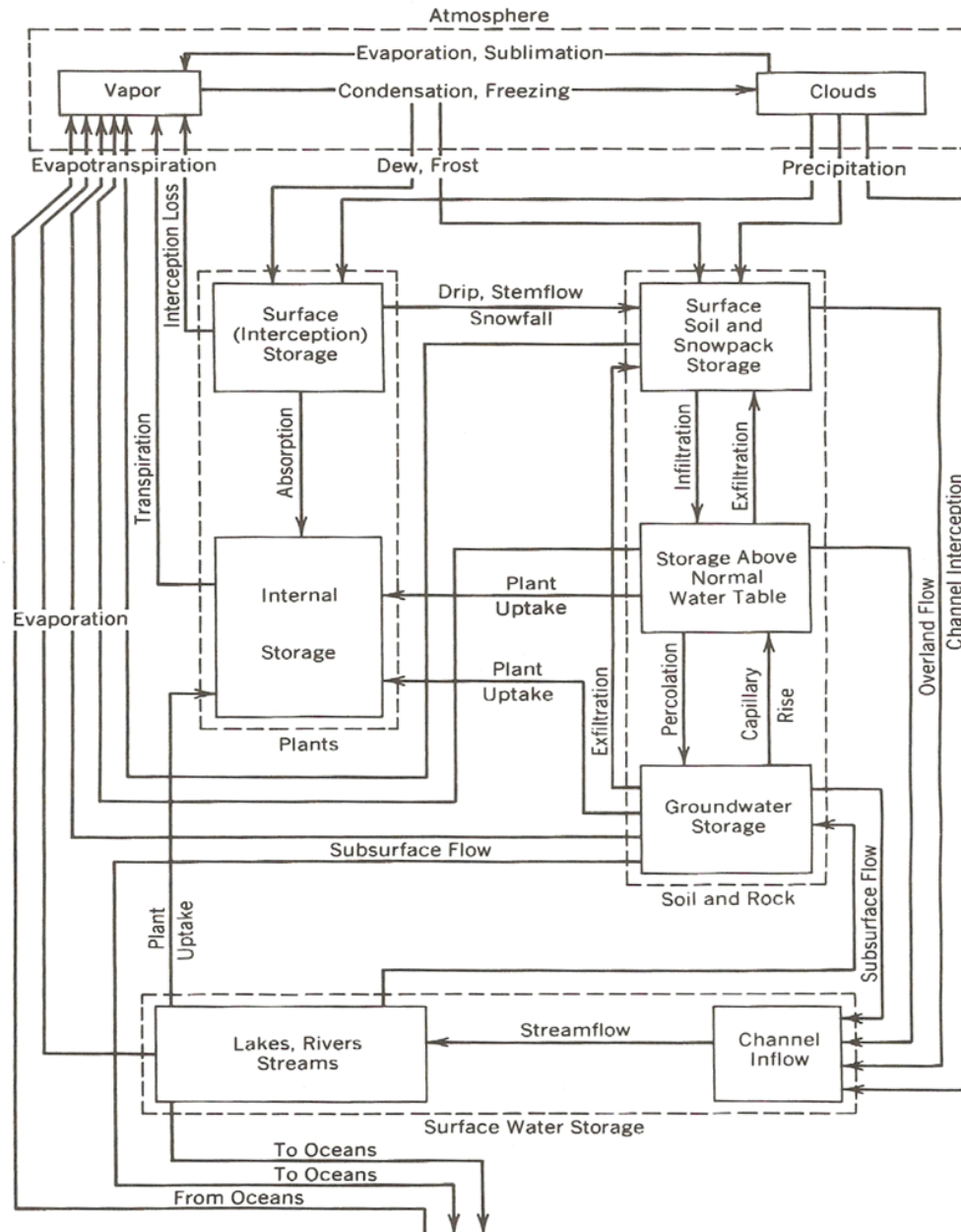


Figure 1 – Schematic diagram of the hydrologic cycle – water movement and storage (reprinted from Satterlund and Adams, 1992, *Wildland Watershed Management*, Wiley, NY)

“Water is unique in that it simultaneously represents both the greatest flow of matter and a major flow of energy through terrestrial ecosystems. More than any other substance on earth, it ties together the cycle of matter and energy through its great mass and the latent heats of vaporization, fusion, and sublimation. It takes large amounts of energy to evaporate water and melt or sublimate ice; energy that is absorbed, moves with, and is released by water moving through the hydrologic cycle” (Satterlund and Adams 1992:106).

