# The Global Water and Energy Cycle

The Global Water and Energy Cycle

# The Hydrosphere:
## *Lecture 1: Basic Hydrologic Concepts*

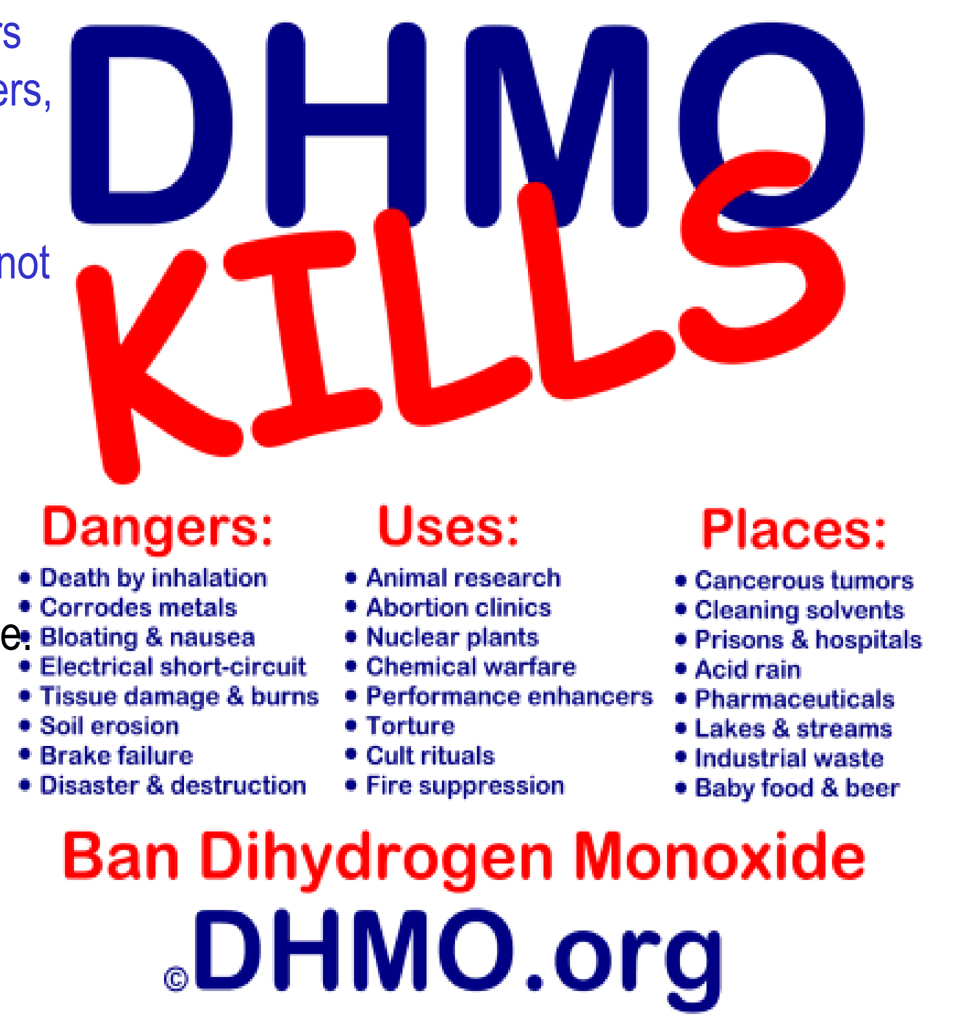
# The Truth about DIHYDROGEN MONOXIDE

**Dihydrogen Monoxide** (DHMO) is perhaps the single most prevalent of all chemicals that can be dangerous to human life. Despite this truth, most people are not unduly concerned about the dangers of Dihydrogen Monoxide. Governments, civic leaders, corporations, military organizations, and citizens in every walk of life seem to either be ignorant of or shrug off the truth about Dihydrogen Monoxide as not being applicable to them.

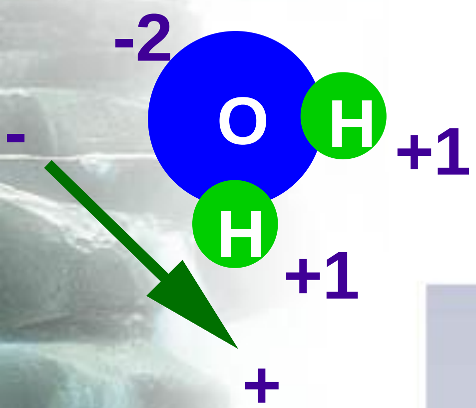
- also known as **hydric acid**, and is the major component of acid rain.
- contributes to the **greenhouse effect**.
- may cause **severe burns.**
- contributes to the **erosion** of our natural landscape.
- accelerates **corrosion and rusting**.
- may cause **electrical failures** and decreased effectiveness of automobile brakes.
- has been found in excised **tumors**.

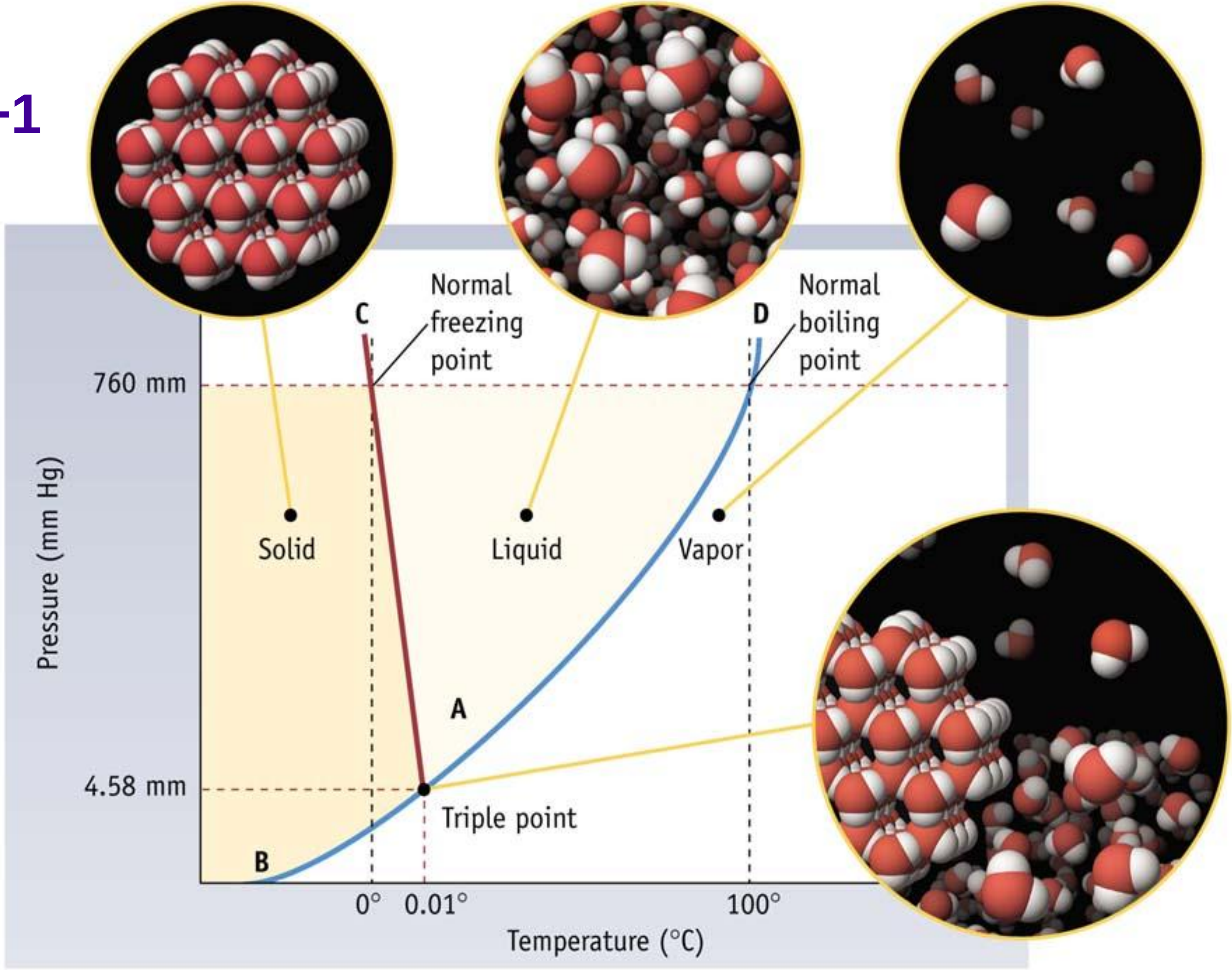
*Write your Congressman!*

*Get the T-Shirt, Only $18.95!*



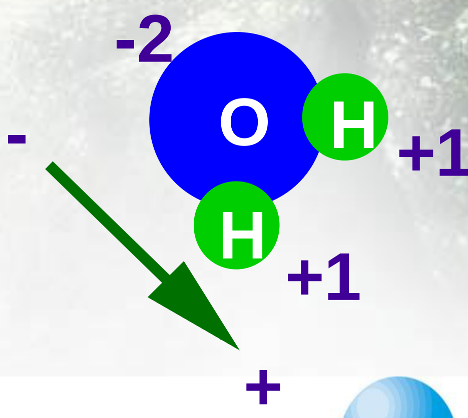
# Water Science: the unique molecule



# Water Science: the unique molecule

**Unusual Properties of Water (mostly due to its dipole)**




**1) Water is a liquid at room temperature**

- Higher melting and boiling point than other hydrogen compounds.

**2) The density of solid water (ice) is less than liquid water**

- Ice floats on water

**3) Water has a relatively high heat capacity**

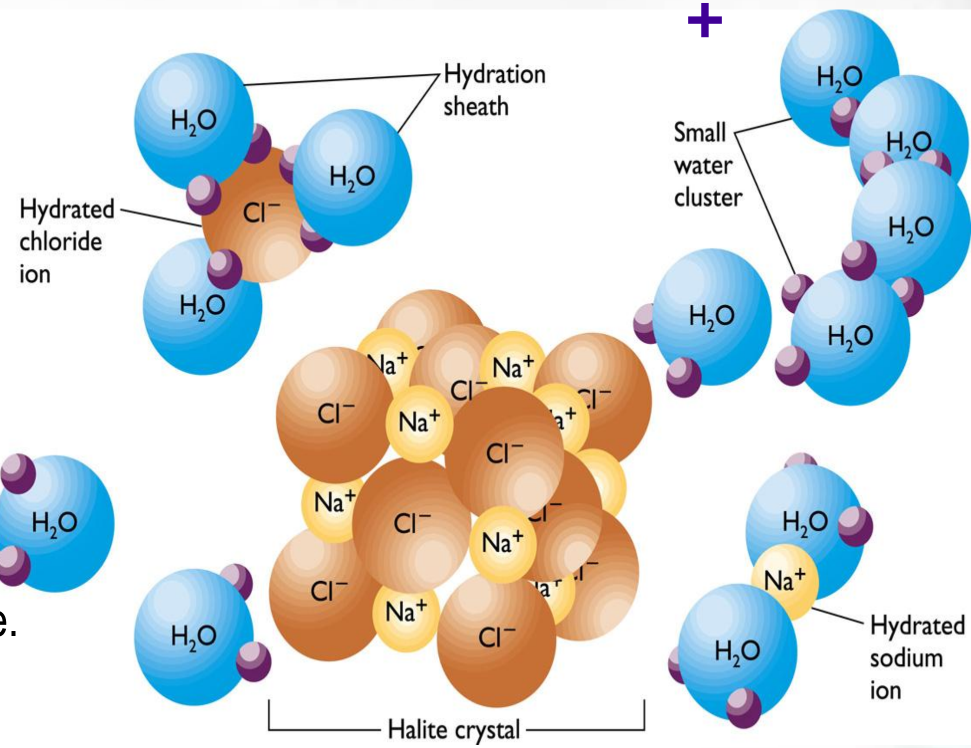
- About 10 times that of Copper or Iron
- The climate of earth is moderate

**4) Water has a relatively high heat of vaporization**

- The evaporation of water has a cooling effect

**5) Water is an excellent solvent**

- Many ionic compounds are soluble in water
- Greater solvent power than an other substance.




**6) Surface tension & Capillary Action**

Water "sucks"

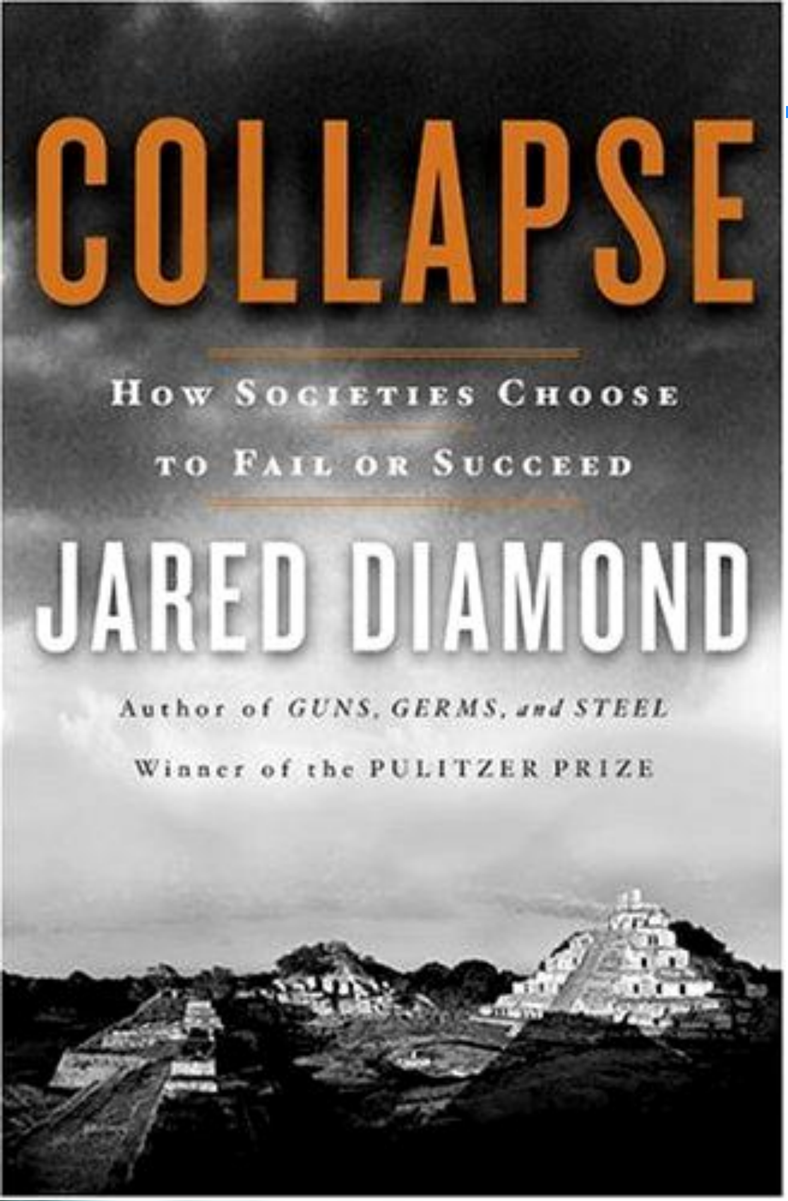
# Unique Properties of Water

- Without doubt, water is the most important substance on Earth
- sustains life as we know it
- exerts a major control on our climate from the local to the global scale
- dominates the processes of landscape evolution
- Is a unique substance:
  - exists in all three phases at natural Earth surface temperatures and pressures.
  - has a liquid phase that is more dense than the solid phase at 4˚C
  - is the most abundant substance on Earth
  - YET in all water's abundance, only a miniscule fraction is available to sustain life and it varies tremendously from place to place.

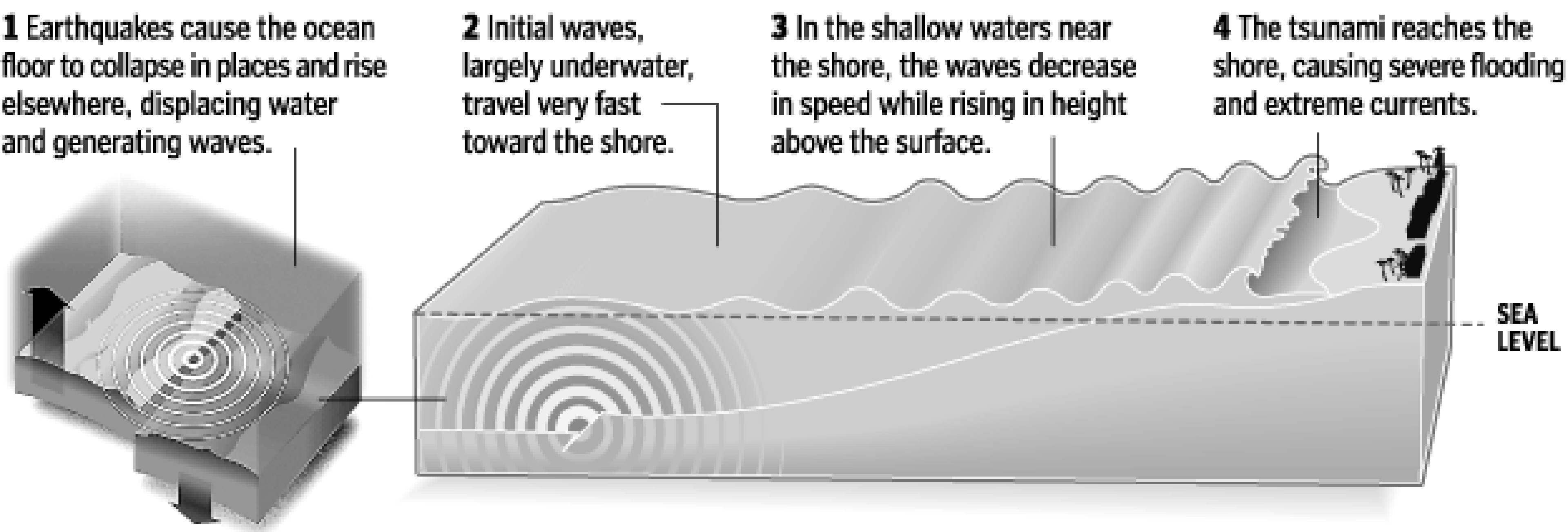
  - high **specific heat（tremendously storage of energy）**
  - Water in a pure state has a neutral **pH**
  - exists as a liquid over an important range of temperature from 0 - 100° Celsius
  - Water **conducts** heat more easily than any liquid except mercury（水银）

# Sciences of Water Quantity

- Hydrology
- Physical Geography
- Geology
- Limnology & Ecology
- Climatology, Oceanography
- Social Science: Human Geography, Sociology, Economics, Anthropology

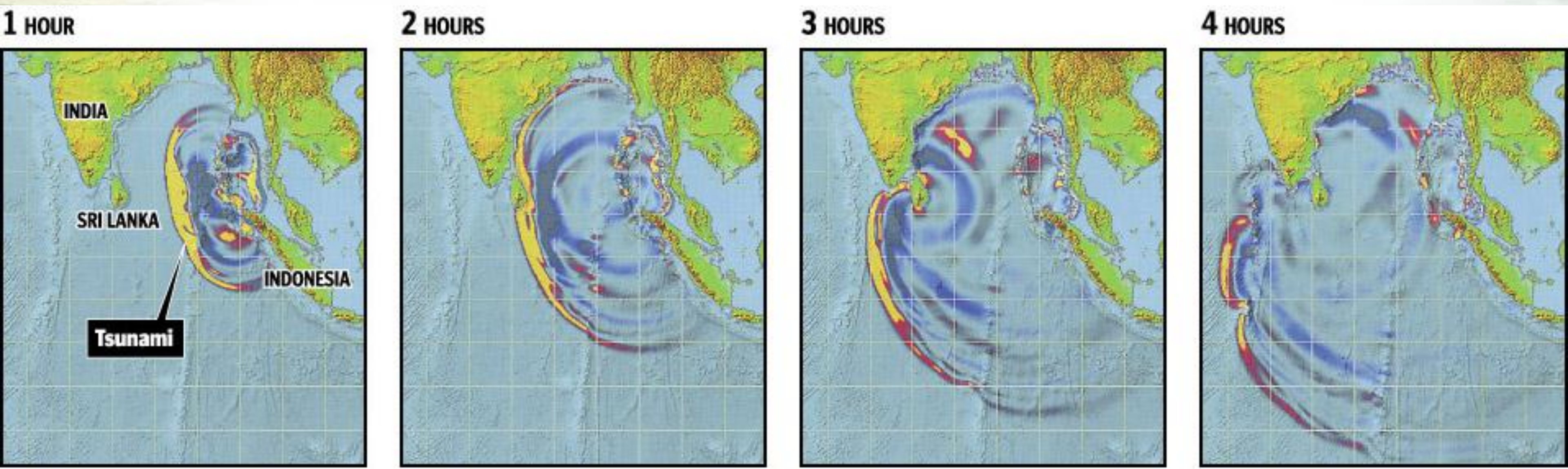



**One Hypothesis: Increased flooding caused by climate change effects can lead to an increase in unwelcome shark attacks.**



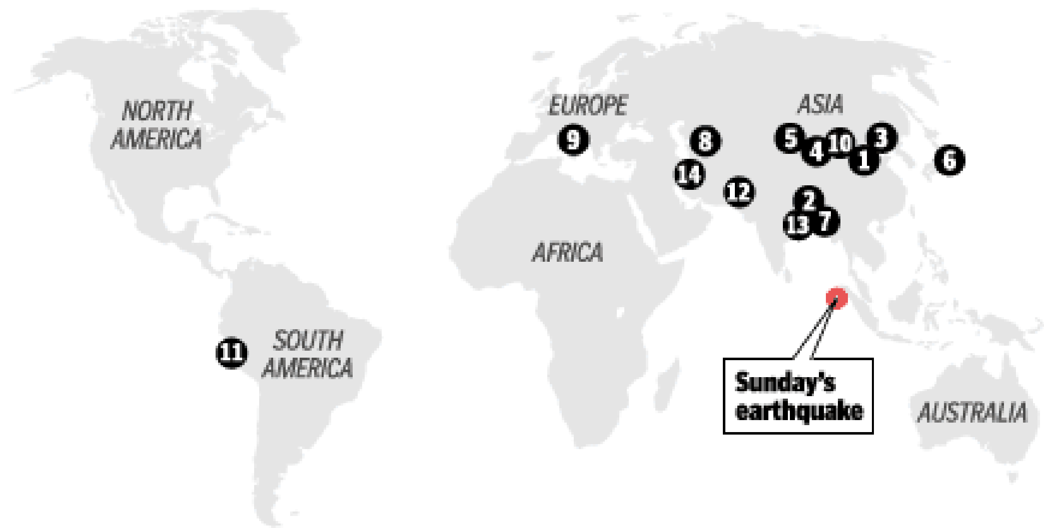

SOURCES: Staff reports, Associated Press
ILLUSTRATION BY THE ASSOCIATED PRESS; GRAPHIC BY THE WASHINGTON POST

# Water is the interface between the Geo-Spheres…..



| Year | Location | Estimated Cost |
|---|---|---|
| 1995 | Japan, Kobe Earthquake | $95 Billion |
| 1992 | United States, Hurricane Andrew | $30 Billion |
| 2004 | Japan, Niigata Earthquake | $25.9 Billion |
| 1988 | Soviet Union, Armenian Earthquake | $20.5 Billion |
| 1980 | Italy, Irpinia Earthquake | $20 Billion |
| 1998 | China, Yangtze Flood | $20 Billion |
| 1991 | Soviet Union, Flood | $19 Billion |
| 1997 | Indonesia, Wild Fires | $17 Billion |
| 1995 | United States, Northridge Earthquake | $16 Billion |
| 1994 | North Korea, Flood | $15 Billion |
| **2004** | **Southern Asia, Earthquake and Waves** | **$13.6 Billion** |
| 1993 | United States, Midwest Flooding | $12 Billion |

2005: Hurricane Katrina and USA Gulf States: $Billions and counting….




| | YEAR | LOCATION | EVENT | ESTIMATED DEATH TOLL |
|---|---|---|---|---|
| 1 | 1931 | Huang He River, China | Flood | 3.7 million |
| 2 | 1970 | Bangladesh | Cyclone | 300,000 |
| 3 | 1976 | Tangshan, China | Earthquake | 255,000 |
| 4 | 1920 | Gansu, China | Earthquake | 200,000 |
| 5 | 1927 | Tsinghai, China | Earthquake | 200,000 |
| 6 | 1923 | Kanto, Japan | Earthquake | 143,000 |
| 7 | 1991 | Bangladesh | Cyclone | 139,000 |
| 8 | 1948 | Turkmenistan | Earthquake | 110,000 |
| 9 | 1908 | Messina, Italy | Earthquake | 70,000-100,000 |
| 10 | 1932 | Gansu, China | Earthquake | 70,000 |
| 11 | 1970 | Peru | Earthquake | 66,000 |
| 12 | 1935 | Quetta, Pakistan | Earthquake | 30,000-60,000 |
| 13 | 1942 | Bengal, India | Hurricane | 40,000 |
| 14 | 1990 | Iran | Earthquake | 40,000-50,000 |

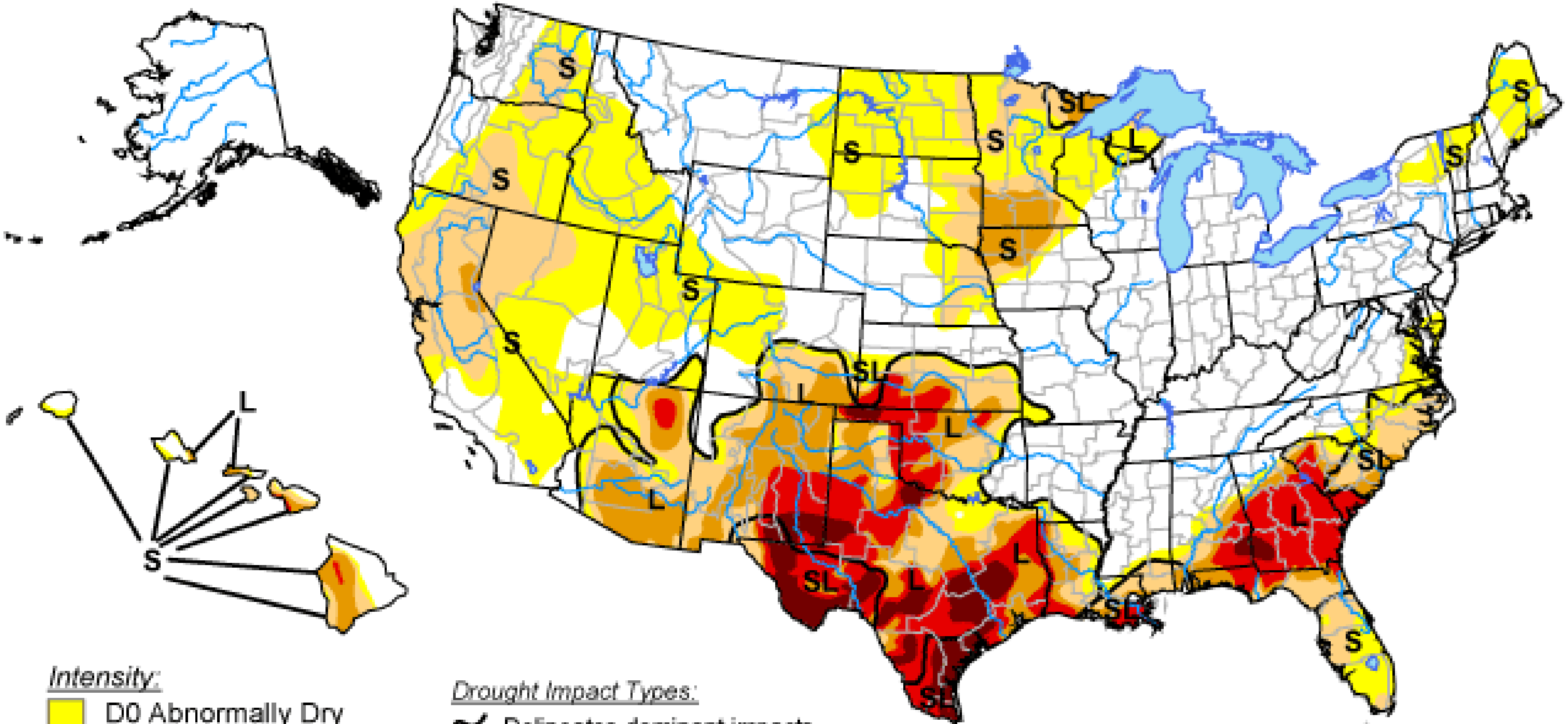
SOURCES: U.S. Geological Survey, The World Almanac

THE WASHINGTON POST

**ıser**, 25 January 2012, Page 11

# U.S. Drought Monitor

**January 17, 2012**
Valid 7 a.m. EST



*Intensity:*

- D0 Abnormally Dry
- D1 Drought - Moderate
- D2 Drought - Severe
- D3 Drought - Extreme
- D4 Drought - Exceptional

*Drought Impact Types:*

~ Delineates dominant impacts

S = Short-Term, typically <6 months
(e.g. agriculture, grasslands)

L = Long-Term, typically >6 months
(e.g. hydrology, ecology)

*The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.*

**http://droughtmonitor.unl.edu/**

***Released Thursday, January 19, 2012***

***Author: Laura Edwards, WRCC, South Dakota State University***

Figure 2.1 Distribution of the global population not served with improved water supply, by region

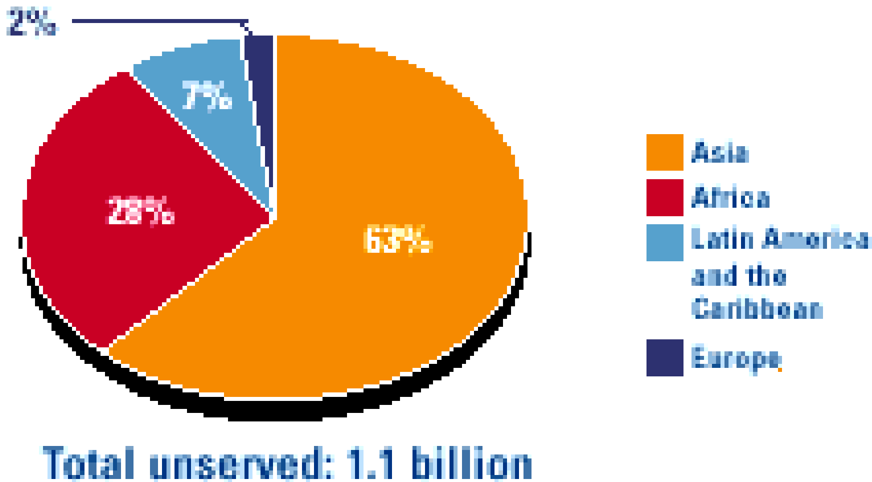
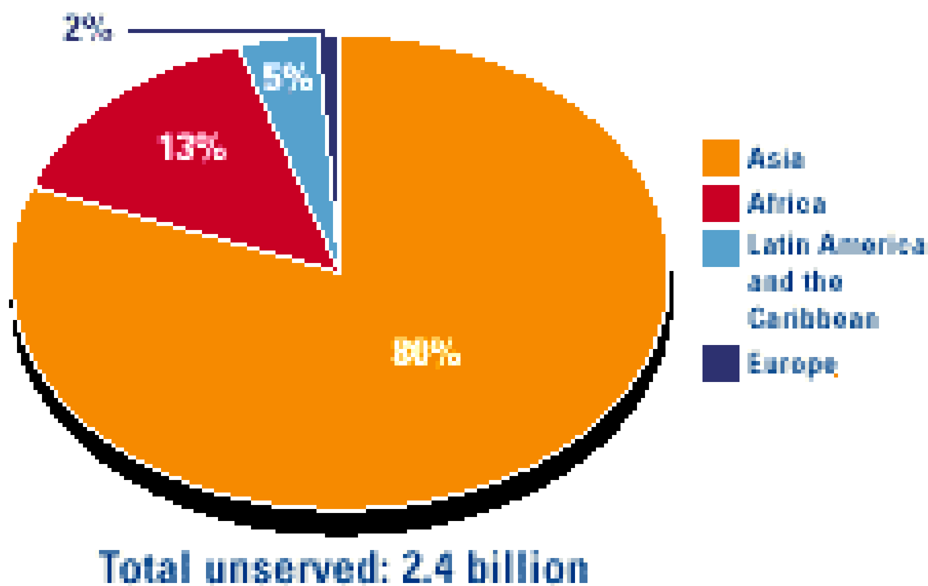


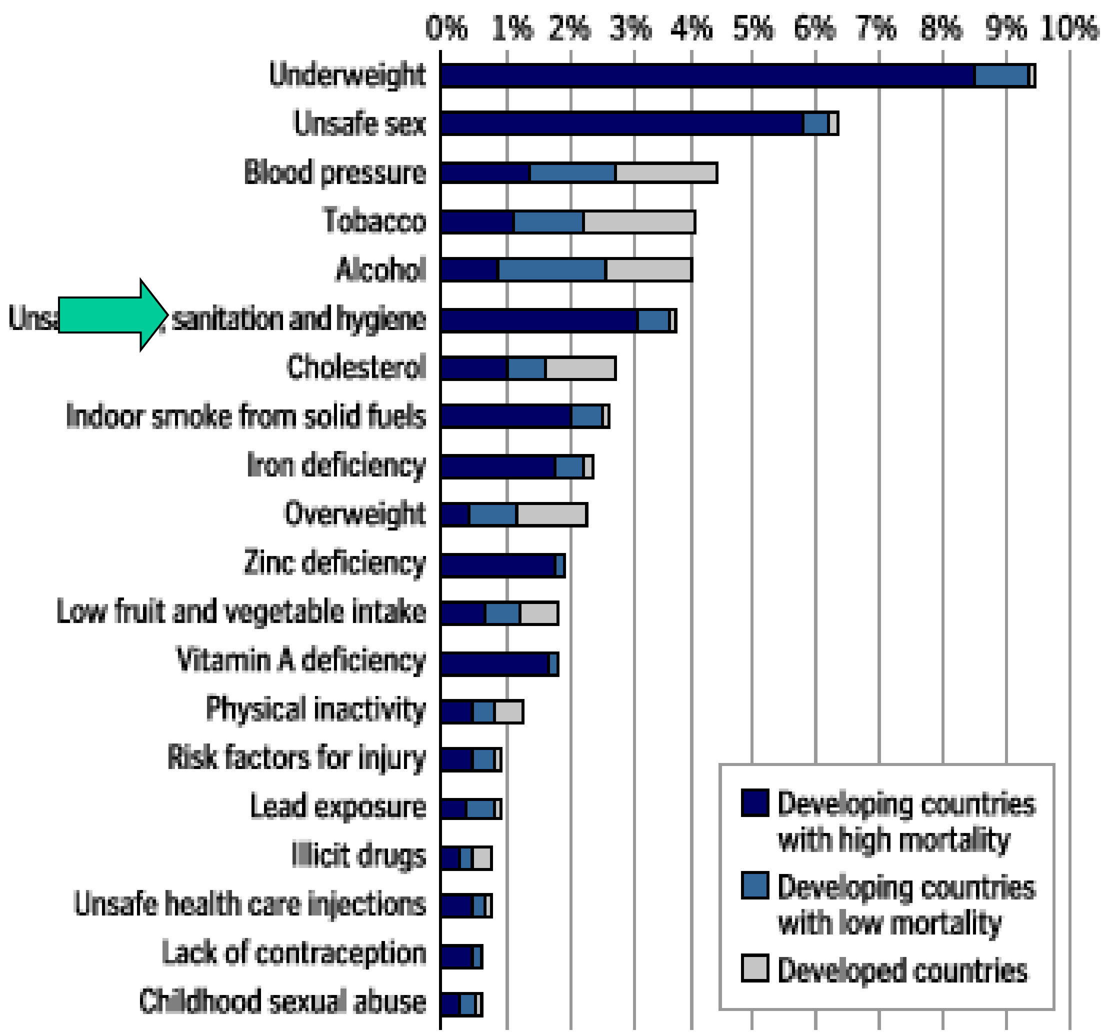

Figure 2.2 Distribution of the global population not served with improved sanitation, by region



# Causes of Early Death

*Starvation contributed to the most lost life years in developing countries, according to a major World Health Organization study. Other high-ranking factors, such as blood pressure and tobacco use, shorten life spans in developing and developed countries.*

**Percentage of lost healthy life years attributable to 20 leading selected risk factors**




SOURCE: World Health Organization

THE WASHINGTON POST

http://www.who.int/whr/2002/chapter4/en/index10.html

# WHO Global Water & Sanitation Report

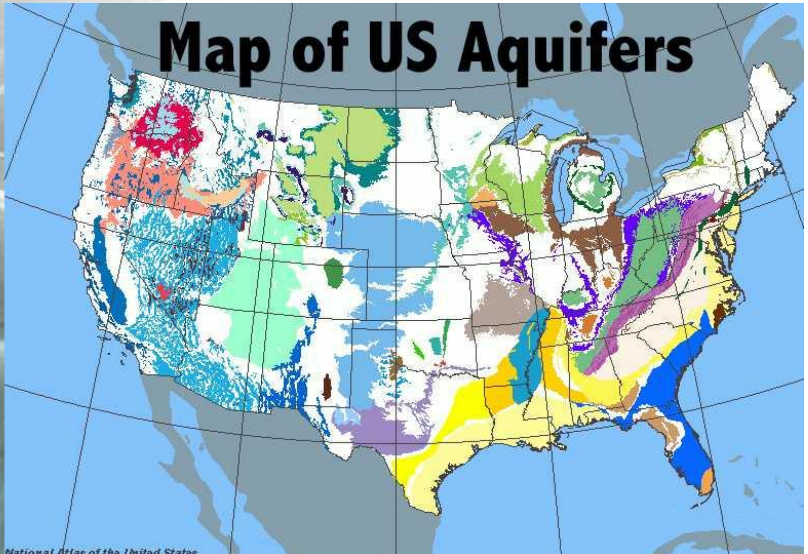
http://www.who.int/water_sanitation_health/Globassessment/Global1.htm#Top

- people served with some form of improved water supply rose from 79% (4.1 billion) in 1990 to 82% (4.9 billion) in 2000
- proportion of the world's population with access to sewage disposal facilities increased from 55% (2.9 billion people served) to 60% (3.6 billion) from 1990 to 2000
- The majority of those without access live in Asia and Africa, where fewer than one-half of all Asians have access to improved sanitation and two out of five Africans lack improved water supply
- Sanitation coverage in rural areas is less than half that in urban settings, even though 80% of those lacking adequate sanitation (2 billion people) live in rural areas – some 1.3 billion in China and India alone

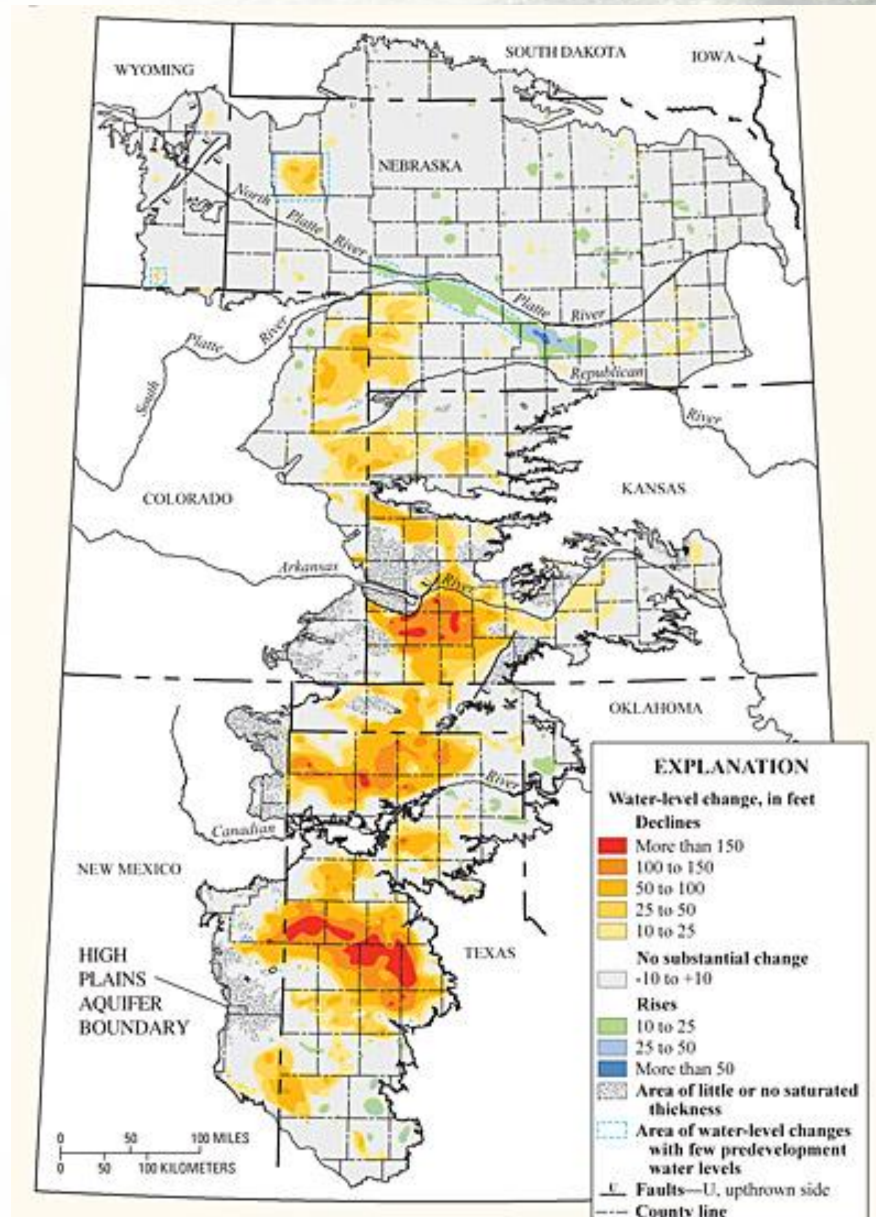
# Approximate residence time of water found in various reservoirs.

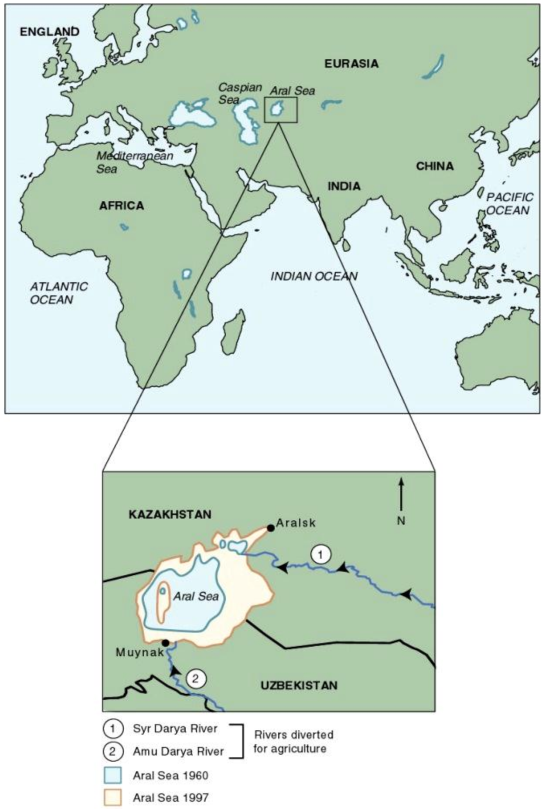
| Reservoir | Approximate Residence Time |
|---|---|
| Glaciers | 40 years |
| Seasonal Snow Cover | 0.4 years |
| Soil Moisture | 0.2 years |
| Groundwater: Shallow | 200 years |
| Groundwater: Deep | 10,000 years |
| Lakes | 100 years |
| Rivers | 0.04 years |

# Ground Water "Mining": depleting faster than recharge

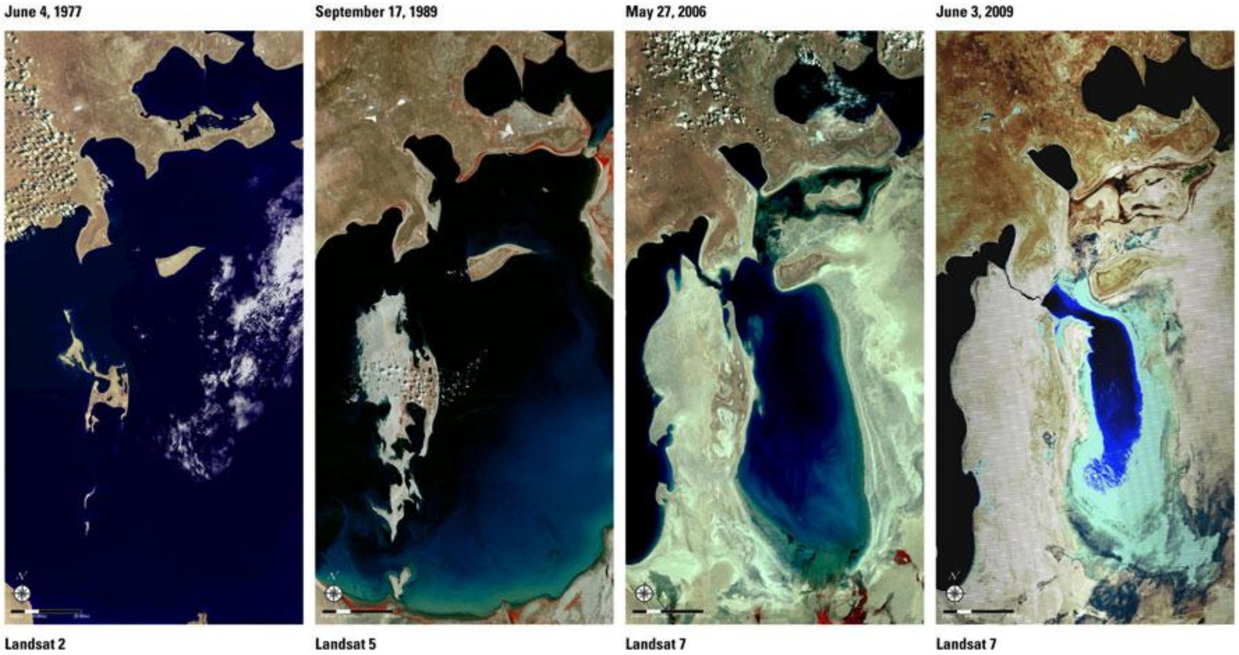



Pumping 1,200 gallons per minute on the H. Jones farm nine miles west of Hastings, NE. NSHS.






## Fig 20.9 The Aral Sea is drying up and dying as a result of diversion of water for agriculture.



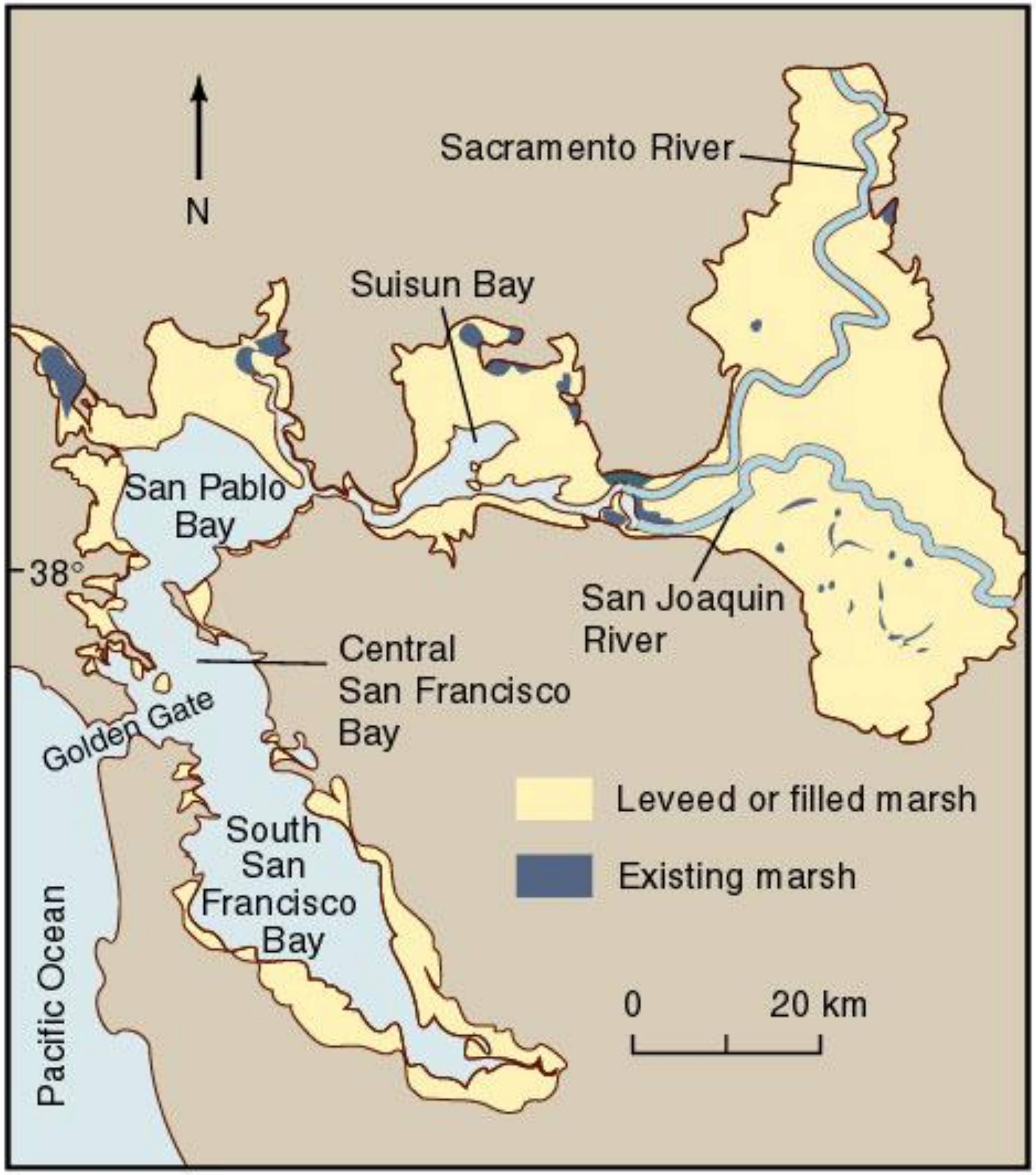
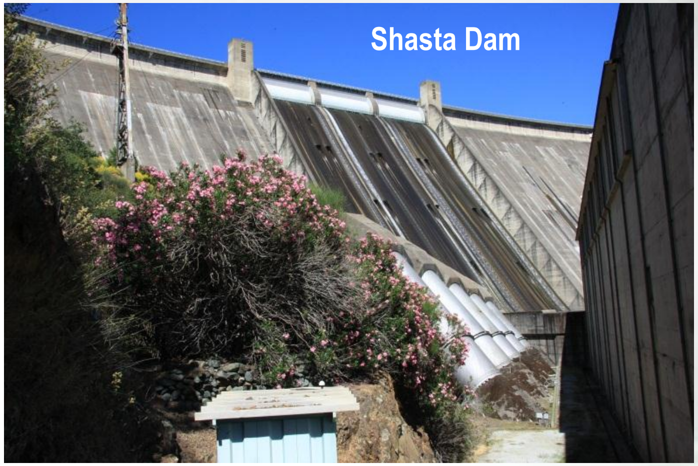
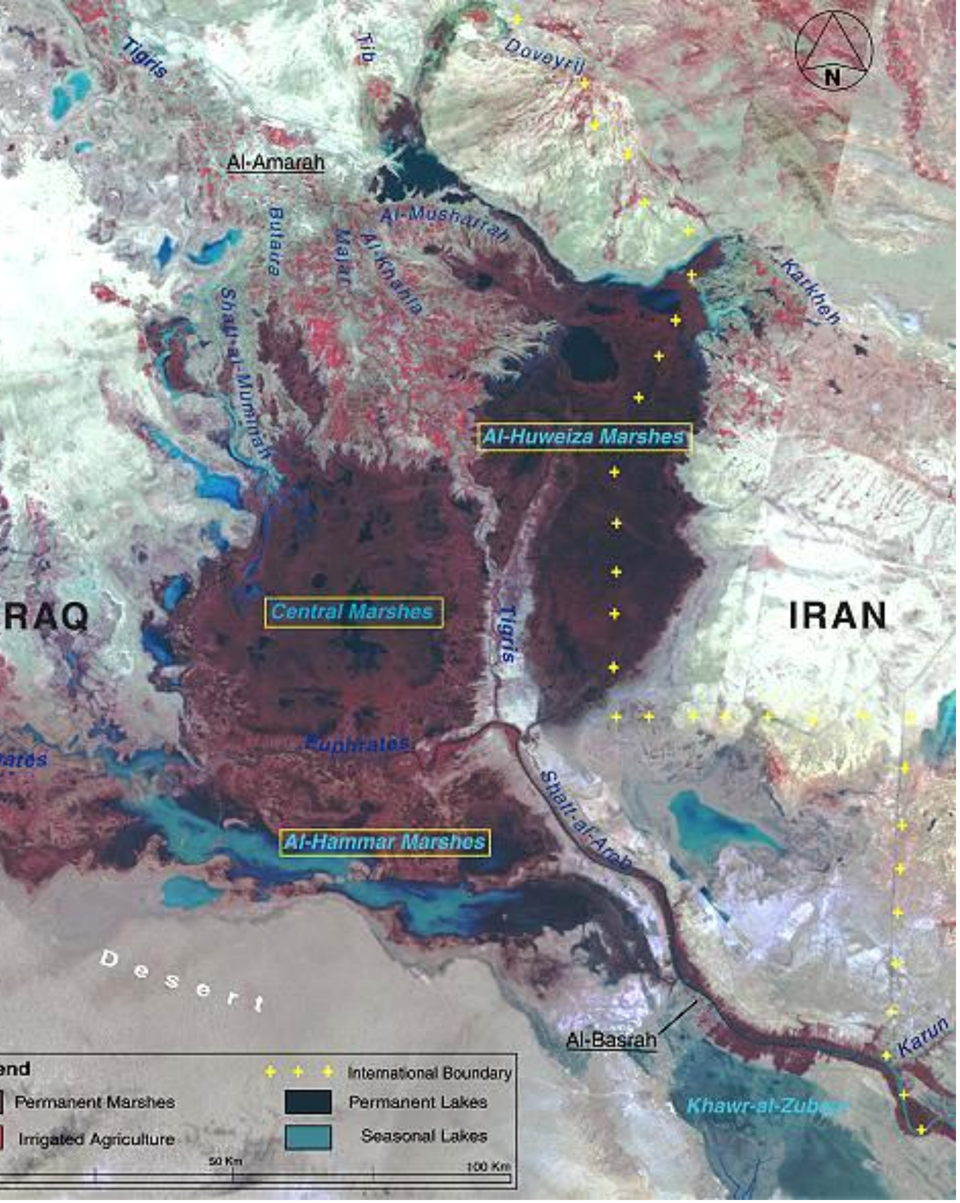