Energy Balance (Law of Conservation of Energy ...for solar radiation)

$$R_n + H_s + LE + G + M = 0$$

$R_n$  = net radiation

$H_s$  = sensible heat exchanged with the atmosphere

$LE$  = latent heat exchanged with the atmosphere (via fusion, vaporization, sublimation)

$G$  = heat exchanged with the ground (soil) and vegetation

$M$  = metabolic heat of photosynthesis and respiration

“Exchange” [or transfer] is the key word ...it happens at the “active surface” (Geiger, 1959)

Geiger, Rudolph., 1959. *The Climate Near the Ground*. Translated by Stewart et al., Harvard University Press, Cambridge, Massachusetts [...focusing on the ~100 meters of the atmosphere near the earth’s surface ...mature trees are 20 to 40 meters tall]

Because  $G$  and  $M$  are relatively constant, and small relative to the other terms, and since all energy is derived from the sun ...a simplified energy balance can be written as

$$R_n = H_s + LE$$

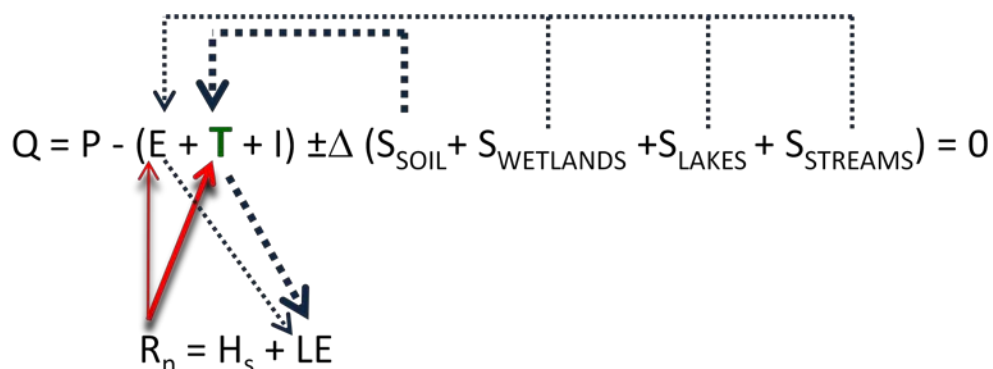
Net radiation (solar and terrestrial) influences, and is influenced by, sensible heat transfer (conduction and convection) and changes in state (ice, liquid water, water vapor) of water (latent heat transfer)

- ♦ Fusion ...melting or freezing
- ♦ Vaporization ...evaporation or condensation
- ♦ Sublimation ...ice directly to water vapor ...or water vapor directly to ice

Simplified water balance equation for the growing season (no snow, plants hydrated)

$$P - (E + T + I) - Q \pm \Delta (S_{SOIL} + S_{WETLANDS} + S_{LAKES} + S_{STREAMS}) = 0$$

...then solved for water yield ( $Q$ ) and related to the energy balance (on clear day with a dry forest canopy)



Trees (and other vascular plants) are *not* passive wicks. They *actively* regulate the flow of water and gases. They respond in minutes to changes in environmental conditions.