**Fig 20.15 Loss of marshlands in the San Francisco Bay and estuary from about 1850 to the present.**

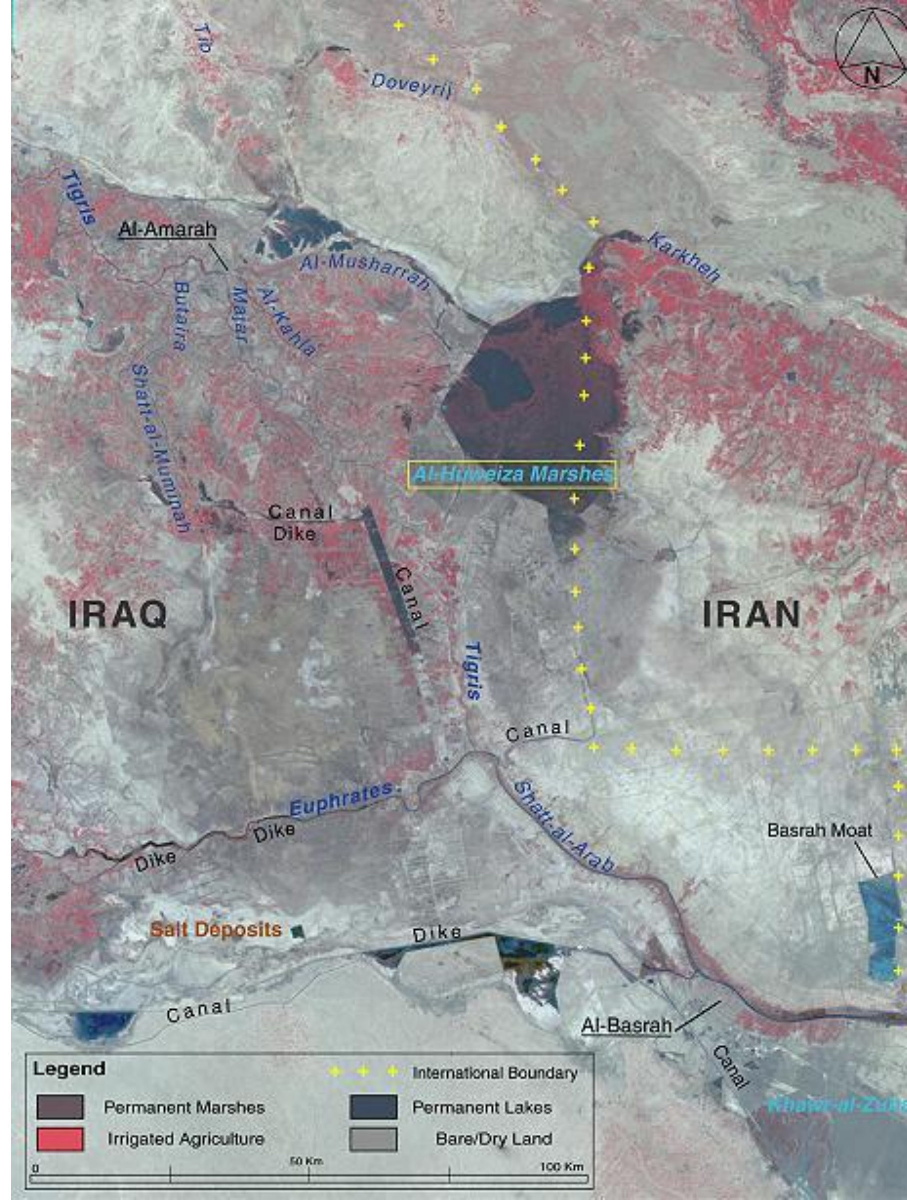



# Fig 20.23 The Colorado River basin.

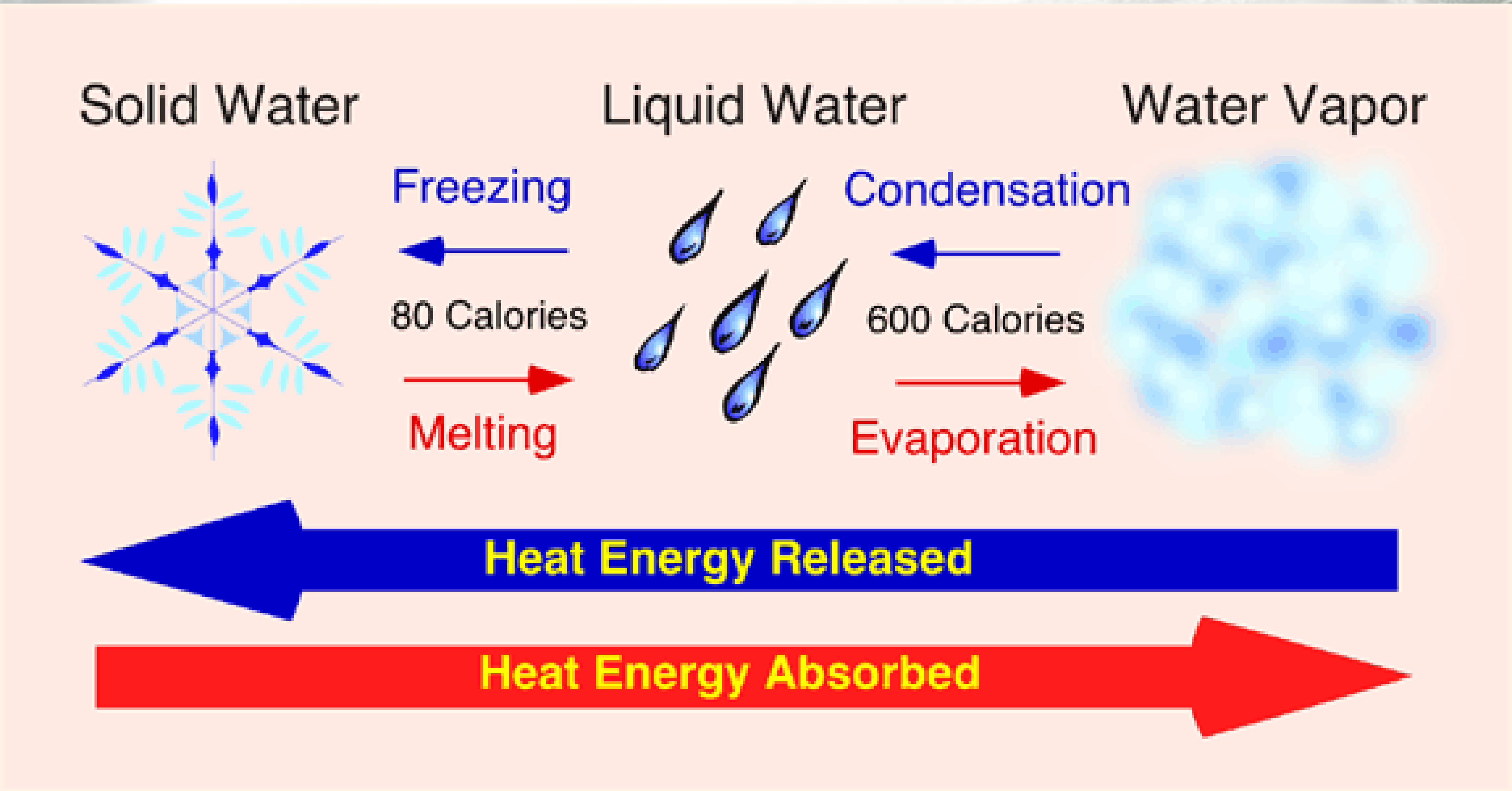
Tigris
Tib
Doveyrij
N
Al-Amarah
Al-Musharrah
Butaira
Majar
Al-Kahla
Karkheh
Shatt-al-Muminah
Al-Huweiza Marshes
Central Marshes
RAQ
IRAN
Tigris
Euphrates
Shatt-al-Arab
Al-Hammar Marshes
Desert
Al-Basrah
Karun
Permanent Marshes
Irrigated Agriculture
International Boundary
Permanent Lakes
Seasonal Lakes
50 Km
100 Km

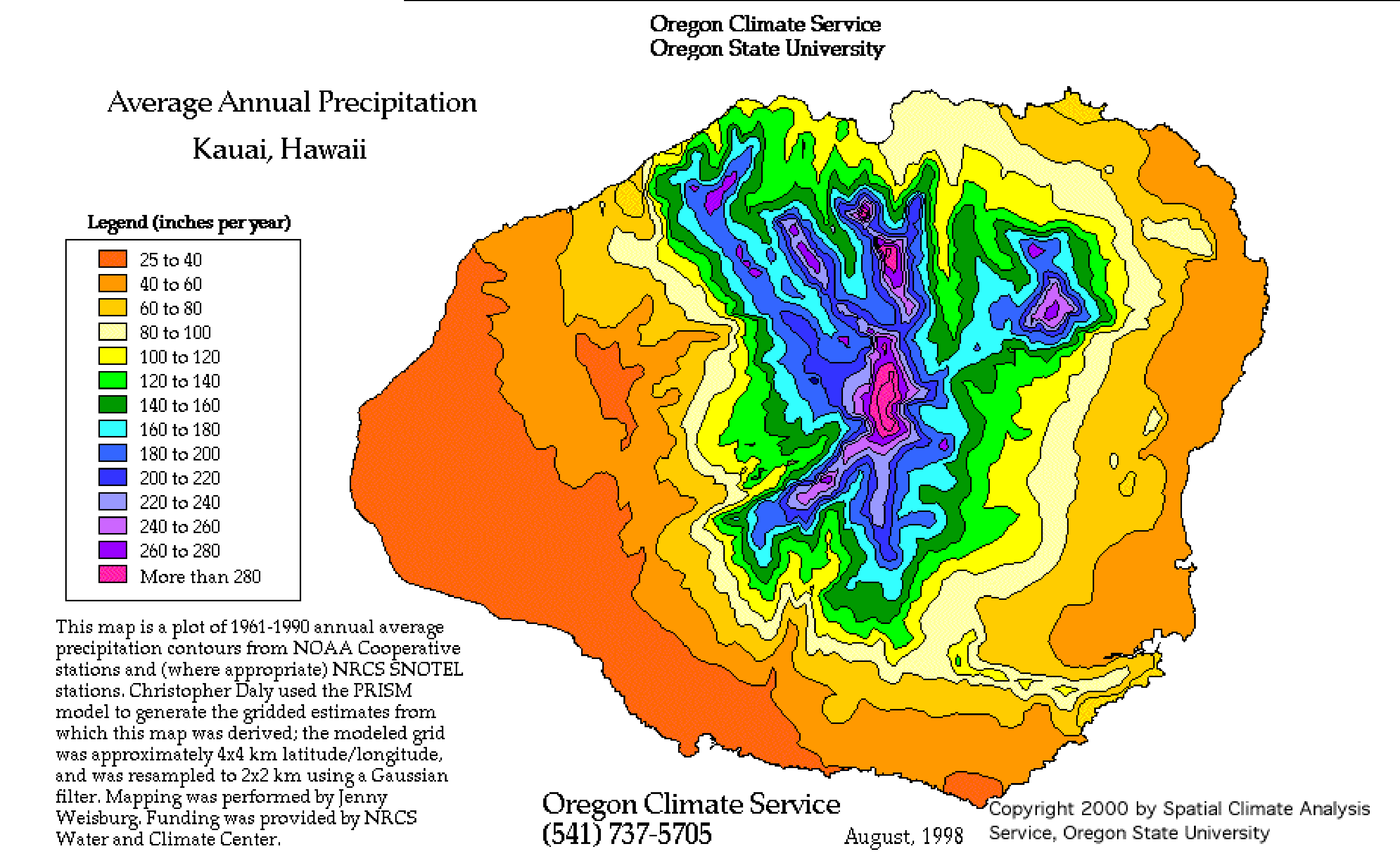

1973



Tib
Doveyrij
N
Tigris
Al-Amarah
Al-Musharrah
Karkheh
Butaira
Majar
Al-Kahla
Shatt-al-Muminah
Al-Huweiza Marshes
Canal
Dike
Canal
IRAQ
IRAN
Tigris
Canal
Euphrates
Dike
Dike
Shatt-al-Arab
Basrah Moat
Salt Deposits
Dike
Canal
Al-Basrah
Canal
Legend
International Boundary
Permanent Marshes
Permanent Lakes
Irrigated Agriculture
Bare/Dry Land
0
50 Km
100 Km


2000

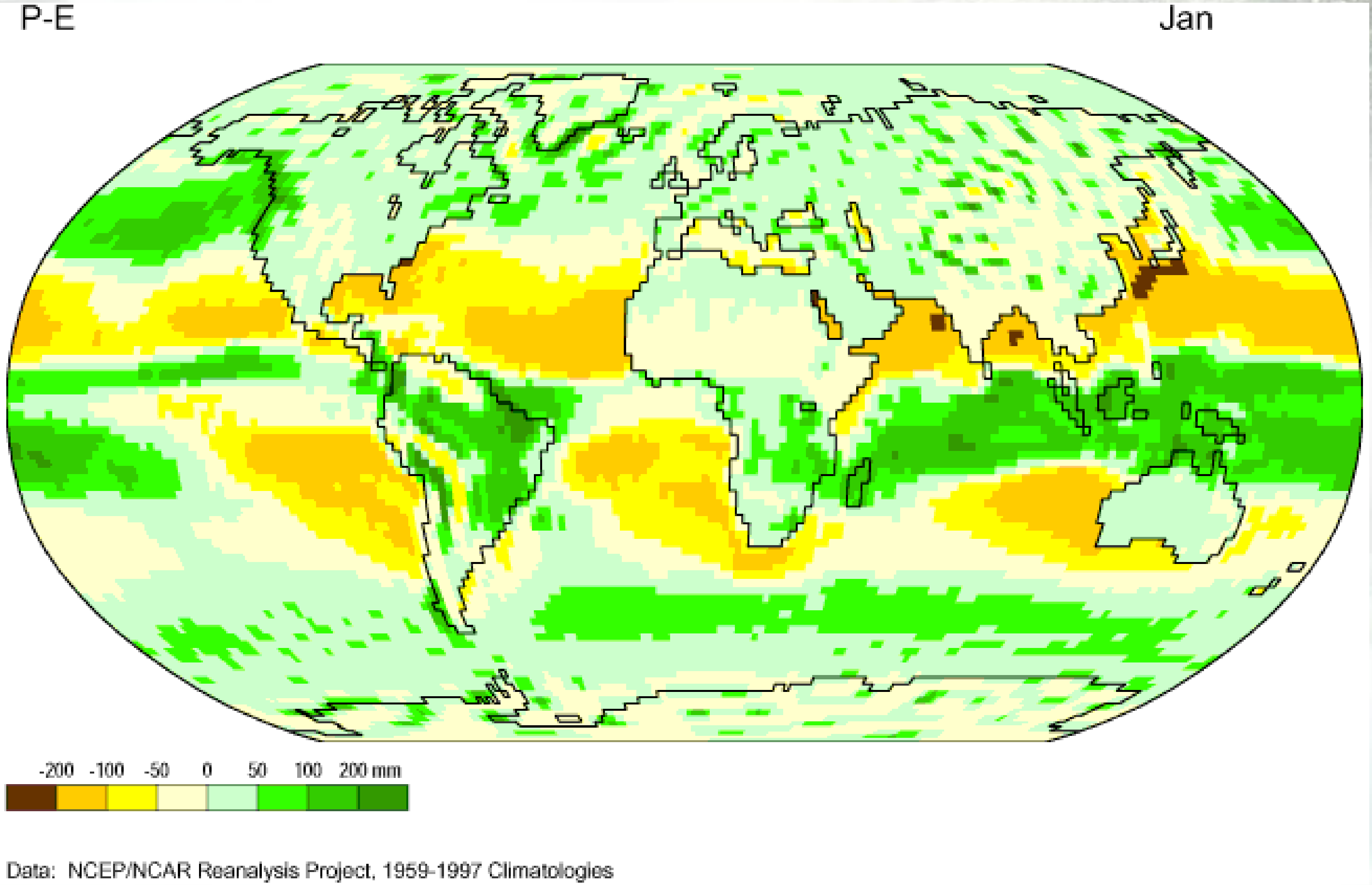

Solid Water
Liquid Water
Water Vapor
Freezing
80 Calories
Melting
Condensation
600 Calories
Evaporation
Heat Energy Released
Heat Energy Absorbed




**The wettest place in the world is Tutunendo, Colombia, with an average rainfall of 463.4 inches (1177 centimeters) per year. The place that has the most rainy days per year is Mount Wai-'ale'ale on the island of Kauai, Hawaii. It has up to 350 rainy days annually.**

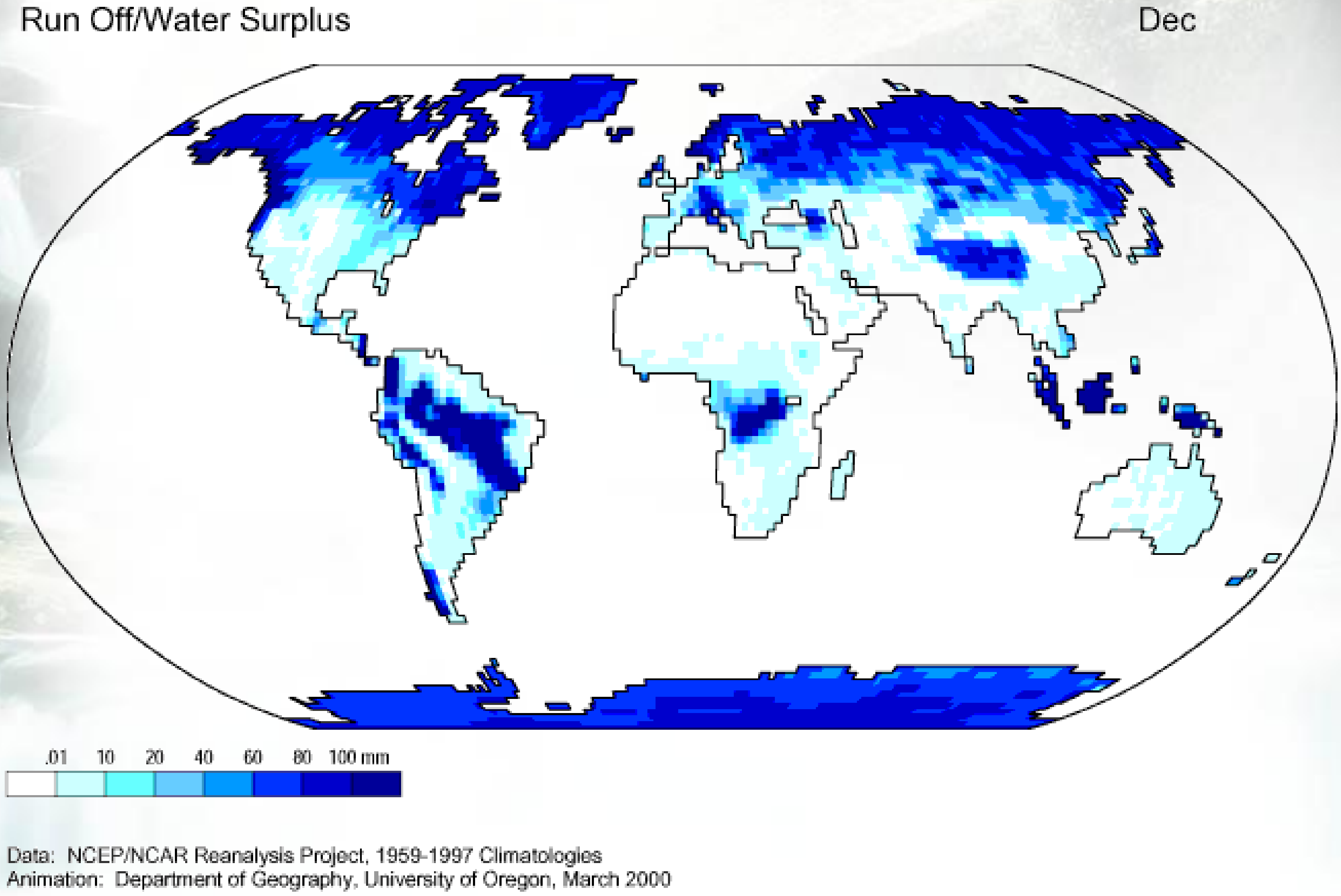
**In contrast, the longest rainless period in the world was 14 years, from October 1903 to January 1918, at Arica, Chile.**