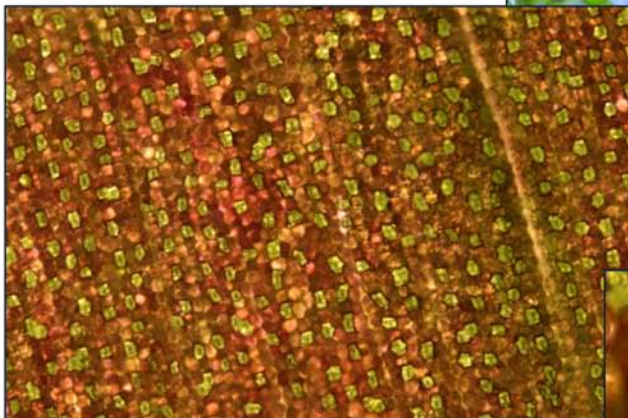
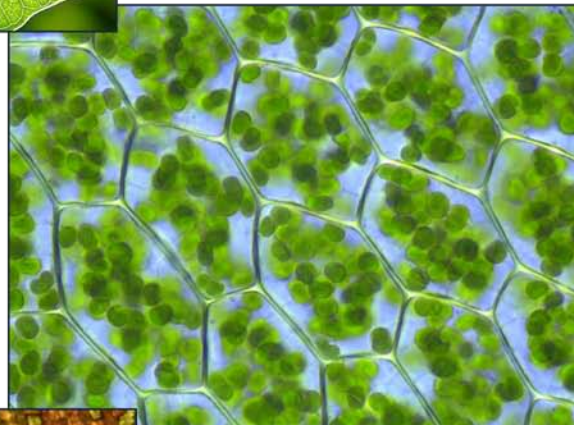


Plants!

The original solar collector

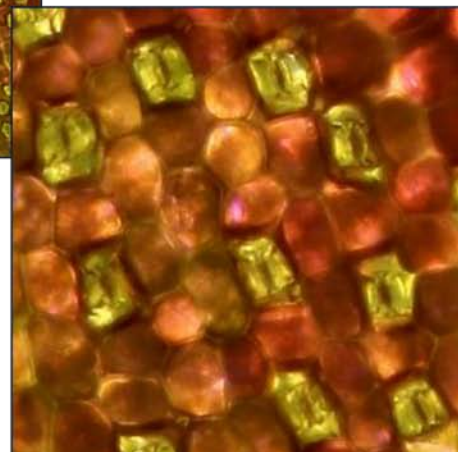
Millennial nano[bio]technology

Chloroplasts  
for photosynthesis



Stomata  
for gas exchange  
(CO<sub>2</sub> and water vapor)