# Precipitation minus evapotranspiration for an average January, 1959-1997




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

# Precipitation minus evapotranspiration for an average July, 1959-1997

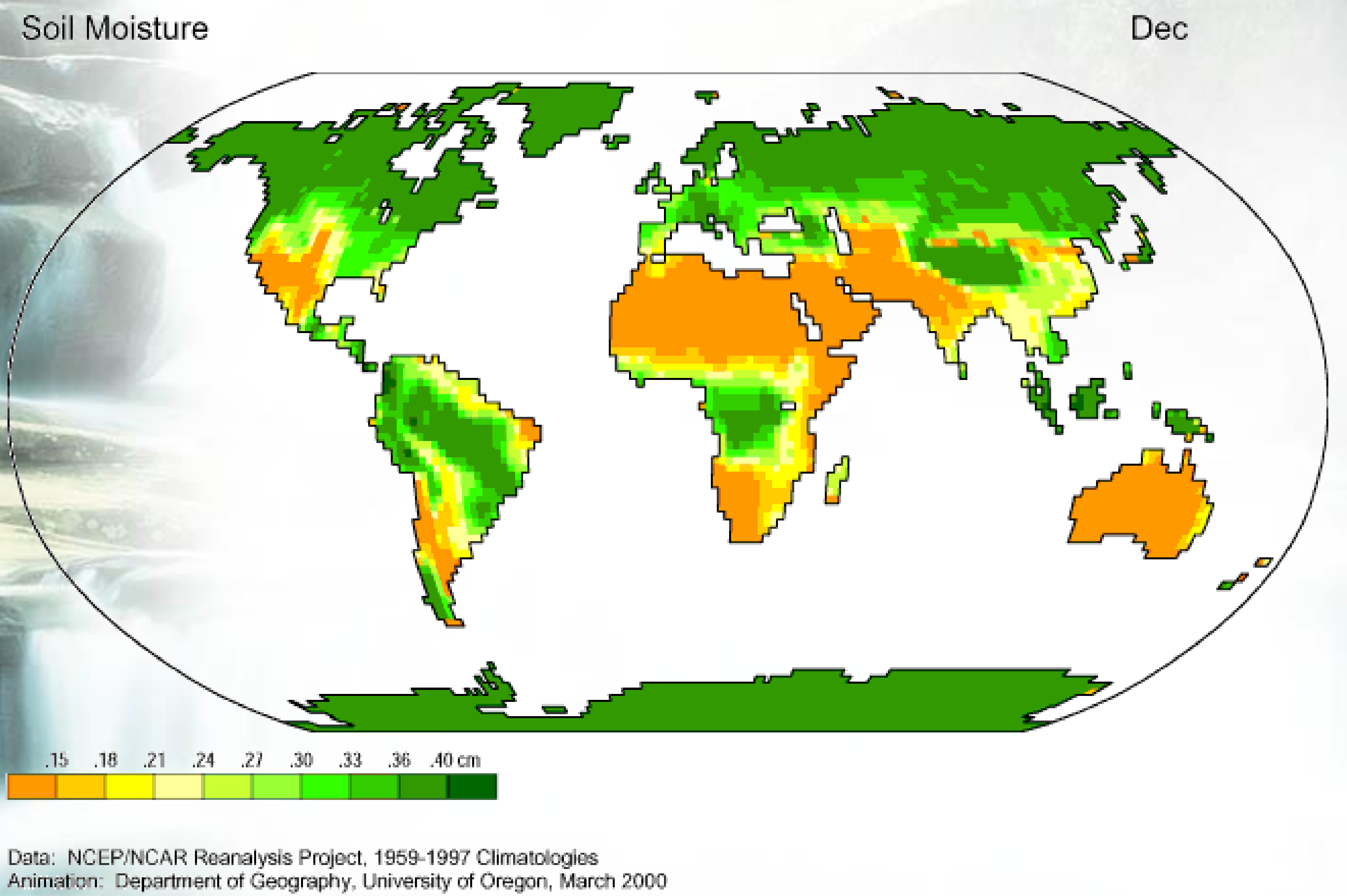



http://geography.uoregon.edu/envchange/clim_animations/

# Runoff

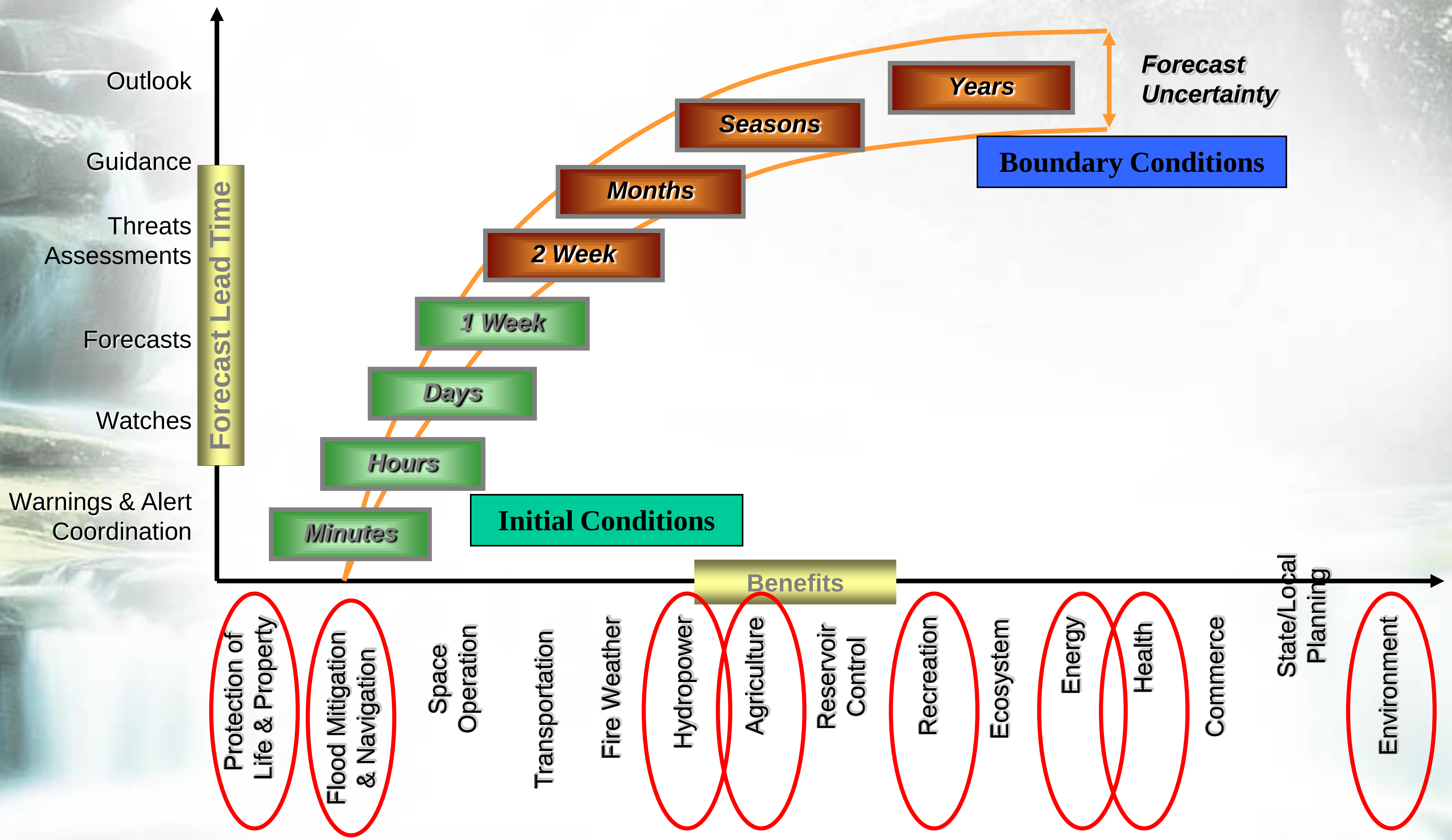
- Most carried by major rivers
- 70 rivers account for 50% of world's runoff
- Amazon River carries 25% of world's runoff!
- streamflow accounts for 85-90% of total sediment transport to the ocean basins (glaciers account for 7%)
- Stored in lakes, wetlands, artificial reservoirs

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



**The global water and energy cycle encompasses the movements, transformations, and reservoirs of water, energy, and water-borne materials throughout the Earth system and their interactions with ecosystems and the global water system. The global water and energy cycle operates on the full continuum of space and time scales and involves phase changes and energy exchanges.**

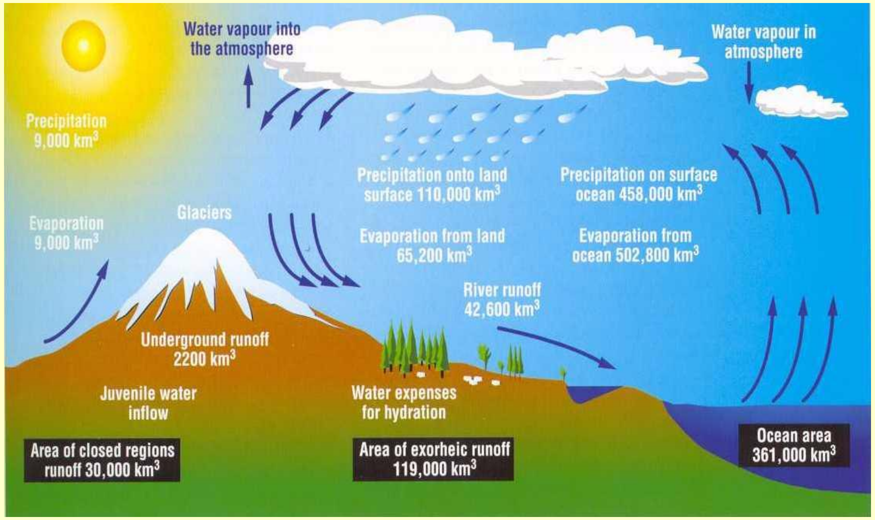
# Water Needs and Timescales

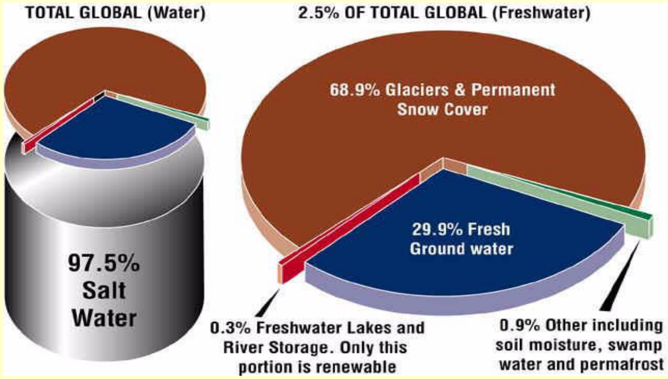


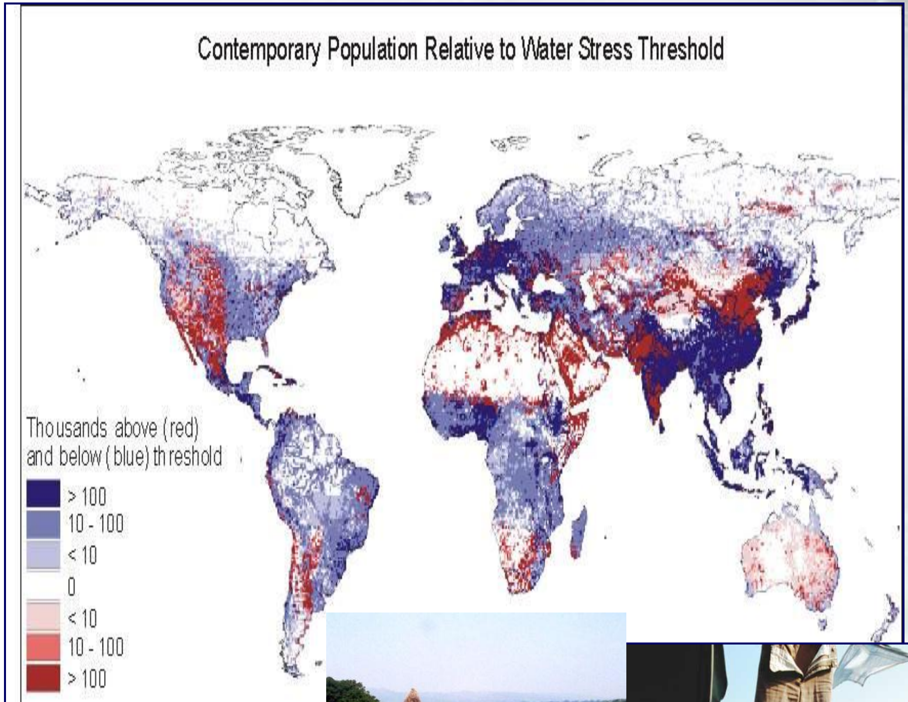
# The importance of Water




***"The Grim Arithmetic of Water"---Official Discussing Emerging Freshwater Crisis---Source: September 2002 National Geographic***






**Population is dramatically increasing**

*Ultimately, a limited water supply will meet limited needs*

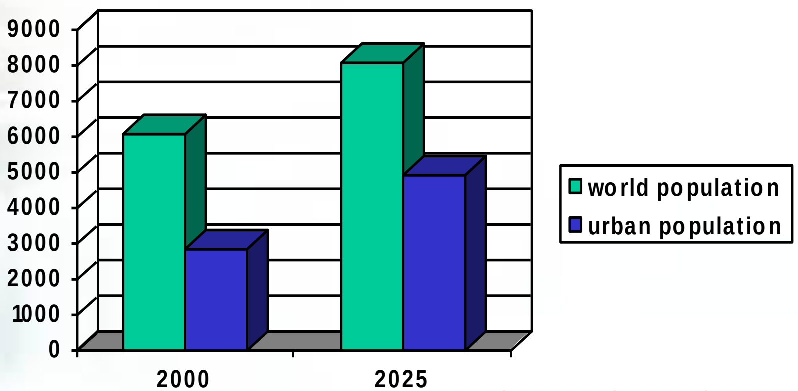
# Importance of Water

**Water is a fundamental basis of life on Earth, affecting:** climate, pollution, food, human habitation, human conflict, and more

**Understanding the Earth's hydrologic cycle provides:**

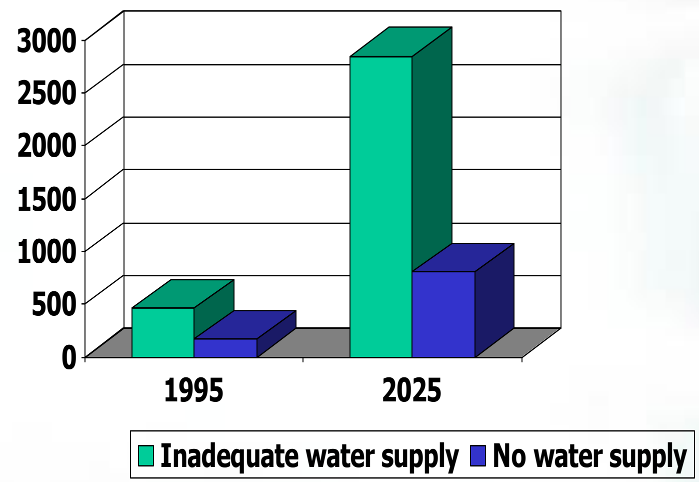
- **improved forecasts:** precipitation, drought, floods, food and water availability, agricultural & fisheries productivity, disease vectors
- **improved management:** agriculture, transportation, planning, social assistance requirements, other human activities

**A Growing Need:** Growing demand, Diminishing resources, Failing public services *(Inadequate institutional structures, Insufficient investment, Lack of maintenance, Poor management, Political interference),* Enormous investment requirements




- Deaths from water scarcity (12 M / year)
- Increased poverty in developing countries

**World population suffering from water shortage (millions)**

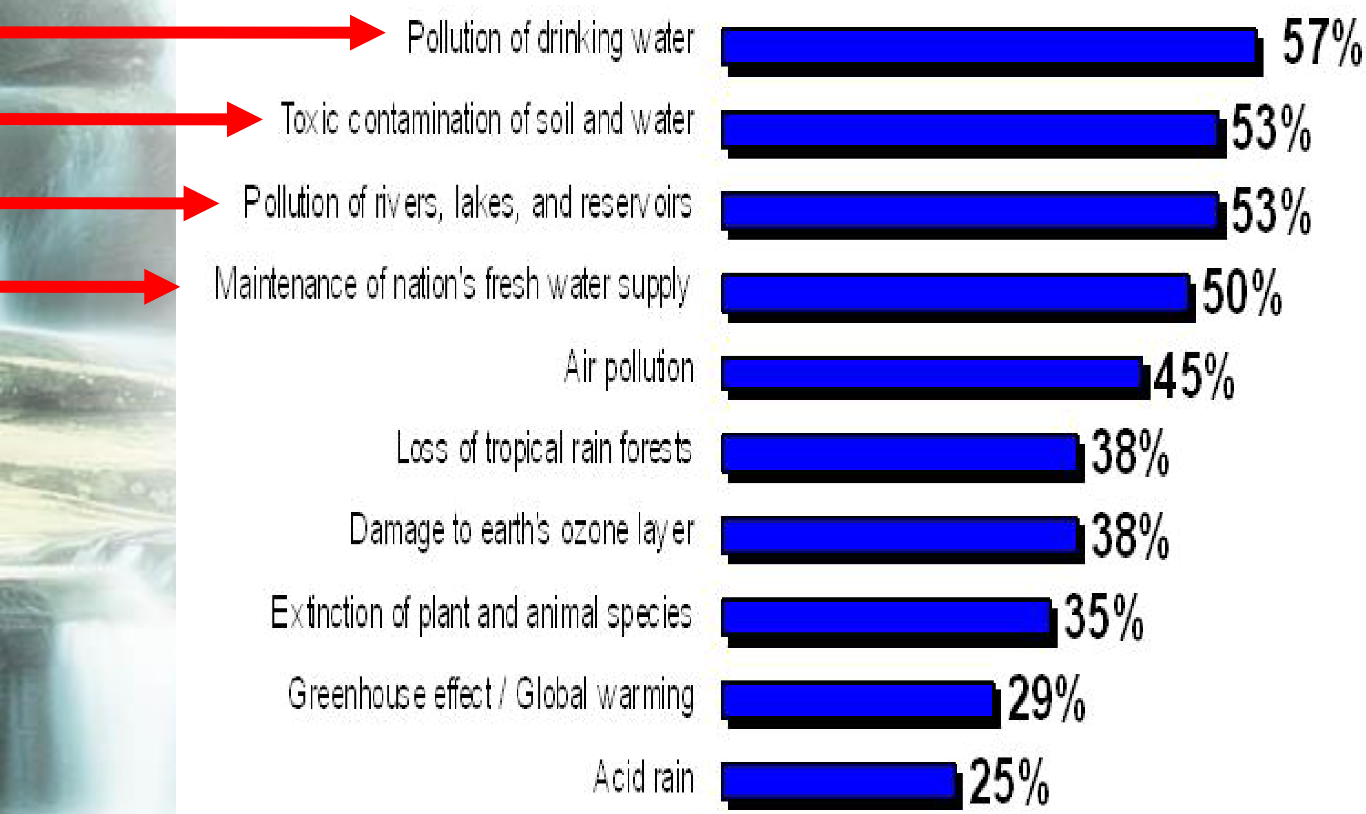


# Importance of Water Applications

## MOTIVATION

**TOP 4 CONCERNS**

**Poll percentage that worried "a great deal" about:**




**Ranking of environmental concerns (taken from Gallup News Service: *Americans Sharply Divided on Seriousness of Global Warming*, March 25, 2002)**

# The “Water Sector”

Water is vital for life and livelihood: It is precious but scarce
Water cannot be manufactured, unlike other commodities

- Water supplies are fixed

Available water resources need to be

- Developed in a sustainable way
- Managed to derive optimal benefits
- Conserved and preserved as scarce resource

The need and therefore the potential market and business opportunities are enormous,

***but is it a good and attractive business?***

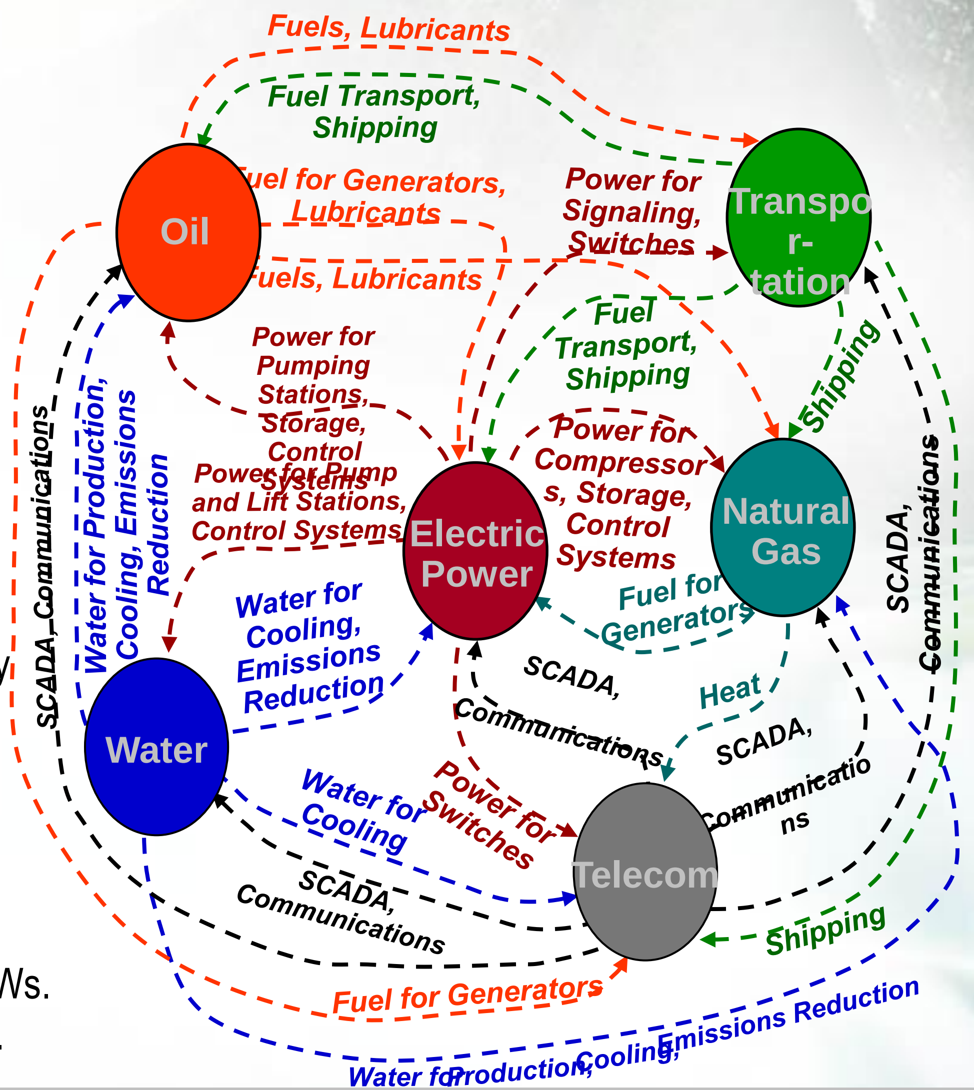
## U.S. Drinking Water Statistics

- 160,000 public water systems (PWSs).
- 84% of U.S. population served by PWSs.
- PWSs produce 51 billion gallons drinking water/day
- 2.3 million miles of distribution system pipes.

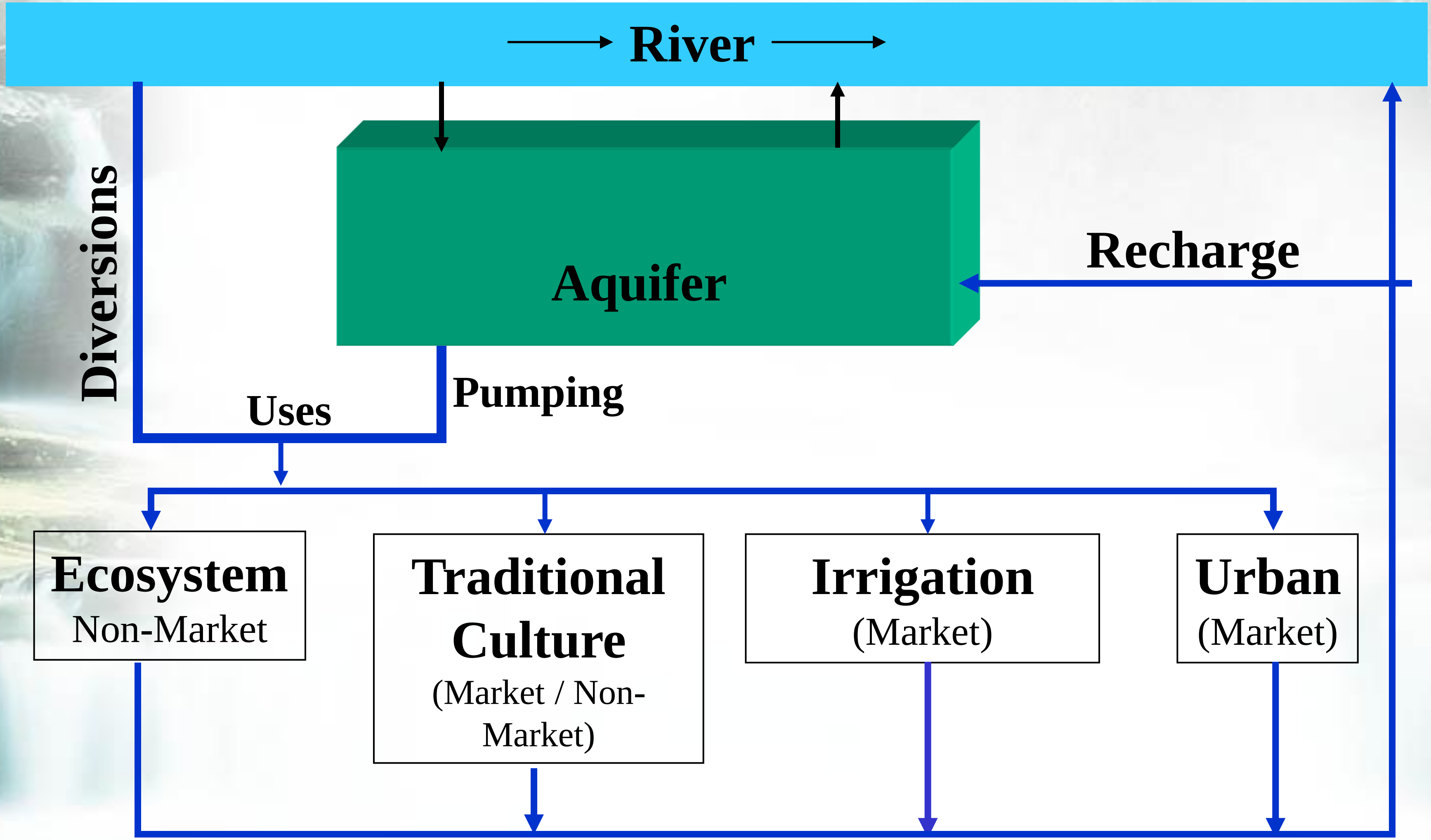
## U.S. Wastewater Statistics

- 16,255 publicly owned treatment works (POTWs).
- 75% of U.S. population served by POTWs.
- 27,000 commercial/industrial facilities rely on POTWs.
- 32 billion gallons of wastewater treated every daily.