Stomata enlarged  
to show guard cells



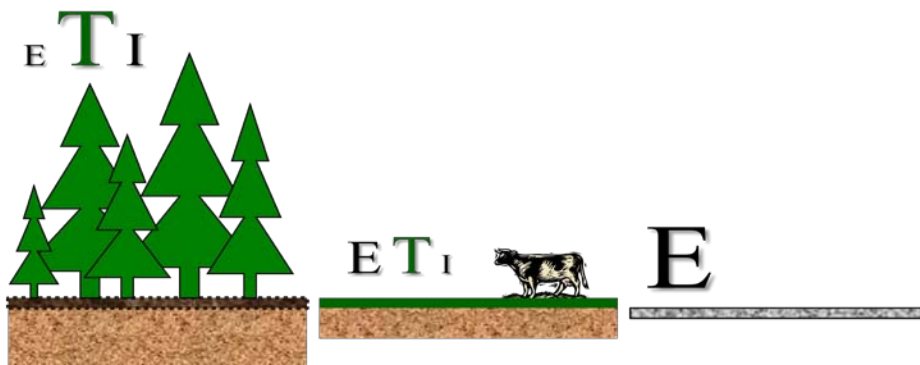
Wikipedia images

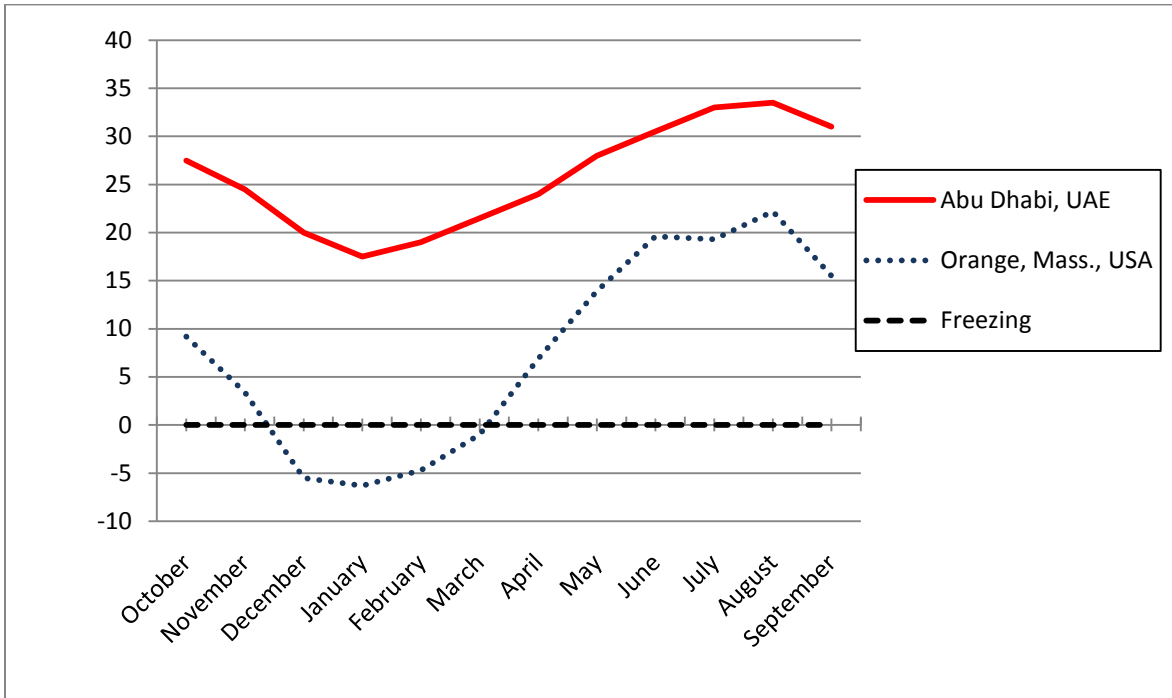
## Soil-Plant-Atmosphere Continuum

<b>Atmosphere</b>	<b>Atmosphere</b>	<i>Atmosphere</i> – source and sink for water and global circulation system
<b>Plant</b>	↑↓	<i>Forest</i> – a complex community of plants, animals, and microorganisms
	<b>Forest</b>	
	↑↓	<i>Tree</i> –vegetative canopy of the forest ...the primary active surface for radiant energy exchange ...aerodynamically rough surface for evaporation and transpiration
	<b>Tree</b>	
	↑↓	<i>Leaf</i> – solar collector, heat and gas exchanger, reaction vessel, food producer, etc.
	<b>Leaf</b>	
	↑↓	<i>Stomata</i> –specialized structures where carbon dioxide enters the leaf and water vapor and oxygen (from transpiration and photosynthesis) exit to the atmosphere
	<b>Stomata</b>	
	↑↓	<i>Xylem</i> vessel elements transmits water and nutrients (N,P,K, etc.) up from the roots, through the stem, to the leaves; <i>phloem</i> vessel elements transmit the products of photosynthesis (sugars) throughout the plant.
	<b>Xylem and phloem</b>	
	↑↓	
	<b>Roots</b>	<i>Roots</i> –structural supports and absorbers of water and nutrients
	↑↓	
<b>Soil</b>	<b>Soil</b>	<i>Soil</i> –a complex assemblage of mineral and organic components, air, and water that supports and sustains plants and moderates water flow