**Water sector is part of a system of systems**

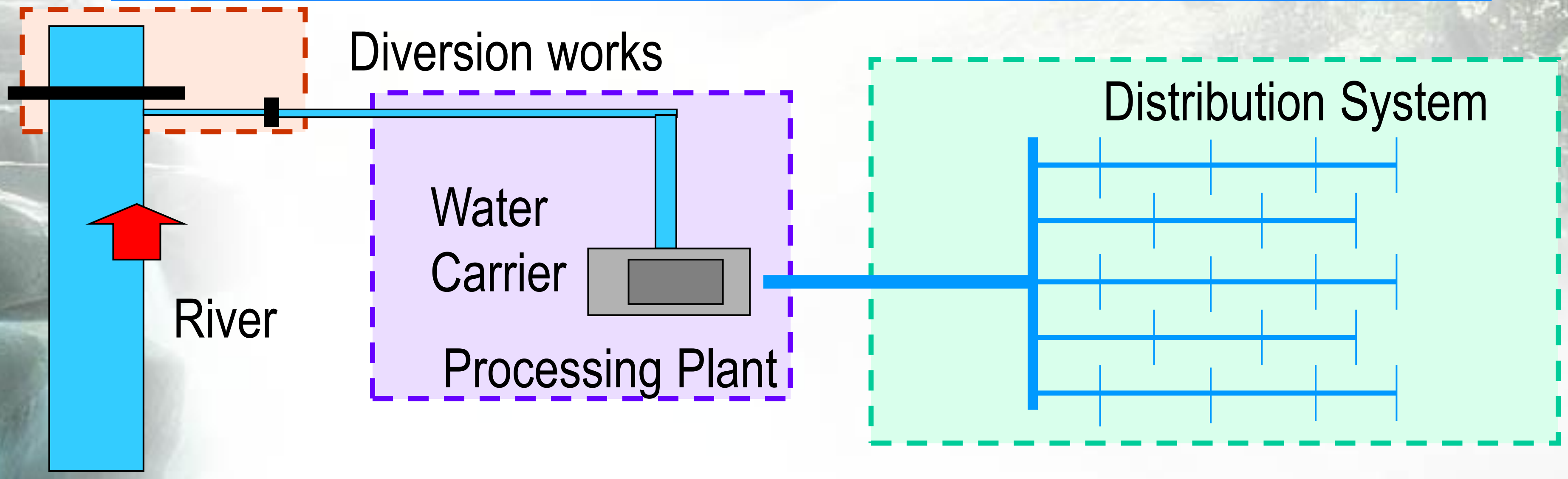


# Water Sector: Integrated Systems




J.Chermak WR 572, University of New Mexico Spring 2005

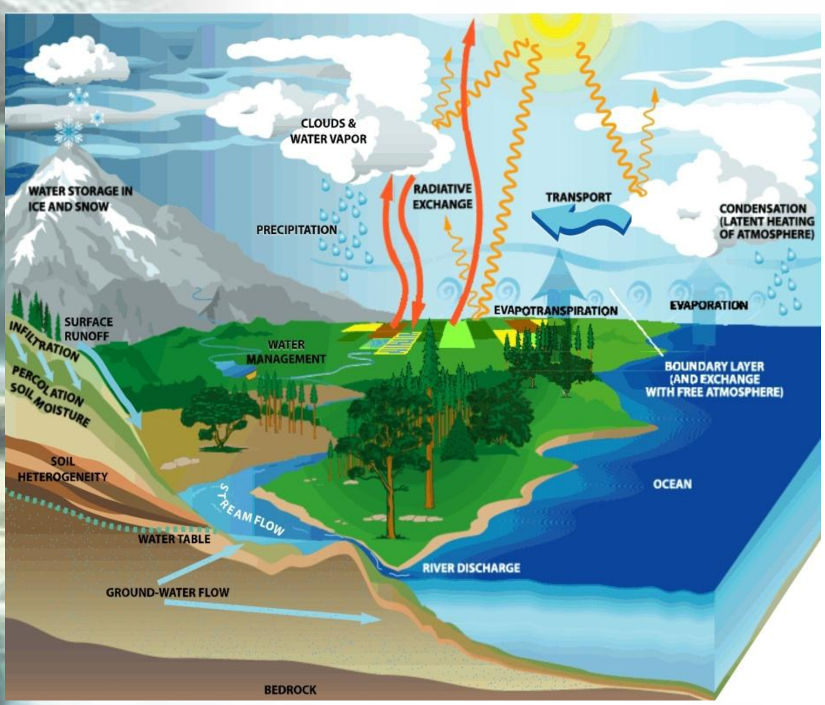
# Water Sector: System Components




- Water resource development & management
- Supply, treatment, transport & storage
- Environmental management & conservation
- Research, administration & policy development
- River management, navigation & flood control & waste assimilation
- Hydropower & Agricultural irrigation
- Industrial, commercial & touristic water use
- Municipal & household water use & sanitation
- Wastewater collection & treatment, and sludge disposal

# The Water and Energy Cycle

**Water in the climate system functions on <u>all</u> time scales:**
**From hours to centuries**




***Role of the Water & Energy Cycle in the Climate System:***

- *Water exists in all three phases in the climate system; its phase transitions regulate global and regional energy balances*
- *Water vapor in the atmosphere is the principal greenhouse gas; clouds represent both positive and negative feedbacks in climate system response*
- *Water is the ultimate solvent which mediates the biogeochemical and element cycles*
- *Water directly impacts and constraint human society and its well-being.*

**The Energy and Water Cycle is *<u>tightly intertwined</u>***

- **Solar radiation drives and feedbacks with the water cycle**
- **Energy is transferred through water movement and phase change**

# Why study the water and energy cycle?...

**Water in Climate**

Fluxes and Feedbacks

Variations in greenhouse gases, aerosols, and solar activity force changes in climate…

**Water in the environment**

**Water supply and quality**

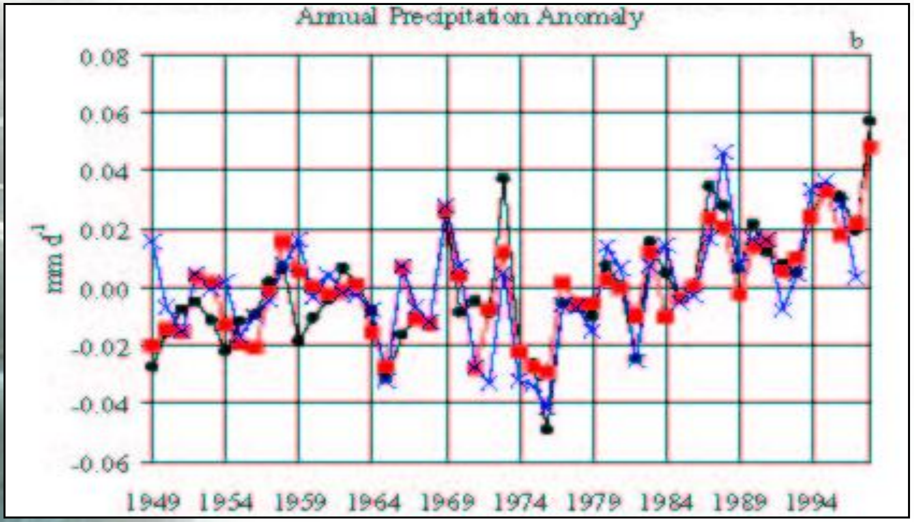
**Water for consumption**

*…but, consequences of climate change are* ***realized through the water cycle.***

*…and climate warming is regulated through water-energy feedbacks.*

*…is the* ***cycling***, ***distribution***, *or* ***extremes*** *of the global water and energy system changing?*

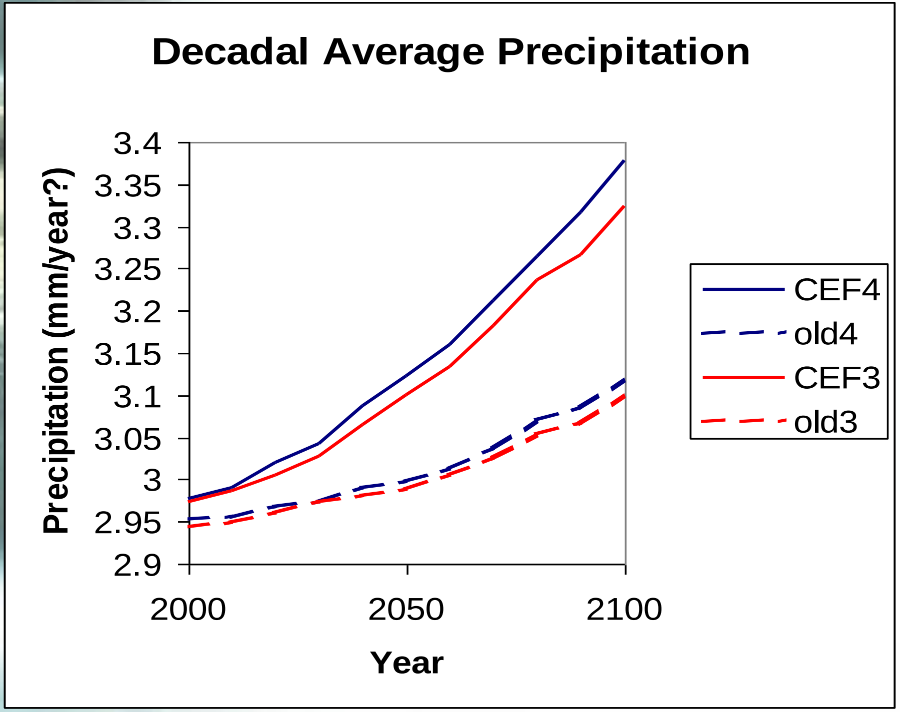
# Global Water Studies: Motivation and Methodology

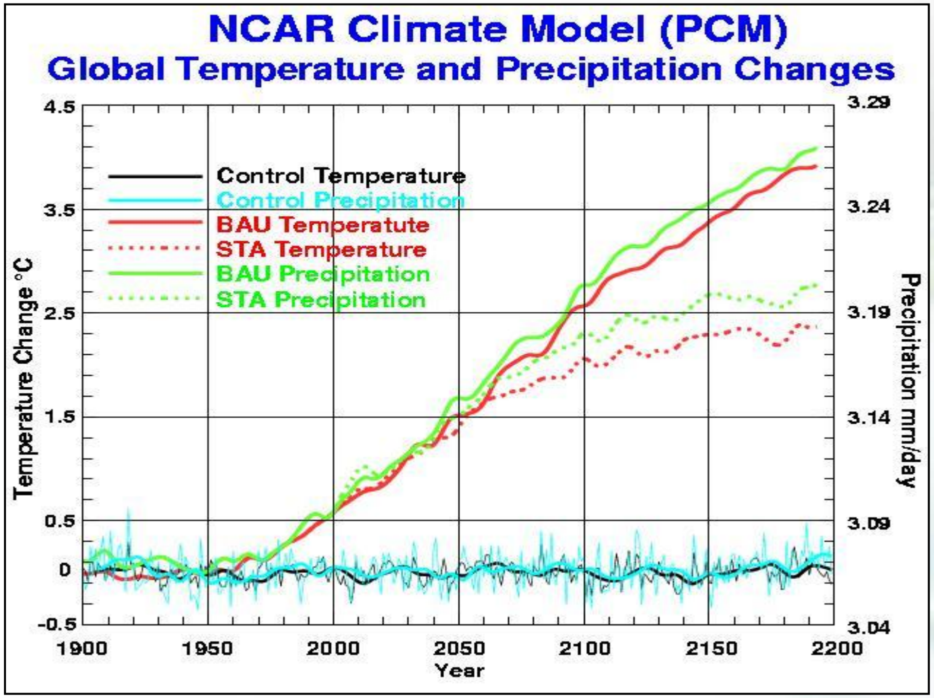



Obs variability: ~0.05 mm/d

Model variability ~0.005 mm/d

Model 100yr trend: ~0.1 mm/d



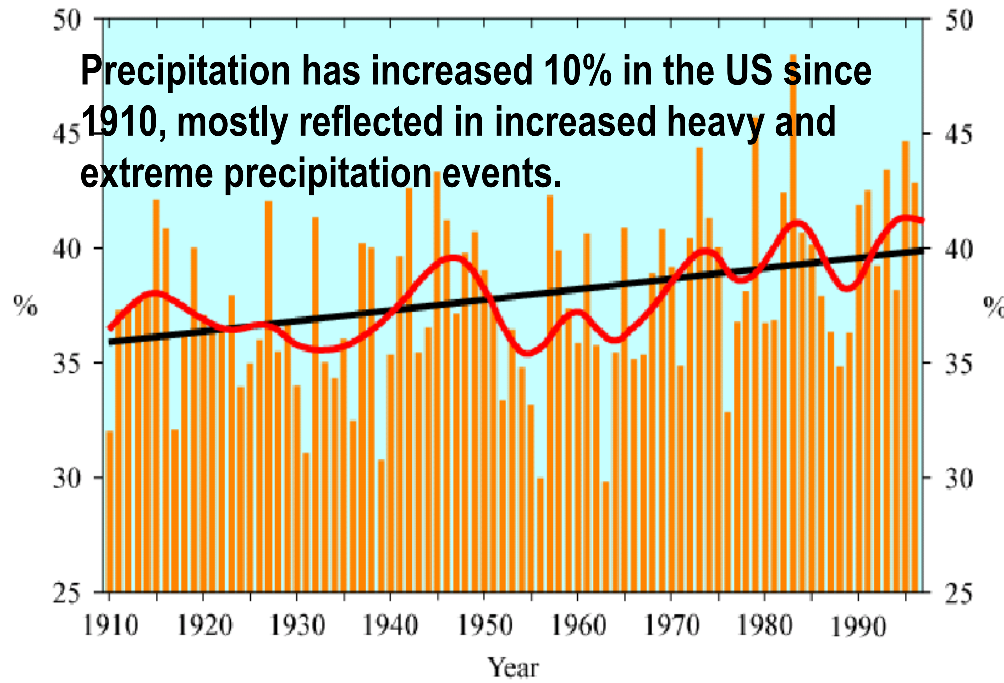



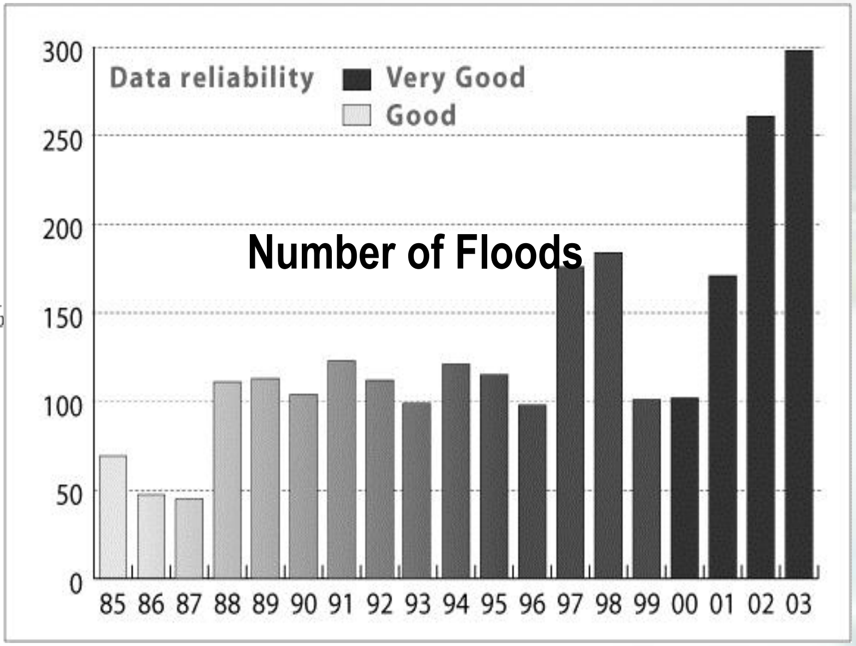
# A generally accepted hypothesis regarding global water cycle changes:

"According to model predictions, the ***most significant manifestation of climate change would be an acceleration of the global water cycle, leading to … a general exacerbation of extreme hydrologic regimes, floods and droughts***" (NASA-GWEC, 2000).

"***There is evidence that suggests that the global hydrologic cycle may be intensifying, leading to an increase in the frequency of extremes***" (USGCRP water cycle science plan)

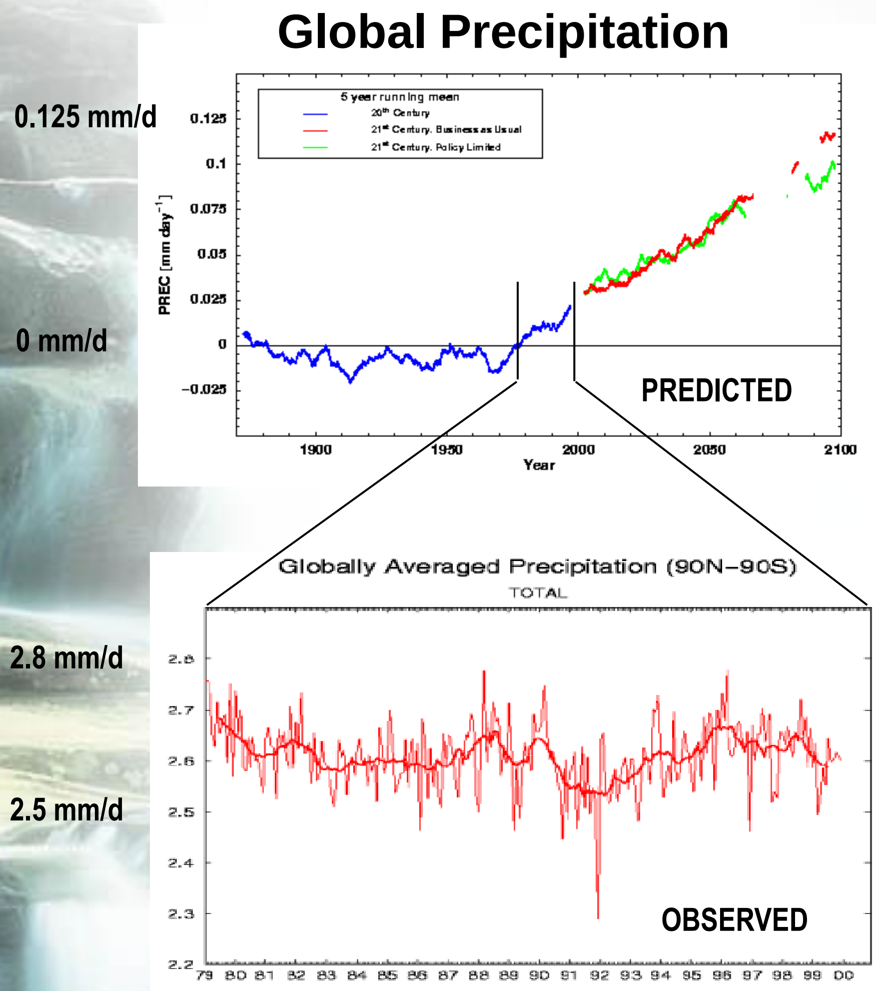
***Climate models generally project an acceleration in the rate of global water cycling and an increase in global precipitation*** … (Morel, GEWEX News, 2001)

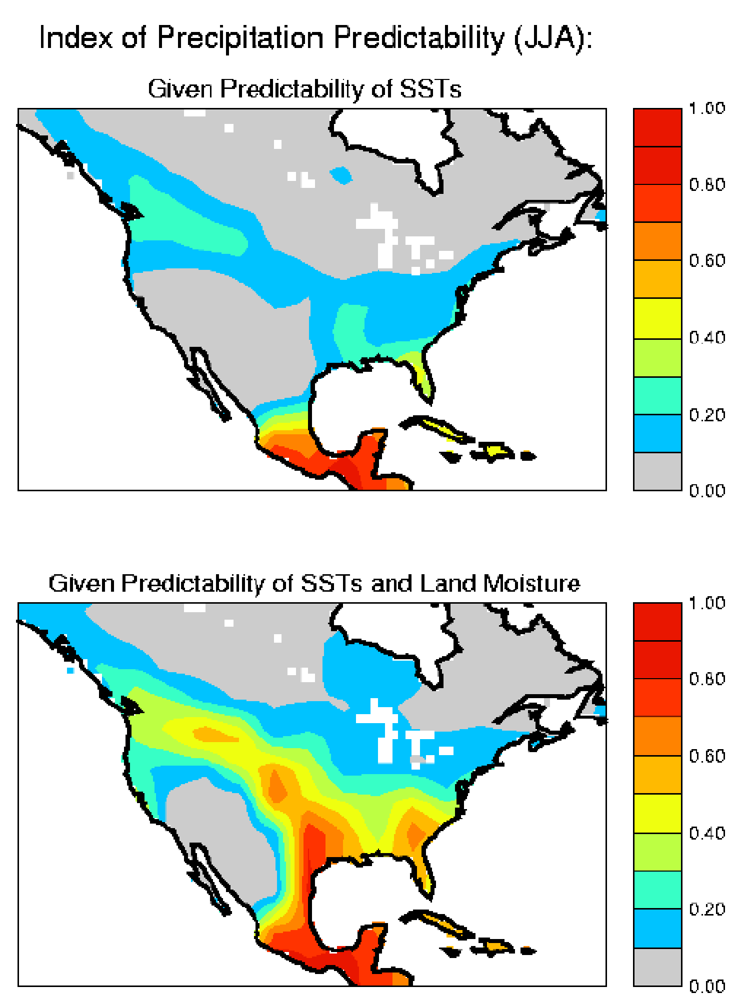



From Dartmouth

# Current state of climate-change science



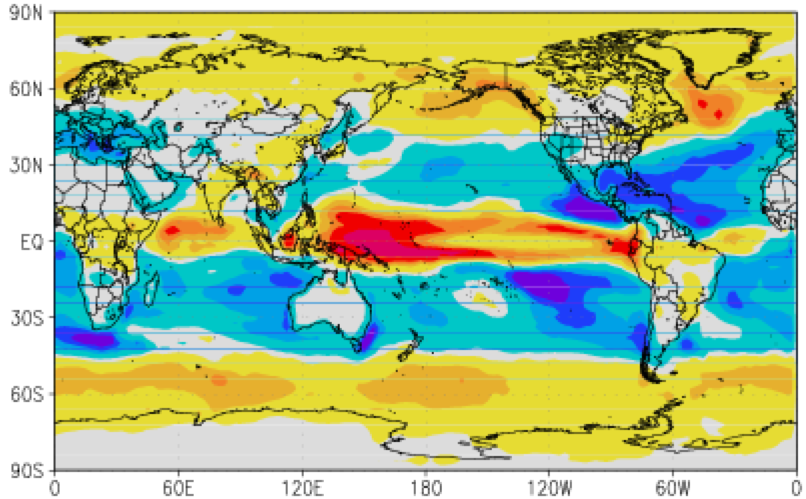




- Models can match observed global warming
- Models can't match significant trends or simulate precipitation variations is inadequate
- Significant water cycle prediction skill is achievable

# Multi-model ensemble mean change from IPCC GCMs

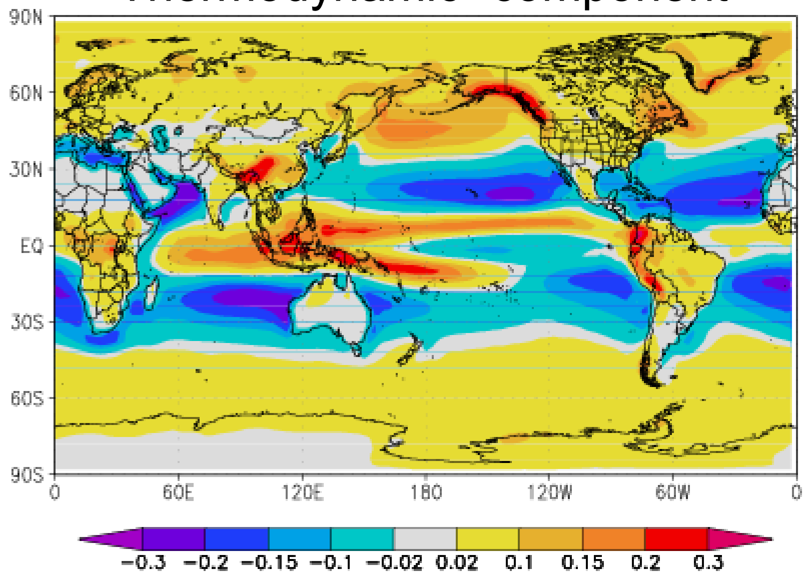
Change in (P-E) for 2100 minus 2000

'Dry regions get drier, wet regions get wetter"

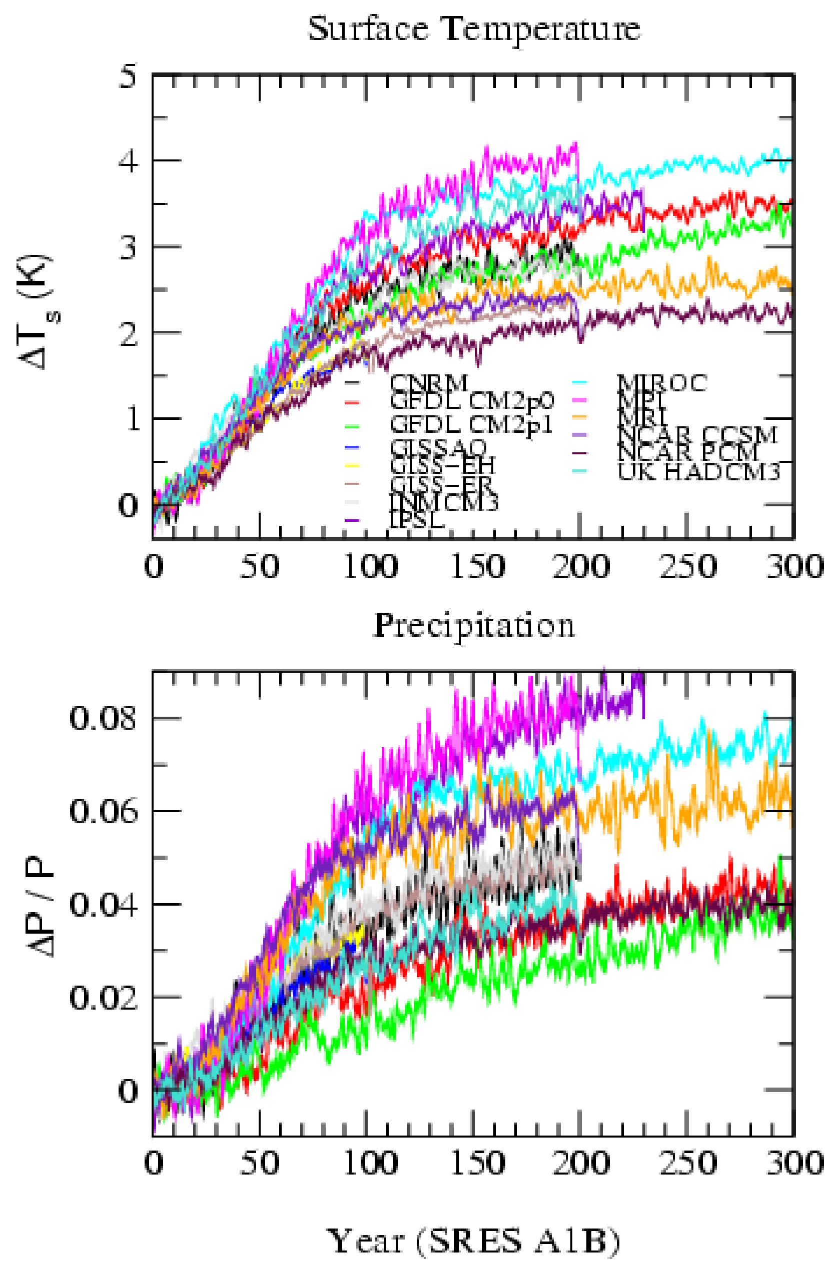



Held and Soden (2006)

"Thermodynamic" component




Δ(P-E) mm/day

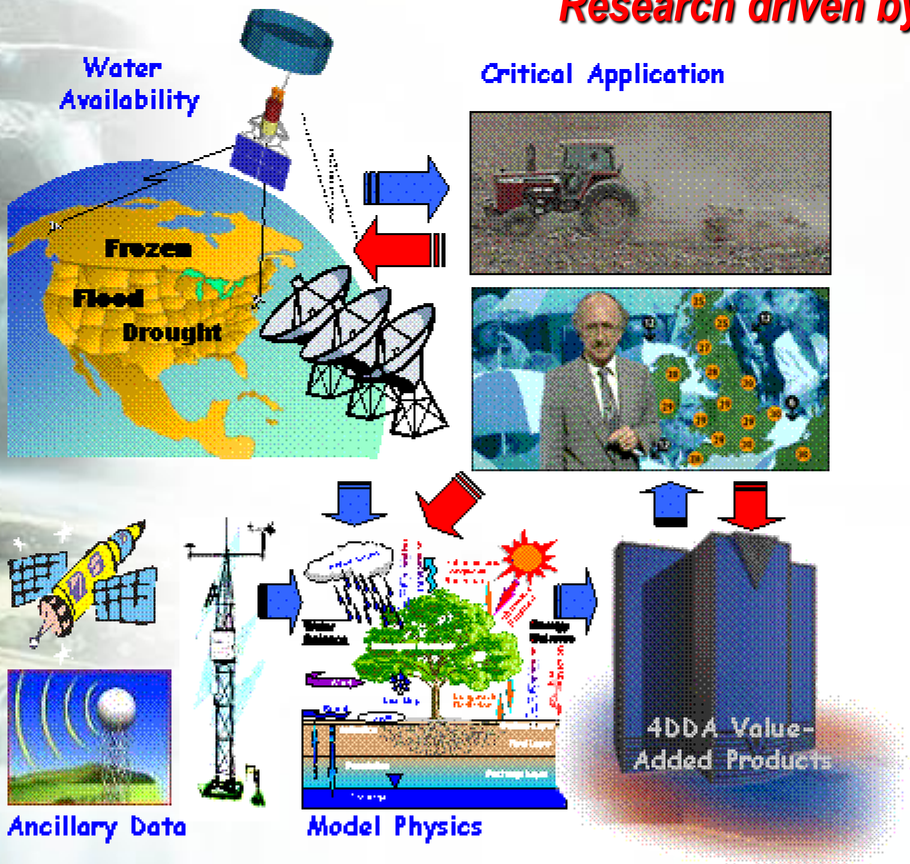



Vecchi and Soden (2007)

# Linking Science to Consequences

*End-to-end coordination enabling understanding and prediction of the Earth system:*

***Research driven by the needs of society***




**Use the adequate tool for the job…**

***To deliver social, economic and environmental benefit to stakeholders through sustainable and appropriate use of water by directing towards improved integrated water system management***

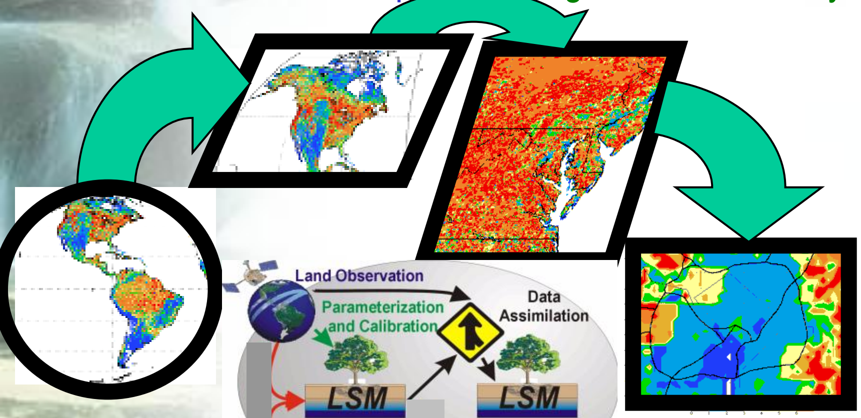
# Land Information System http://lis.gsfc.nasa.gov

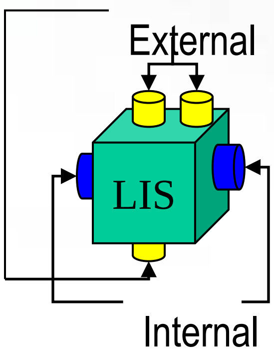
Co-PIs: P. Houser, C. Peters-Lidard

**2005 NASA SOY co-winner!!**

**Summary:** LIS is a high performance set of land surface modeling (LSM) assimilation tools.

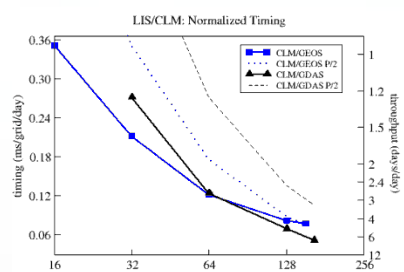
**Applications:** Weather and climate model initialization and coupled modeling, Flood and water resources, precision agriculture, Mobility assessment …

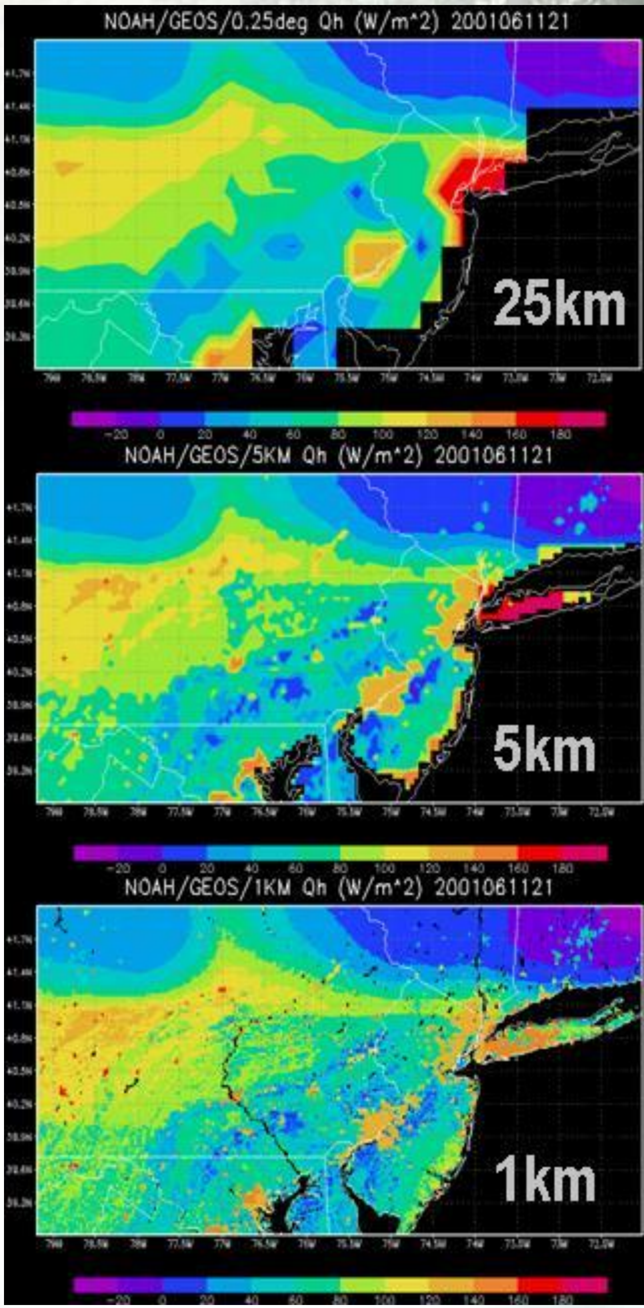



| | Memory (MB) | Wallclock time (minutes) | CPU time (minutes) |
|---|---|---|---|
| LDAS | 3169 | 116.7 | 115.8 |
| LIS | 313 | 22 | 21.8 |
| *reduction factor* | 10.12 | 5.3 | 5.3 |

200 Node "LIS" Cluster
Optimized I/O, GDS Servers



# State of the Water & Energy Cycle

Evaluate the research community's current ability to detect, analyze, understand and explain global water cycle change, variability, prediction and predictability.

## Water and Energy Cycle Data Integration

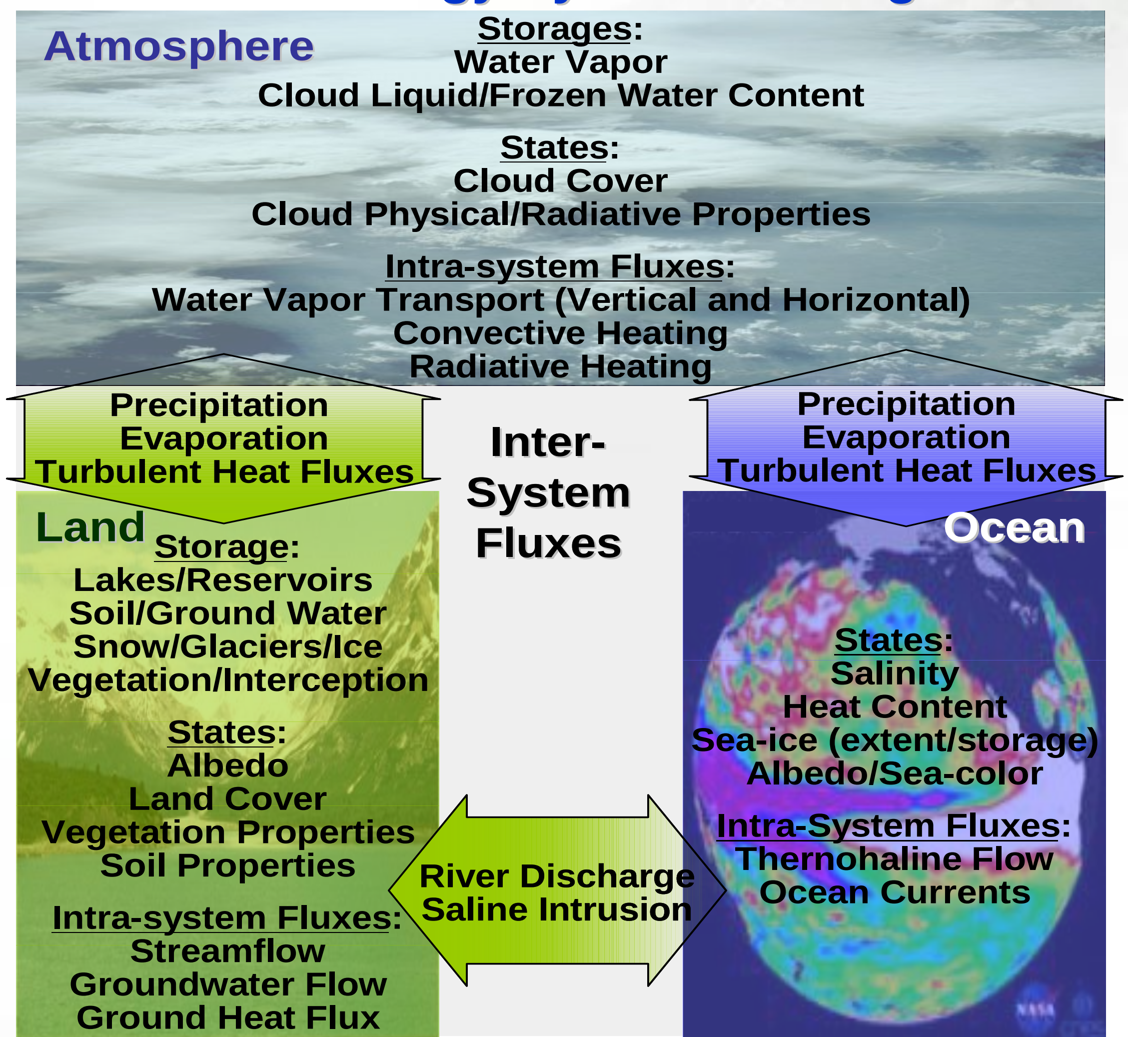



**Figure 1:** Major global water and energy cycle storages and fluxes to be included in the integration center.

# State of the Water and Energy Cycle

| Variable ↓ / Sphere → | Ocean | Terrestrial | Atmosphere |
|---|---|---|---|
| Internal or State Variable | upper ocean currents (I/S)<br>sea surface temperature (I/S)<br>sea level/surface topography (I/S)<br>sea surface salinity (I/S)<br>sea ice (I/S)<br>wave characteristics (I/S)<br>mid- and deep-ocean currents (I)<br>subsurface thermal structure (I)<br>subsurface salinity structure (I)<br>ocean biomass/phytoplankton (I/S)<br>subsurface carbon(I), nutrients(I)<br>subsurface chemical tracers(I) | topography/elevation (I/S) land cover (I/S)<br>leaf area index (I)<br>soil moisture/wetness (I/S)<br>soil structure/type (I/S)<br>permafrost (I)<br>vegetation/biomass vigor (I/S)<br>water runoff (I/S)<br>surface temperature (I/S)<br>snow/ice cover (I/S)<br>subsurface temperature (I/S)<br>subsurface moisture (I/S)<br>soil carbon, nitrogen, phosphorus, nutrients (I) | wind (I/S )<br>upper air temperature (I/S)<br>surface air temperature (I/S)<br>sea level pressure (I)<br>upper air water vapor (I/S)<br>surface air humidity (I/S)<br>precipitation (I/S)<br>clouds (I/S)<br>liquid water content (I/S) |
| Forcing or Feedback Variable | ocean surface wind & stress (I/S)<br>incoming SW radiation (I/S)<br>incoming LW radiation (I/S)<br>surface air temperature (I/S)<br>surface air humidity (I/S)<br>precipitation (I/S)<br>evaporation (I/S)<br>fresh water flux (I/S)<br>air-sea $CO_2$ flux (I)<br>geothermal heat flux (I)<br>organic & inorganic effluents (I/S)<br>biomass and standing stock (I/S)<br>biodiversity (I)<br>human impacts-fishing (I) | incoming SW radiation (I/S)<br>incoming LW radiation (I/S)<br>PAR radiation<br>surface winds (I)<br>surface air temperature (I/S)<br>surface humidity (I/S)<br>albedo (I/S)<br>evapotranspiration (I/S)<br>precipitation (I/S)<br>land use (I/S)<br>deforestation (I/S)<br>land degradation (I/S)<br>sediment transport (I/S)<br>air-land $CO_2$ flux (I) | sea surface temperature (II/S )<br>surface soil moisture (I/S) surface soil temperature (I/S)<br>surface topography (I/S)<br>land surface vegetation (I/S)<br>$CO_2$ & other greenhouse gases, ozone & chemistry, aerosols (I/S)<br>evapotranspiration (I/S)<br>snow/ice cover (I/S)<br>SW and LW surface radiation budget (I/S)<br>solar irradiance (S) |

*BLUE=Water Cycle Variable; RED=Energy Cycle Variable; GREEN=Carbon/Chemistry Variable; BLACK=Boundary condition*

$$\frac{d\langle Q\rangle}{dt} = \langle E\rangle - \langle P\rangle$$

$$R = P - E \pm \Delta G$$

$$P_o = E_o - D_o + D_l = E_o - R$$
$$P_l = E_l + D_o - D_l = E_l + R$$

$$\frac{\partial S}{\partial t} = -\nabla_H \cdot \vec{R}_o - (E - P).$$

$$P + R_o + \Delta O + G_{do} = E$$

# State of the Water & Energy Cycle

Evaluate our ability to detect, analyze, and understand global water

## Water and Energy Cycle Data Integration

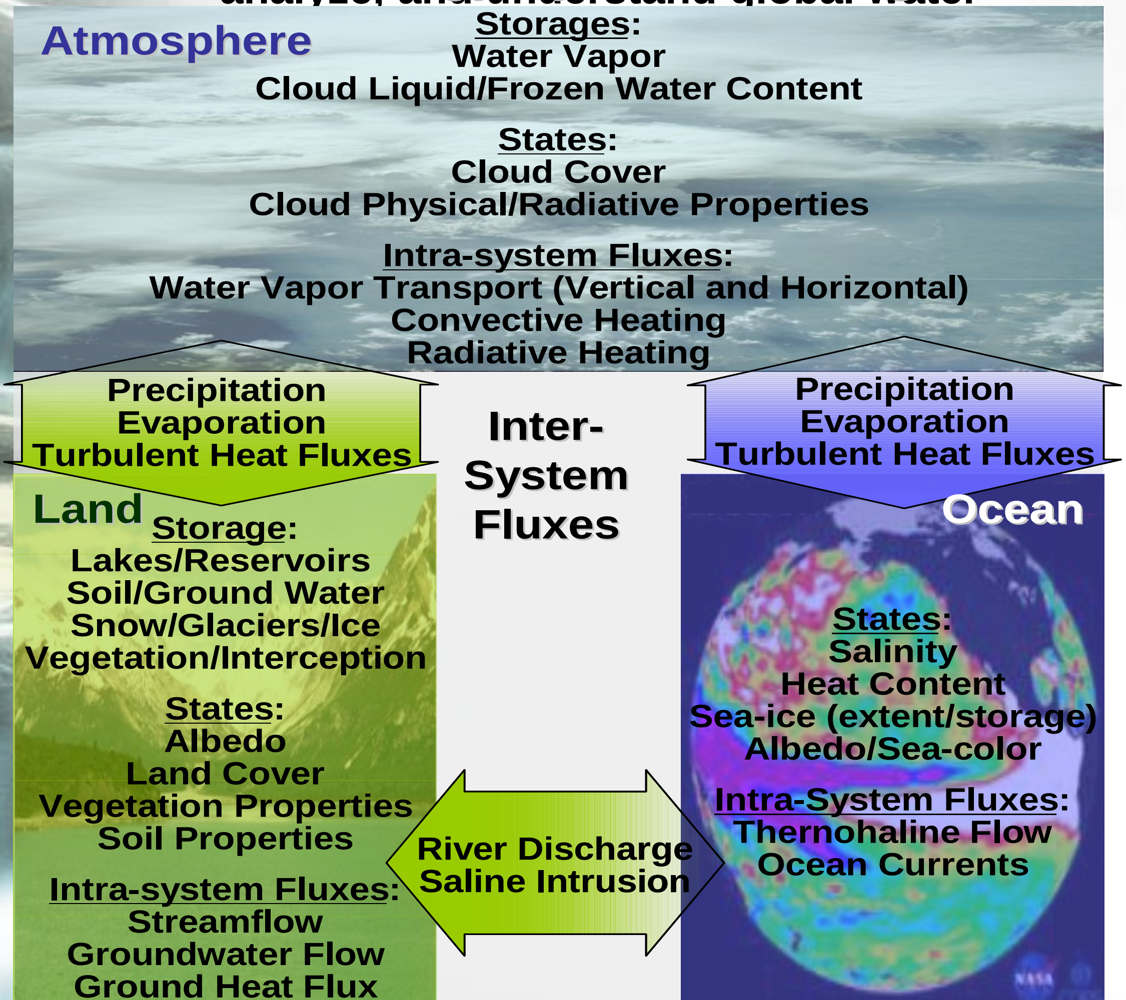



Figure 1: Major global water and energy cycle storages and fluxes to be included in the integration center.

Global Satellite Water Balance Study:

*Schlosser & Houser, 2007*

$$\frac{d\langle Q\rangle}{dt} = \langle E\rangle - \langle P\rangle$$

### Precipitation (1979-1999):

- Global Precipitation Climatology Project (GPCP): Adler et al., (2003)
- CPC Merged Analysis of Precipitation (CMAP): Xie and Arkin (1997)

### Ocean Evaporation (1987-1999):

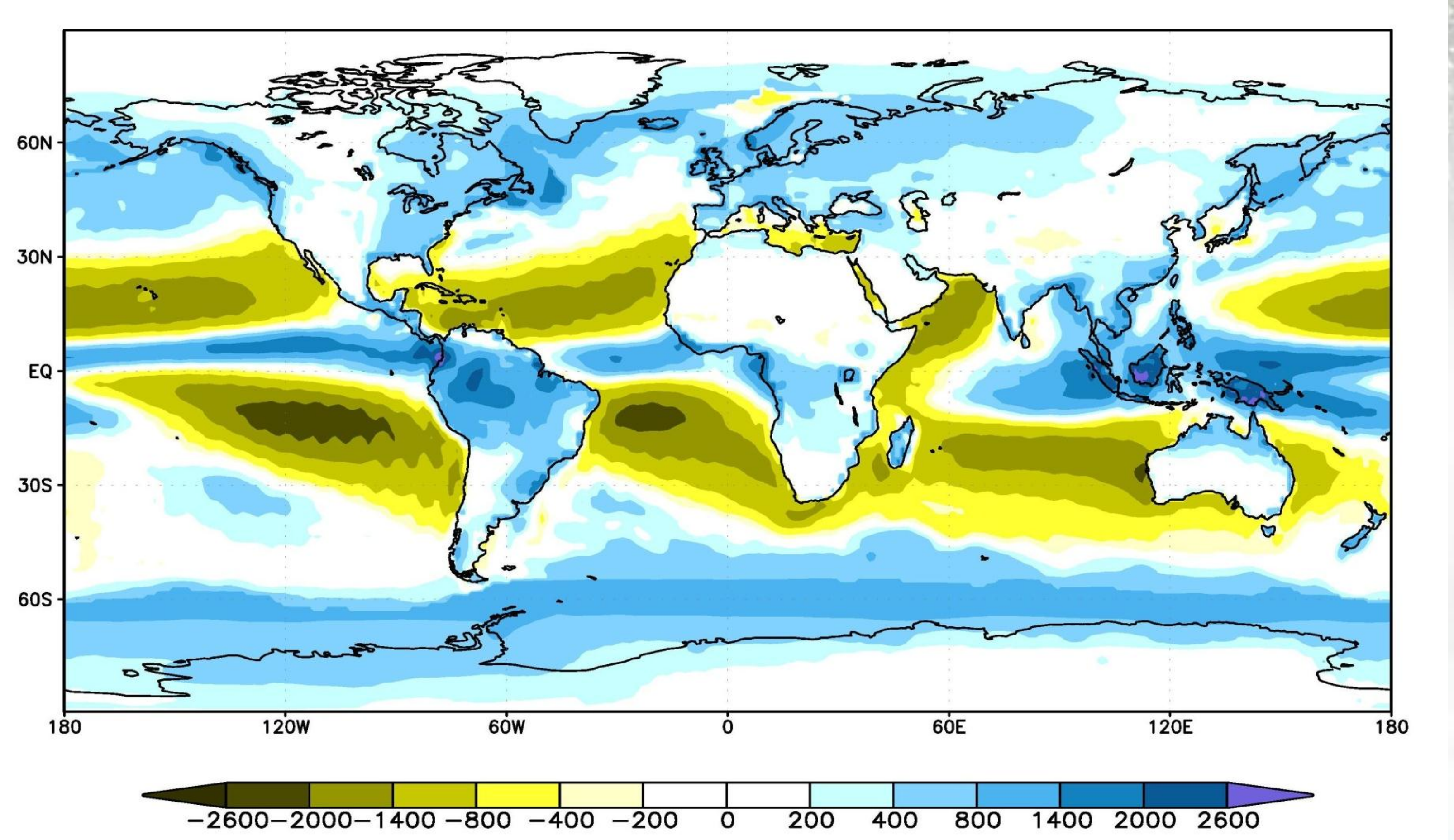
- Goddard Satellite-based Surface Turbulent Fluxes Version 2 (GSSTF2): Chou et al., (2003)
- Hamburg Ocean Atmosphere Parameters and Fluxes from Satellites: Bentamy et al. (2003)

### Land Evaporation:

- Global Offline Land Dataset (GOLD) (1959-2002): Dirmeyer et al., (2005):
- *Global Soil Wetness Project Phase 2 (GSWP2): 1986-1995*

### Precipitable Water: NASA Global Water Vapor Project (NVAP)

# Geographic Distribution of Annual P-E (mm)




- Evaporation excess nearly ubiquitous over sub-tropical oceans, with a sharp contrast at coastal regions.
- Equatorial ocean evaporation minimum consistent with other findings (e.g. Seager *et al.*, 2003).
- Tropical land areas show richest excess in precipitation.
- Major desert regions, tundra, and mountainous regions all indicate deficit to marginally-balanced conditions.
- Mid-latitude and boreal coastal/maritime environments exhibit adequate precipitation supply over evaporation.