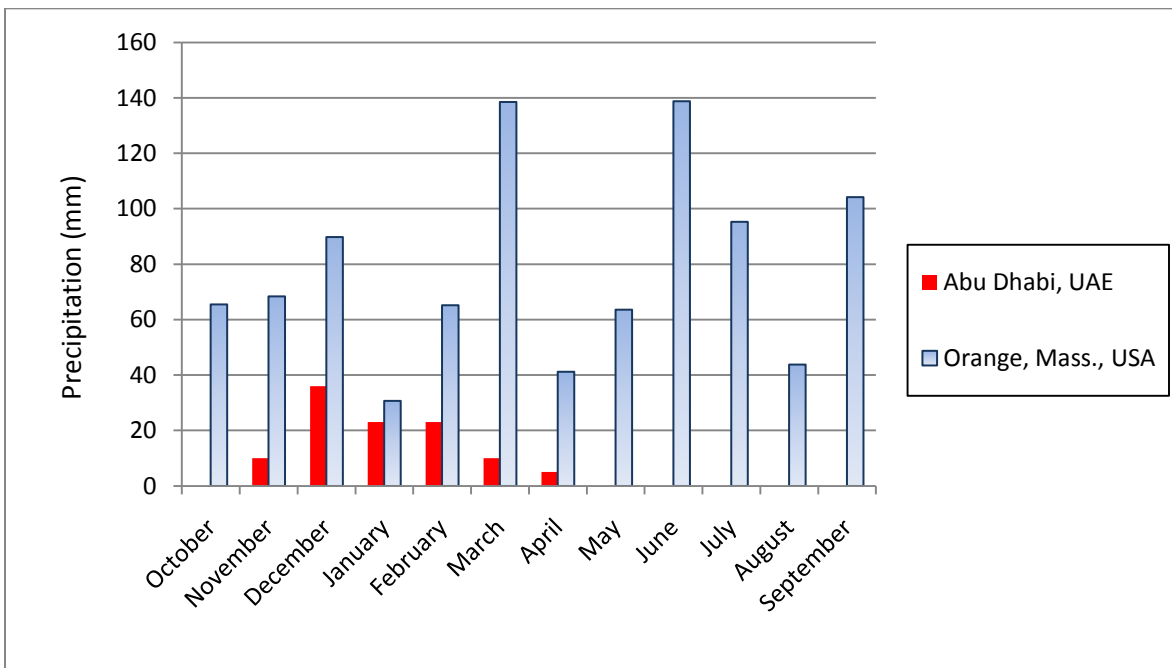
The soil-plant-atmosphere continuum is:

- ♦ a dynamic and responsive system
- ♦ an intricate and complex system in which every part is essential
- ♦ sustained and perpetuated by redundant components
- ♦ robust, resilient, durable, regenerative, ... a marvel of nature



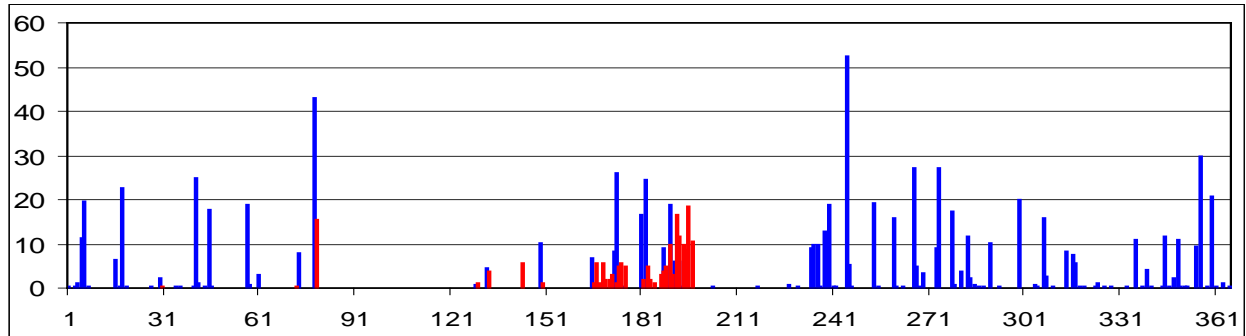


Comparison of monthly mean air temperatures in Abu Dhabi and central Massachusetts