# Annual Mean Statistics

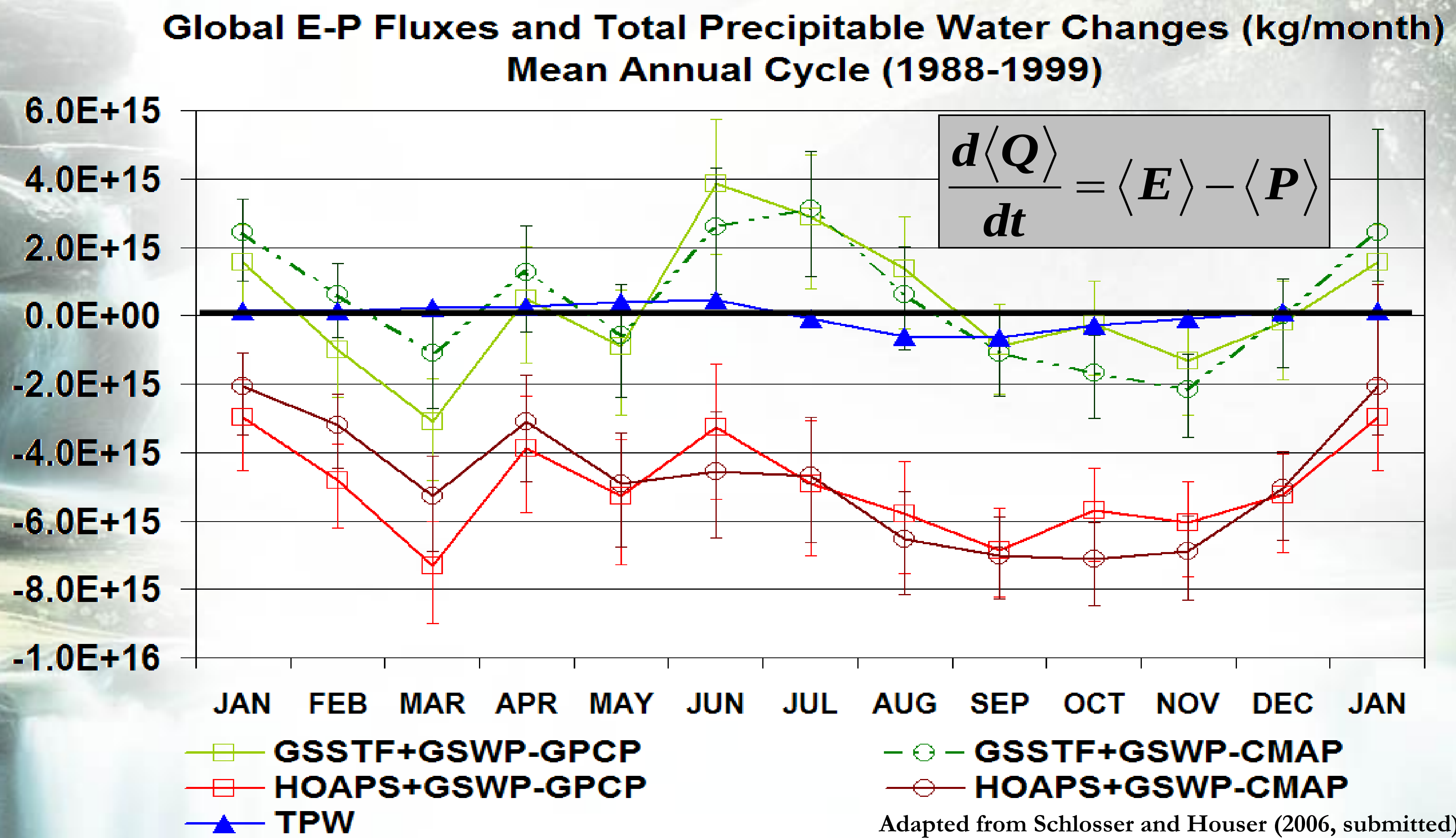
| Units in kg/yr | Precipitation | Evaporation | \| P-E \| |
|---|---|---|---|
| Land | 1.05E+17 ± 0.02E+17 | GOLD1: 0.64E+17 | ~4.0E+16 |
| | 1.02E+17 ± 0.02E+17 | GOLD2: 0.62E+17 | ~4.2E+16 |
| Ocean | 3.80E+17 ± 0.06E+17 | 4.41E+17 | 6.5E+16 |
| | 3.72E+17 ± 0.04E+17 | 3.93E+17 | 1.7E+16 |
| Global | GPCP<br>4.85E+17 ± 0.06E+17 | GSSTF2+GOLD<br>5.03E+17 | ~ 2.4E+16 |
| | CMAP<br>4.74E+17 ± 0.04E+17 | HOAPS+GOLD<br>4.56E+17 | |

Note: Total atmospheric water storage ~ $10^{16}$ kg

- **Global annual mean precipitation and evaporation balance to ~5%.**
- **Imbalance exceeds global estimate of annual precipitation error.**

**Adapted from Schlosser and Houser (2006, submitted)**

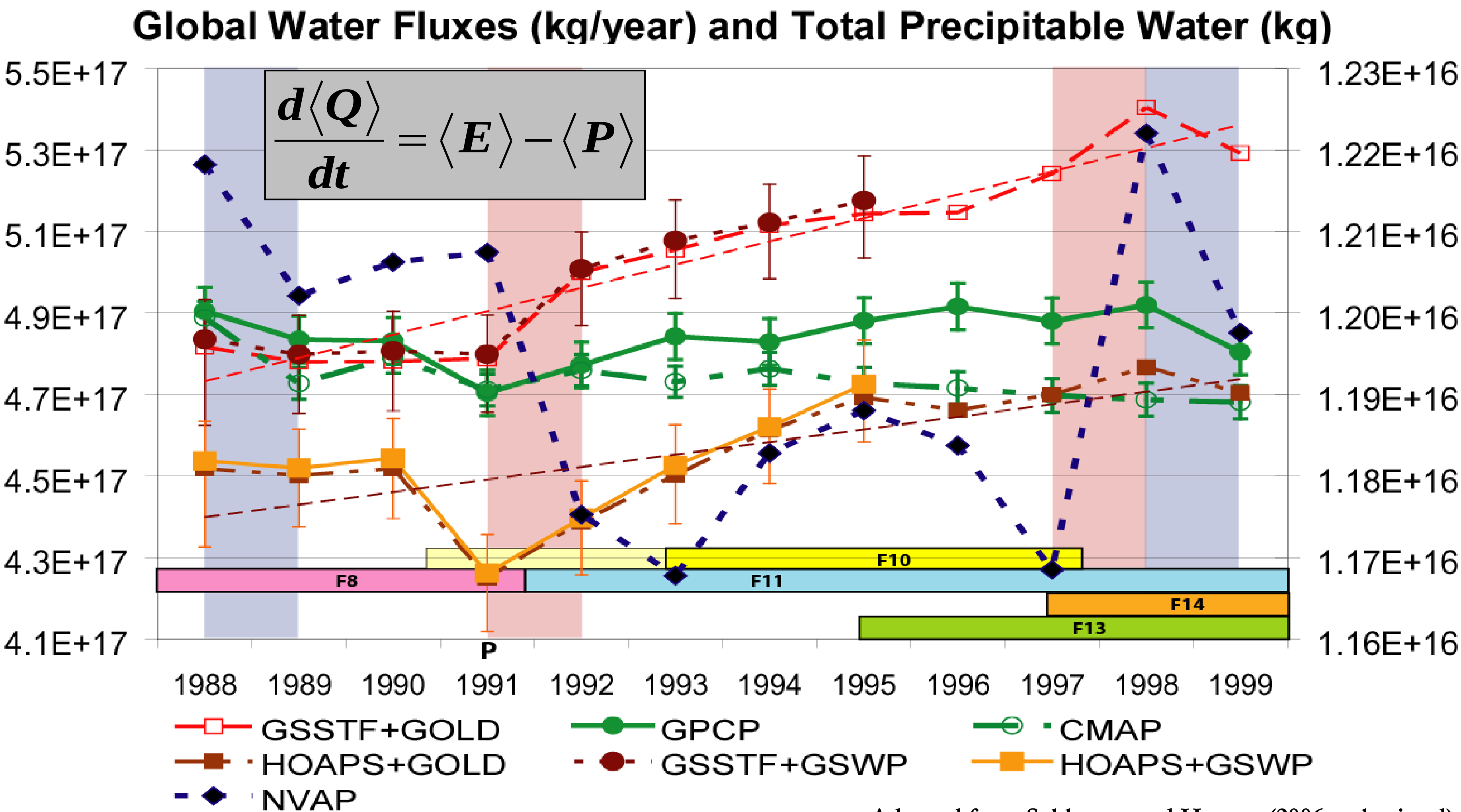
# Averaged Annual Cycles of Global Evap and Precip




Adapted from Schlosser and Houser (2006, submitted)

- **Uncertainties in global precipitation, land evapotranspiration, and/or changes in TPW cannot account for discrepancies in NH warm-season months.**

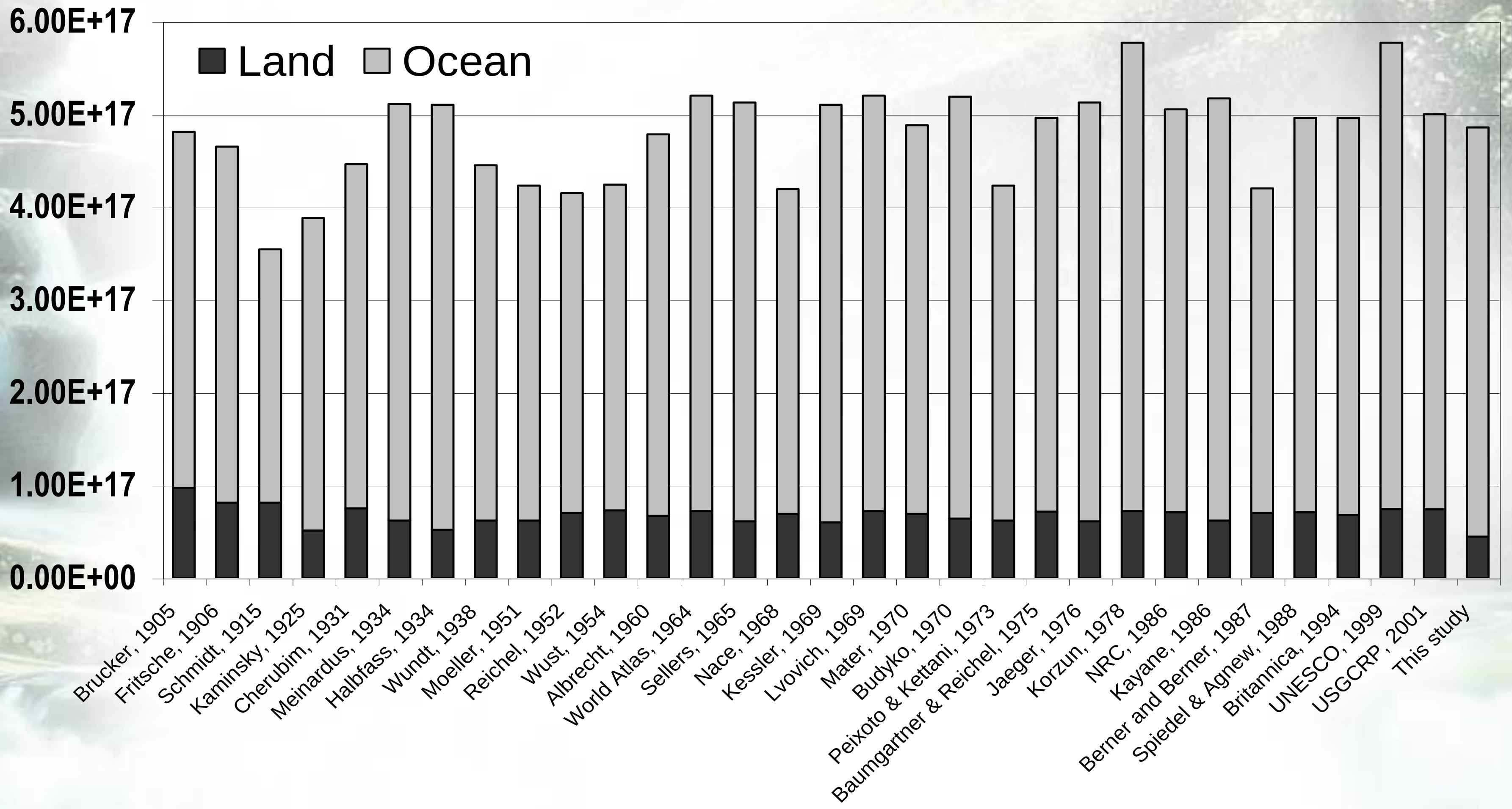
# Annual Timeseries of Global Water Fluxes




Adapted from Schlosser and Houser (2006, submitted)

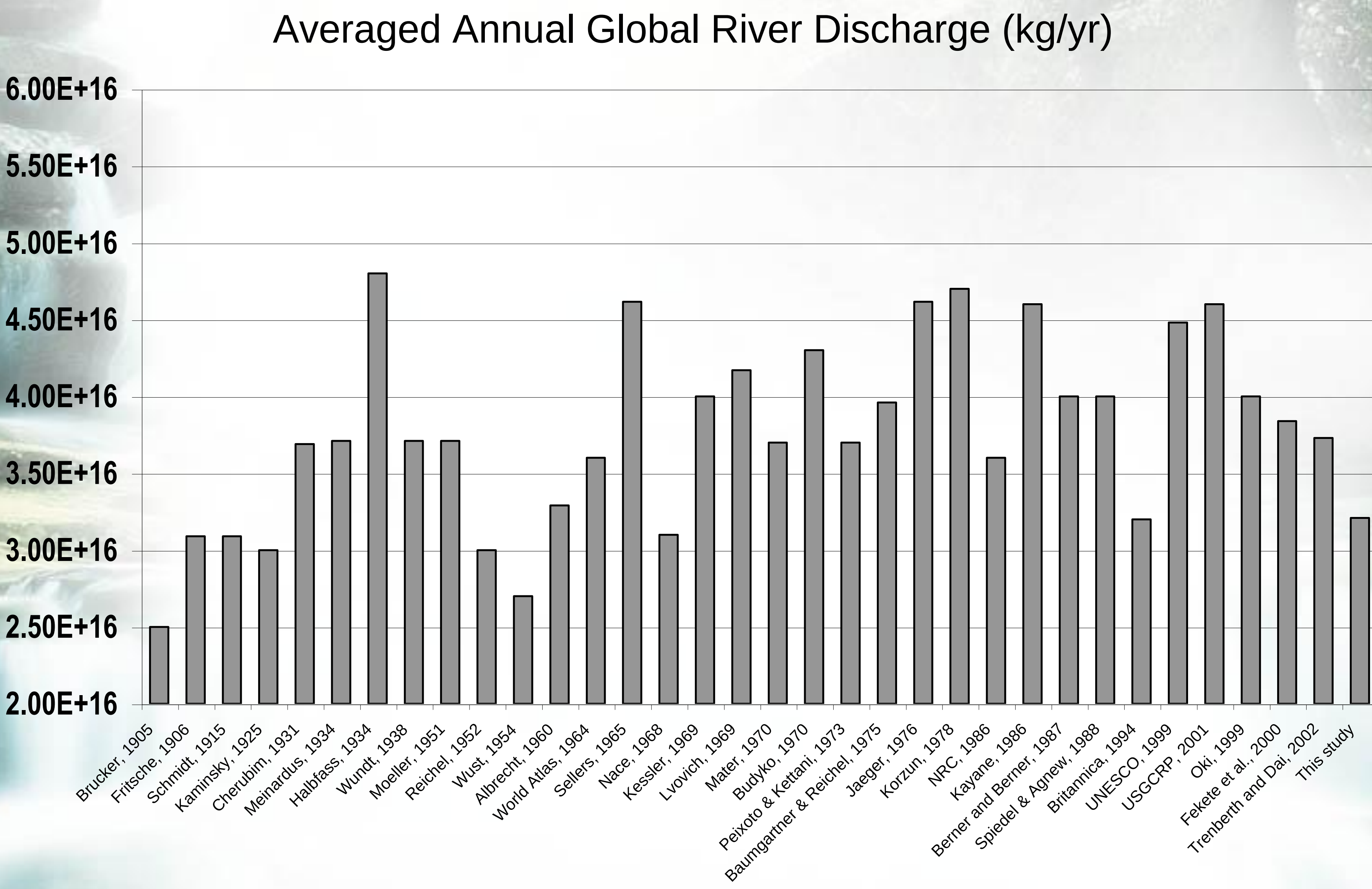
- Uncertainty assessment in global precipitation and land evapotranspiration cannot account for most discrepancies between annual global evaporation and precipitation.

# Comparison of Global Evaporation Fluxes to Previous Estimates

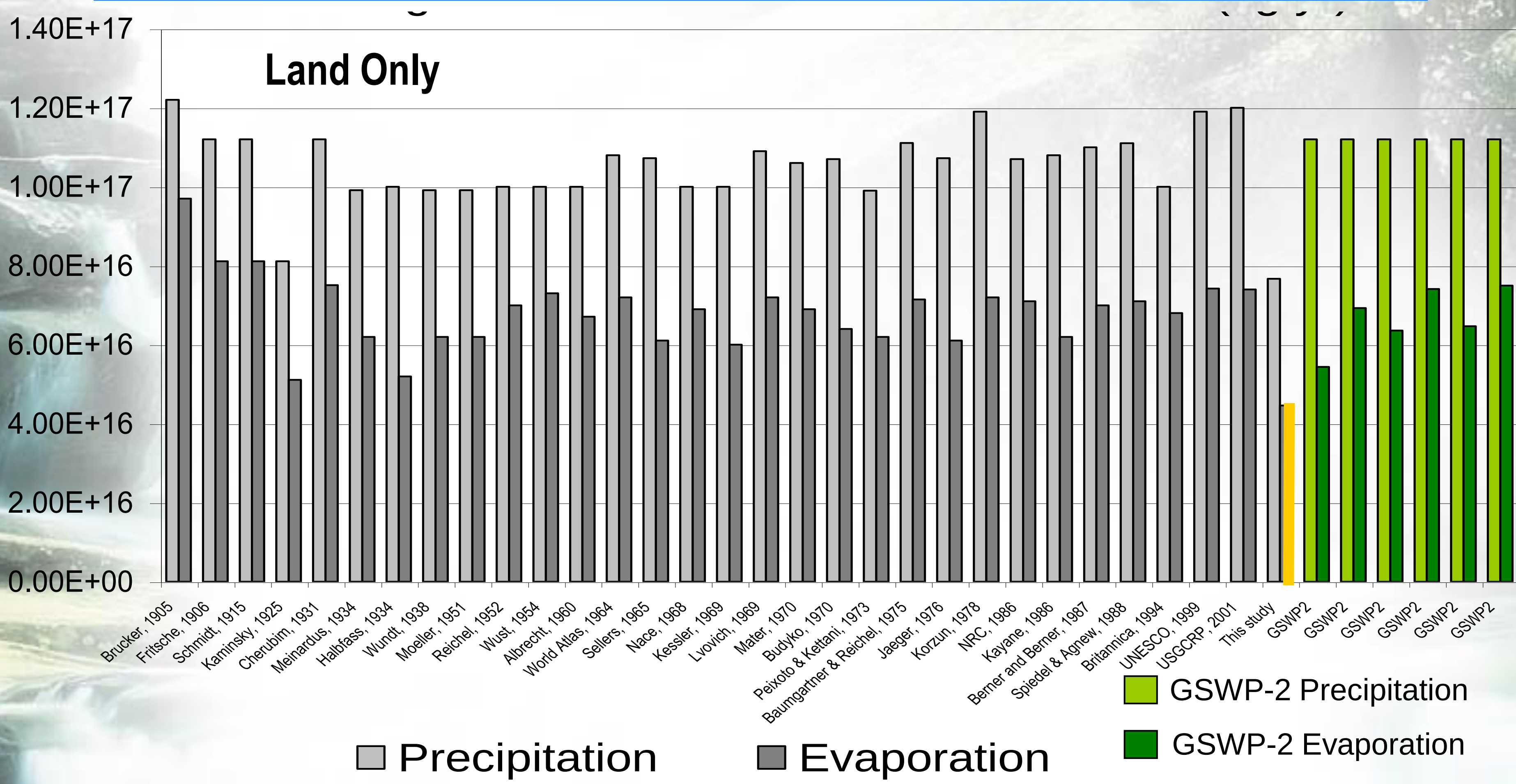



- Global fluxes of precipitation and evaporation are comparable to previous century of estimates.
- No discernable trend is seen in both compilations of the flux estimates.
- The notable disparity with this study is the lower values of both precipitation (not shown) and evaporation flux estimates over land.

# Comparison of This Study to Previous Estimates

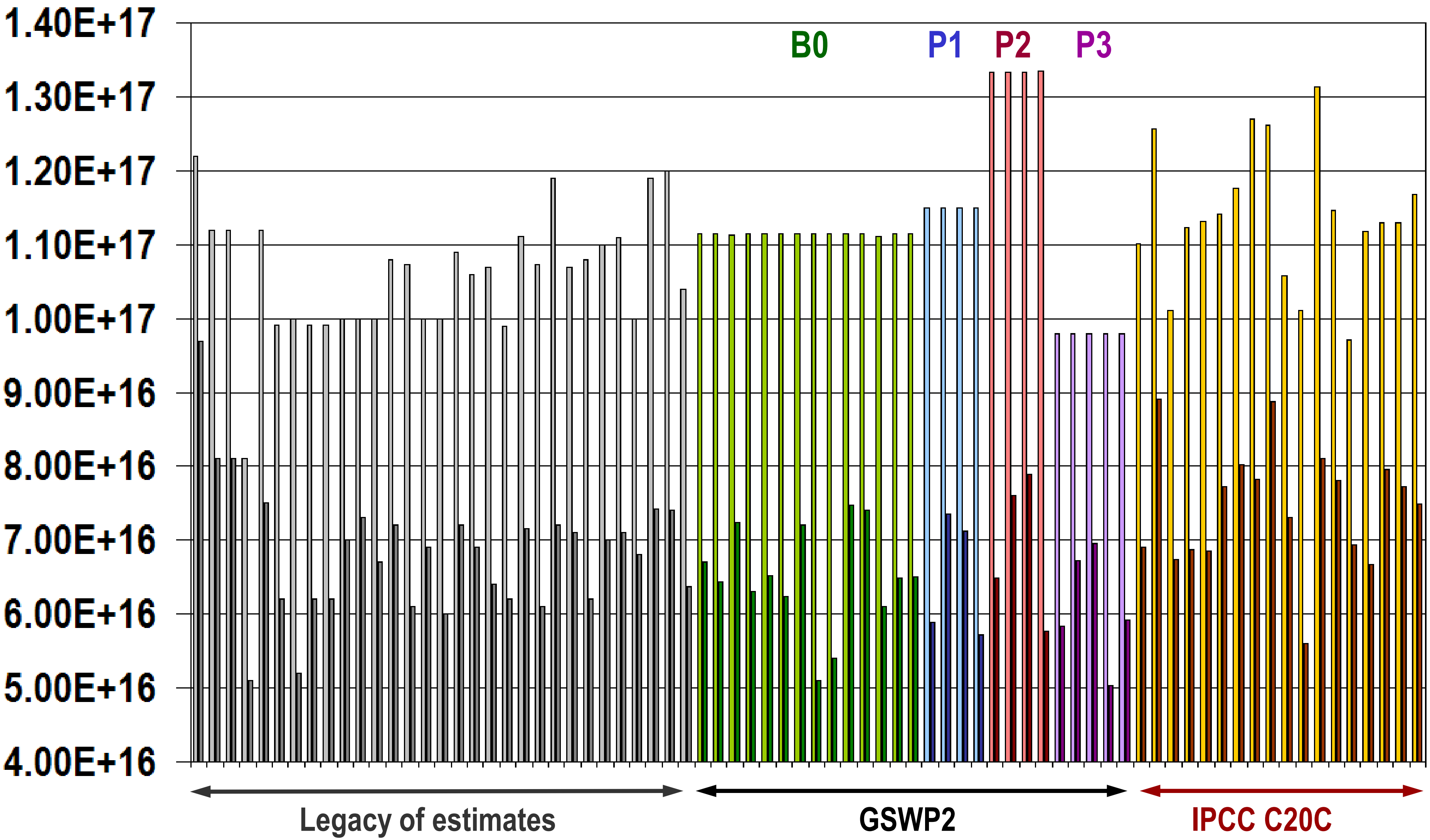


# Assessing Historical Land-Flux Estimates



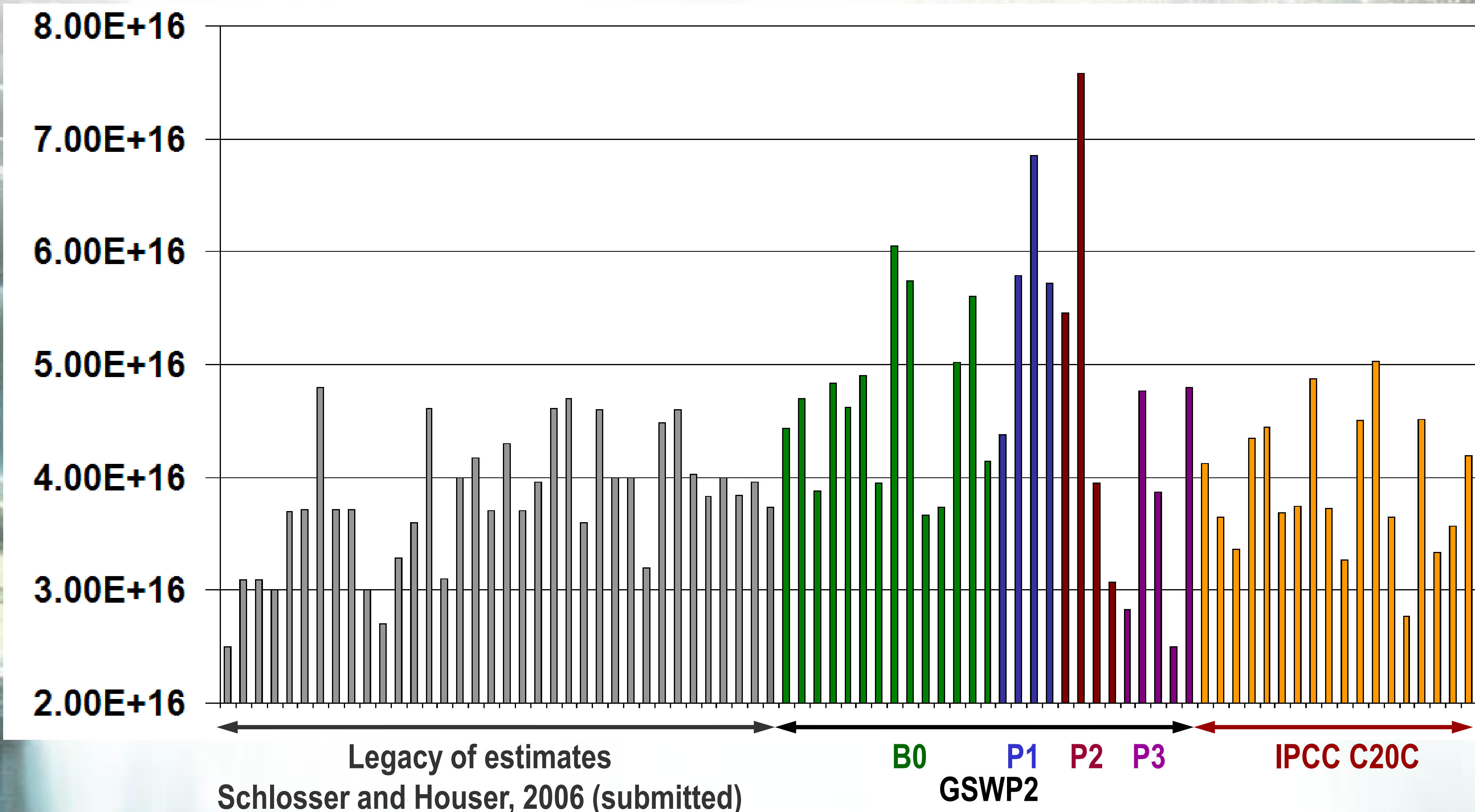

- **Global fluxes of precipitation and evaporation are comparable to previous century of estimates.**
- **No discernable trend is seen in both compilations of the flux estimates.**
- **The notable disparity with the GOLD study is the lower values over land.**
- **Scatter of GSWP2 estimates comparable to previous century's estimates.**

# Mean Annual Global Land Precipitation and Evaporation (kg/yr)



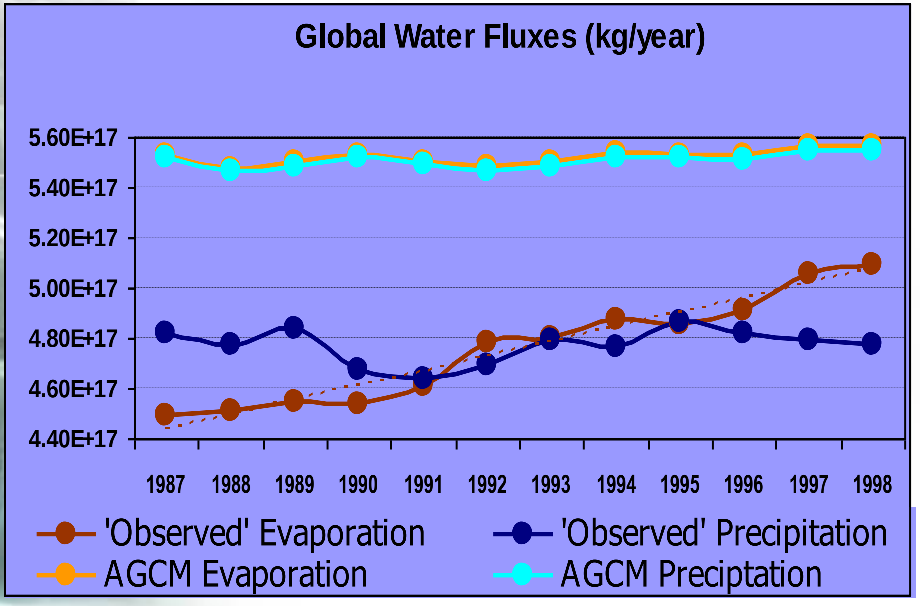

- Model-based (offline and coupled) scatter of estimates marginally higher than compilation of “modern” observationally-based estimates.