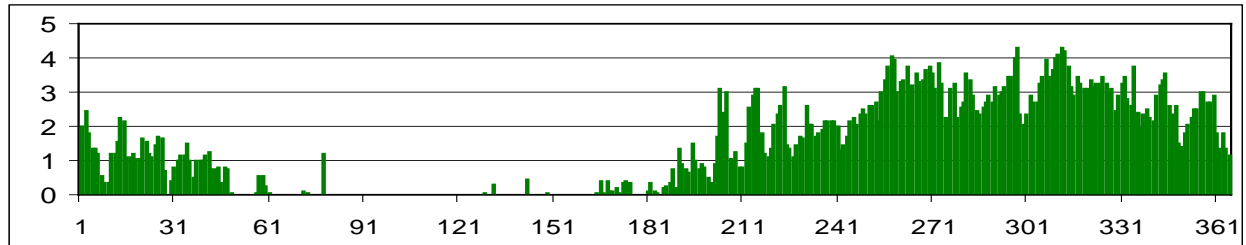


Comparison of monthly mean precipitation in Abu Dhabi and central Massachusetts

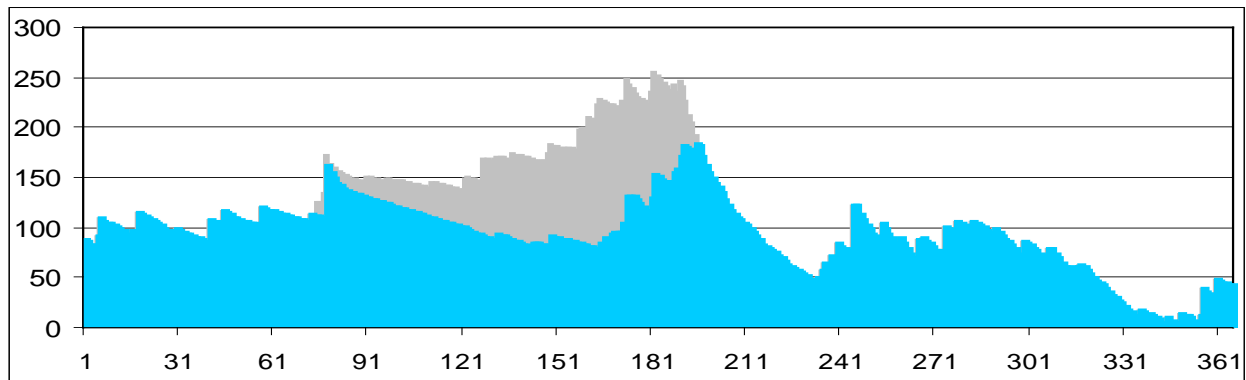
Measured rain (blue bars) and predicted snowmelt (red bars), units = mm/day



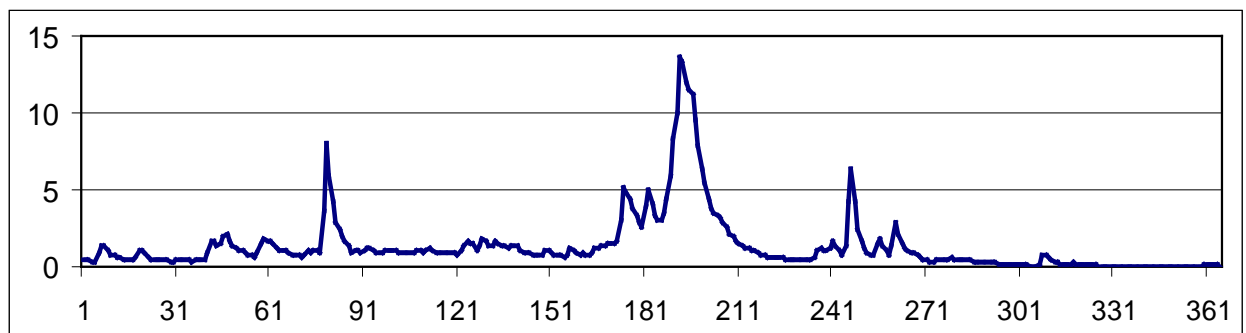
Evapotranspiration (mm/day)



Storage in soils, wetlands, lakes, and ponds (light blue) and the snowpack (grey) (mm)

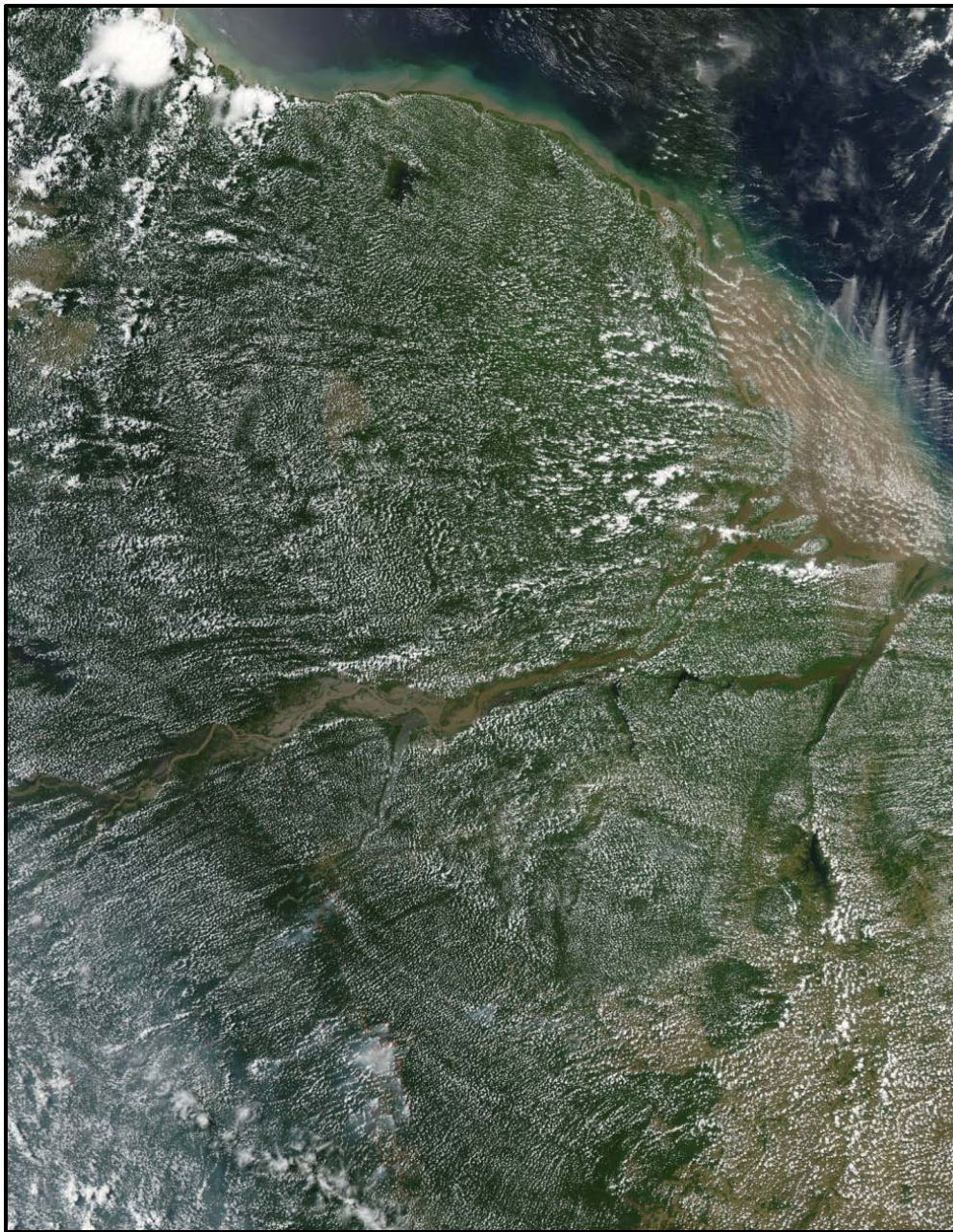


Mean daily streamflow [Q, water yield] (mm/day)



Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep

Water balance components for the 2001 Water Year in the East Branch of the Swift River watershed in north-central Massachusetts (tributary to the Quabbin Reservoir); adapted from de la Crétaz and Barten (2007). *Note the difference in vertical scales.* Data sources: NOAA National Weather Service and U.S. Geological Survey. Evapotranspiration was calculated from air temperature using the Thornthwaite method.



Afternoon  
clouds produced  
by transpiration  
over the  
Amazon  
rainforest in  
Brazil

Jeff Schmaltz

NASA  
Earth  
Observatory

Goddard Space  
Flight Center

*Most deeply, an ethic of stewardship is about respecting the beauty and mystery of the natural world we did not create and cannot fully understand, but over which we have acquired dominance. It is about adding a healthy dose of humility as an antidote to our past hubris. And it is about applying the best of our science, policy, and technology not to further manipulate nature but to better adapt ourselves to its time-tested, life-sustaining cycles.*



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Sandra Postel and Brian Richter, 2003  
*Rivers for Life: Managing Water for People and Nature*