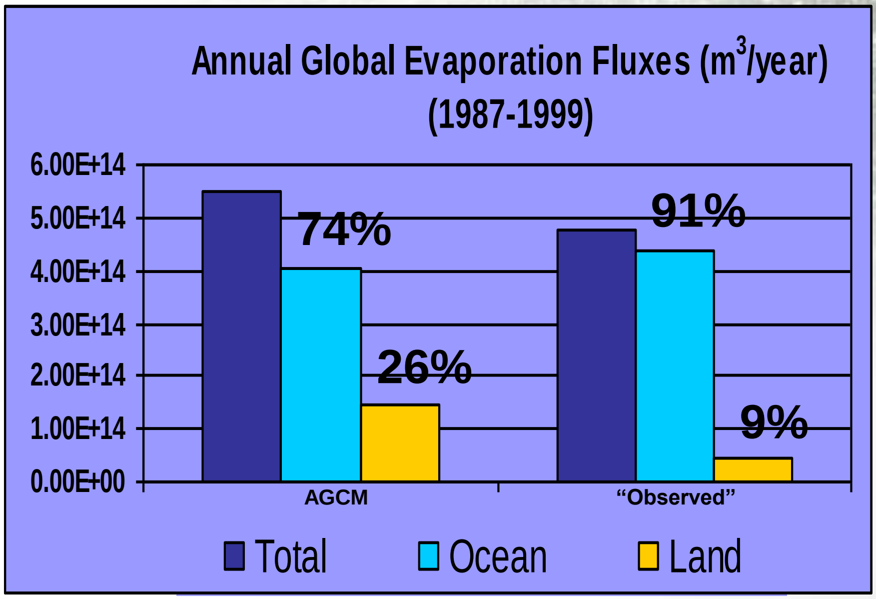
# (Implied) Global Annual River Discharge




- Global fluxes comparable among the more recent estimates.
- Early 20th century fluxes highly variable and exhibit marginal trend.

# AGCM Precipitation and Evaporation Evaluation




Schlosser

- Observed averaged annual evaporation and precipitation mass flux balance to within 1%.
  - However, interannual global variations considerably uncorrelated.

- AGCM mean “rate” of annual global water cycle exceeds observed (~15%).
- AGCM interannual variability of annual global precip/evap ~50%/35% lower than observed.
- Relative contributions of land and ocean fluxes differ considerably.
  - What are the sources of these discrepancies (both in the models and “observations”)?

- Trend in “observed” global evaporation (~1 %/year), but no trend in precipitation.
- Trend in AGCM global water-cycle rate during 1987-1999 and order of magnitude smaller.
  - Source of modeled trend from prescribed SSTs, is the response accurate?
  - Observations insufficient to detect AGCM trend (e.g. Ziegler et al., 2002).

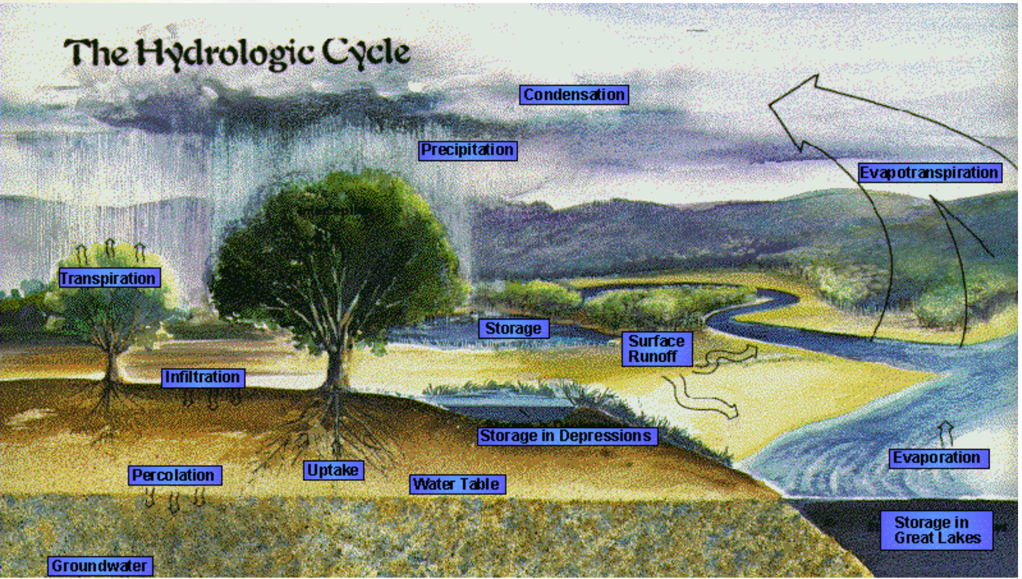
# Hydrologic Basics

**Hydrology:** The science that deals with the waters of the earth and their occurrence, distribution, and circulation at the surface, underground, and in the atmosphere.

**Hydrology: Natural Science that deals with the** transport and distribution of water (liquid, gas, solid) in the atmosphere, on and beneath the earth's surface.

**As Hydrologists: Interested in forecasting means,** extremes, and time series of hydrologic events and processes.

**As Engineers: Charged with the evaluation,** planning and design of facilities to best utilize mitigate and manage water resources including catastrophic hydrologic events.




# History

- 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.
- Early “hydrological cycle” concept – Roman and Greek (streamflow from underground)
- Da Vinci, Palissy (ca 1500) – land phase (streamflow from precipitation)
- Hadley (1700)– ocean-atmosphere-river cycle
- Hydrodynamics (18th century) Bernulie, Euler,
- Dalton’s law of partial pressure
- Establishment of gauge networks (1800 in US and Europe and 1820 in India)
- Darcy’s flow over porous media
- IUGG hydrology section 1922
- AGU hydrology section1930

# Physical quantities

- Basic measurements, M, L, t, Temp
- $[F] = [MLt^{-2}]$
- $E = FL = ML^2 t^{-2}$
- SI and MKS (cgs)
- Precision (significant digits)
- example: 14.0 x 3 = 40, not 42, because one of the multipliers has only one SF.
- example: 14.0 x 3.0 = 42, because one of the multipliers has only two SF.
- example: 14.0 / 3 = 5, not 4.6, because the denominator has only one SF
- example: 14.16 + 3.2 = 17.36 (this is not the final answer!)   17.4 is the correct answer
- example: (3.2 x 4 x 0.035 / 7) + (12 x 0.5) = 0.06 + 6 = 6

- Unit conversion: multiplication by one
- Temperature- C, F and K

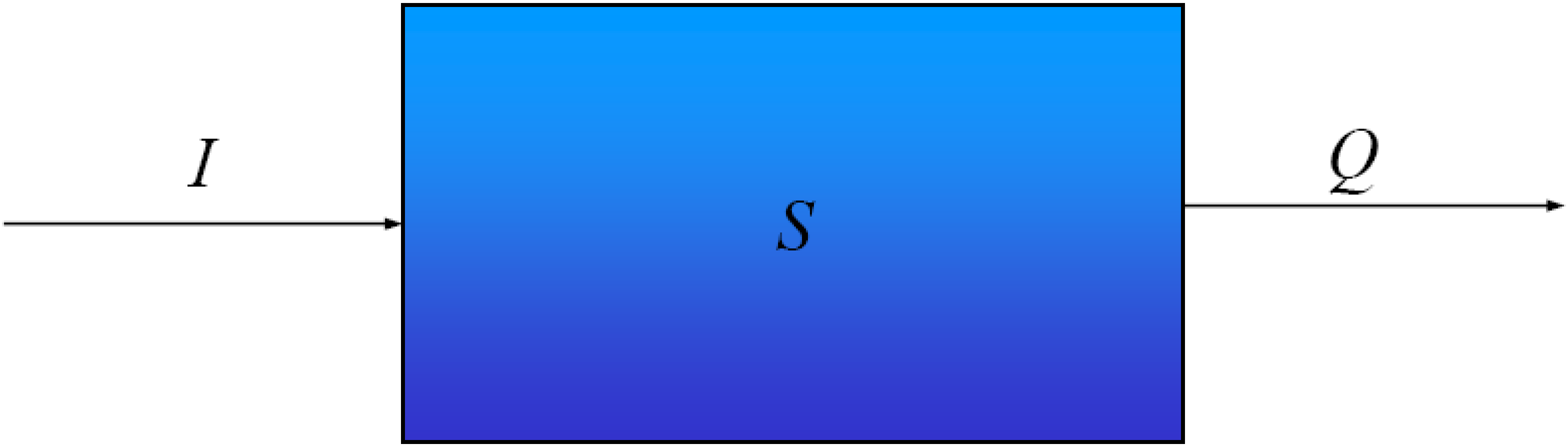
# Conservation Laws

- Mass
- Newton's law
  - ➢ Momentum is conserved
  - ➢ Rate of change of momentum proportional to force (F=ma)
  - ➢ To every action, there is equal and opposite reaction
- Laws of Thermodynamics
  - ➢ Energy is conserved
  - ➢ Impossible to perfectly convert heat to work
- Fick's first law of diffusion
  - ➢ High concentration to low concentration, rate proportion to gradient

Fundamental Law of Hydrology:

# Conservation of Mass

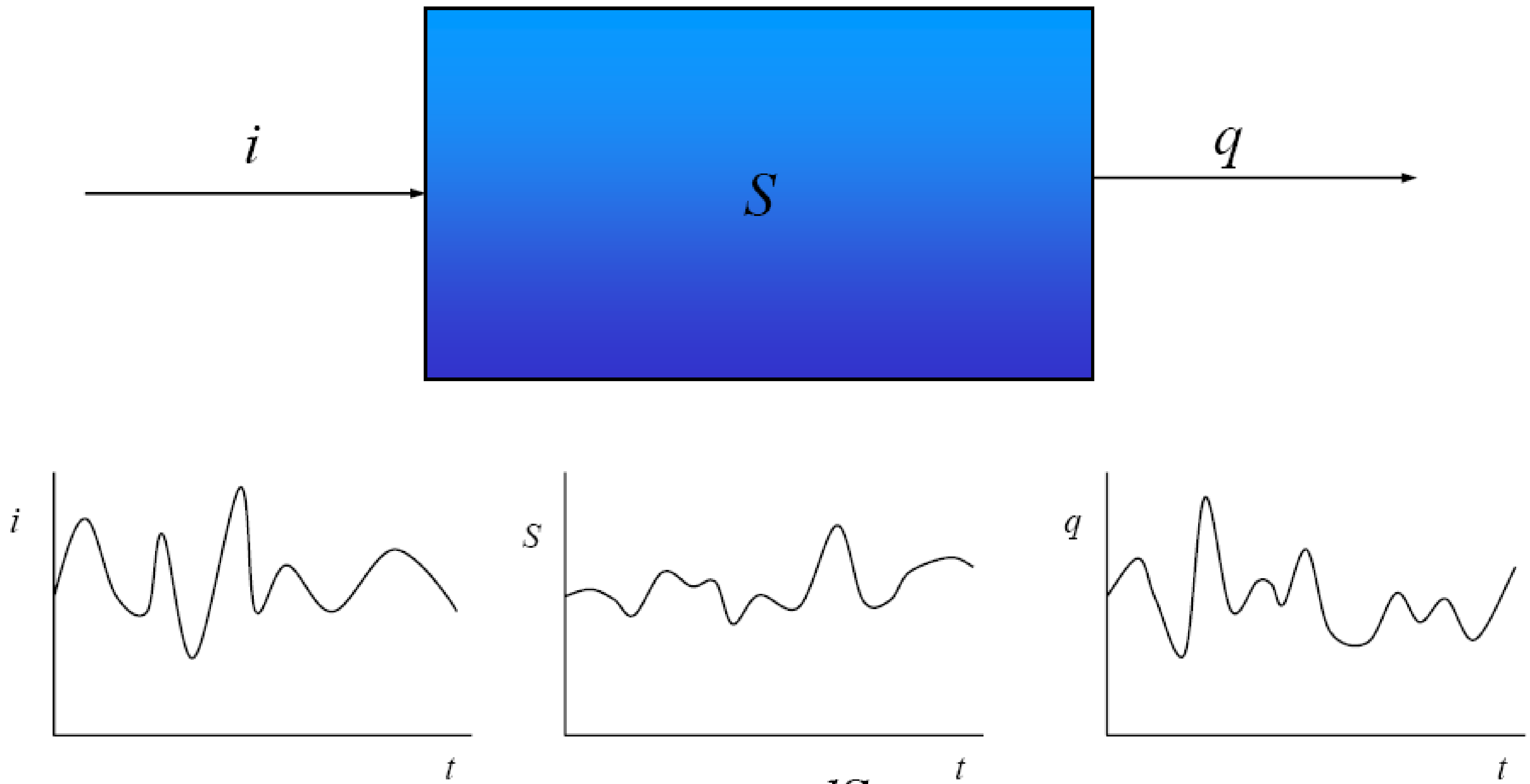
- Conservation of mass
  - Mass is neither created nor destroyed.




$$\Delta S = I - Q$$

# Conservation of mass as rates

## Conservation of mass




$$i = \lim_{\Delta t \to 0} \frac{I}{\Delta t}$$

$$i - q = \frac{dS}{dt}$$

$$q = \lim_{\Delta t \to 0} \frac{Q}{\Delta t}$$

# Conservation Equation

- Amount in – Amount out = Storage Change
- $I - Q = \Delta S$
- Divide by dt and take limit dt →0

  $i - q = dS/dt$

  Can be applied globally or locally

  Equally applicable to energy and water substances

# Residence time

- time required to completely renew a lake's water volume
- average length of time that a 'parcel' of water spends in the reservoir

Figure 2-5a (NALMS 2001)

$$T_R = \frac{S}{m_{Q \text{ or } I}}$$

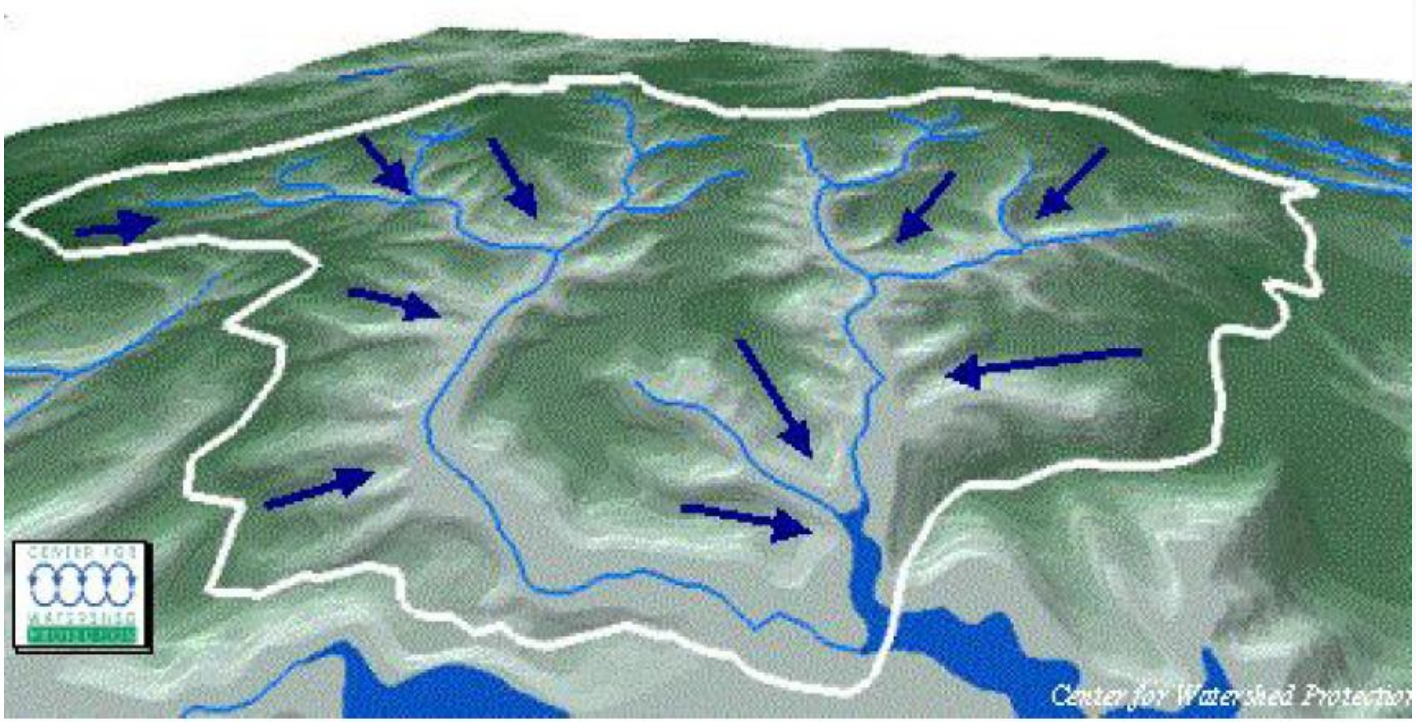
- q = f (S)
- Linear storage q = k S
- Decreases the variability
- Increases the persistence (autocorrelation coefficient)
- Residence time or turnover time tq = S/q, tp =S/p

# Residence time

- $q = f(S)$
- Linear storage $q = k S$
- Decreases the variability
- Increases the persistence (autocorrelation coefficient)
- Residence time or turnover time $t_q = S/q$, $t_p = S/p$

# Regional Water Balance

- Watershed (catchment, river basin, drainage basin)
- Use of DEM to delineate watershed (divide, drainage area, soil type, vegetation, land use, slope, etc)
- Natural hydrologic unit for regional water balance

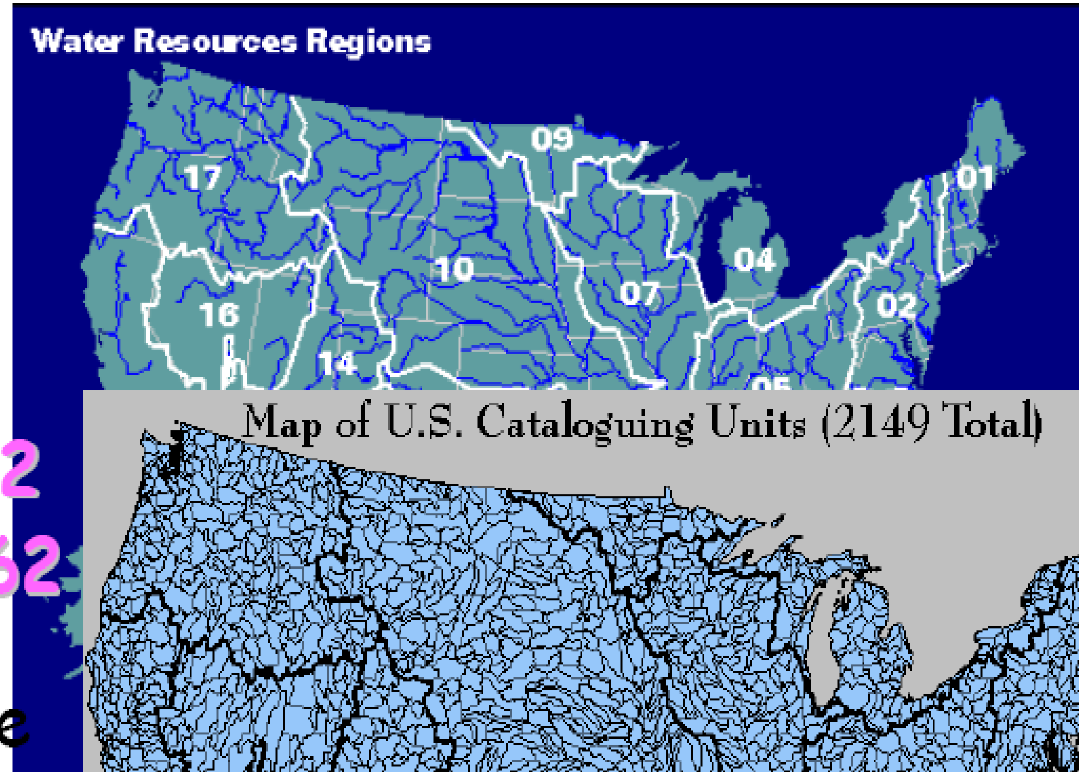


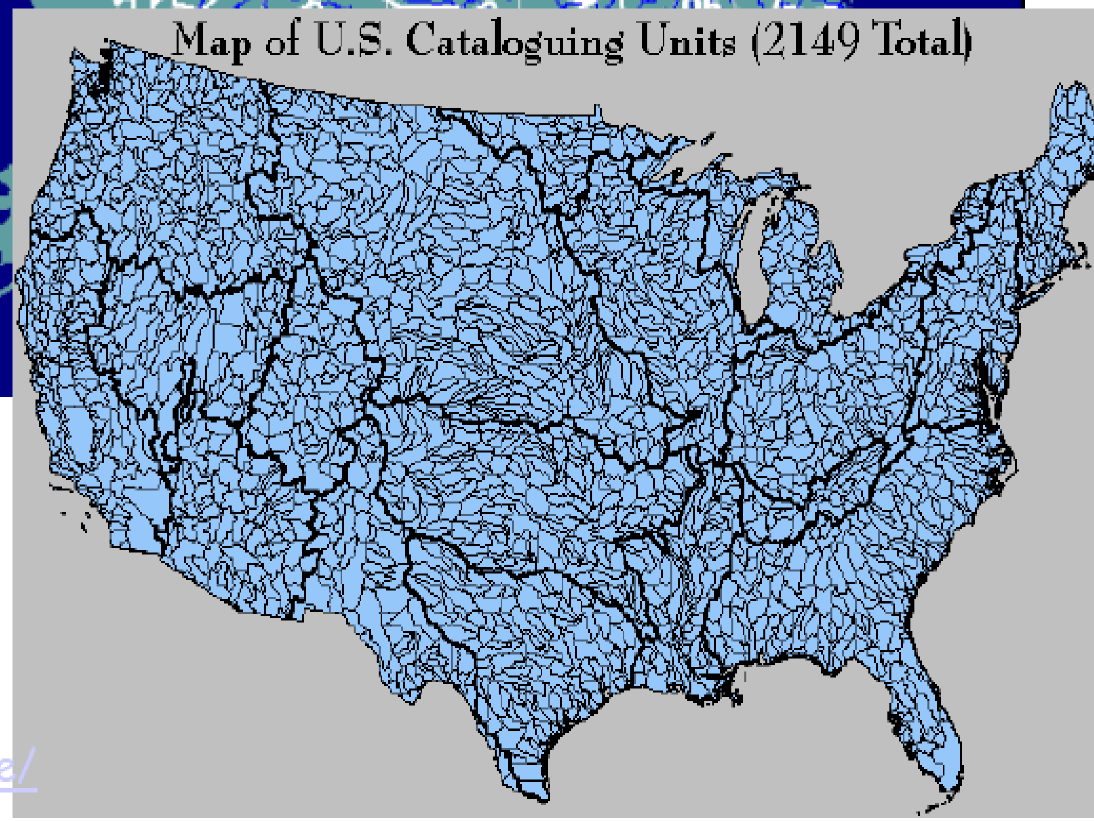

http://www.cwp.org

Incline
Incline
NATIONAL FOR
Sewage Disposal
Mill
23
24
Ponderosa Ranch
Water Tank
Piers
BM 6297
8157
Tunnel
Creek
Tunnel Creek Station
26
25
6272
7323
8407
TUNNEL
30
7906
BM 6280
Twin Lakes
AQUEDUCT
PARK

# USGS hydrologic units

- Four levels:
  - regions 21
  - sub-regions 222
  - accounting units 352
  - cataloging units 2262 'watersheds'
- Hydrologic unit code (HUC)
  - 2 digits for each level
  - EPA's Surf Your Watershed: http://cfpub.epa.gov/surf/locate/index.cfm



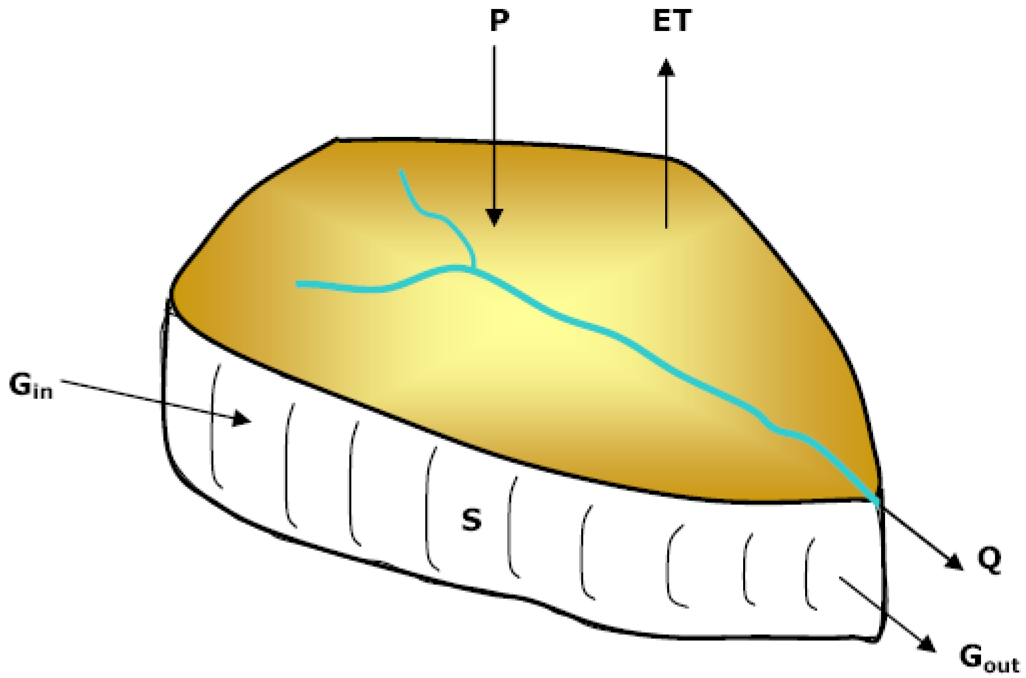



# The Watershed

**Watershed Hydrologic Budgets**

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

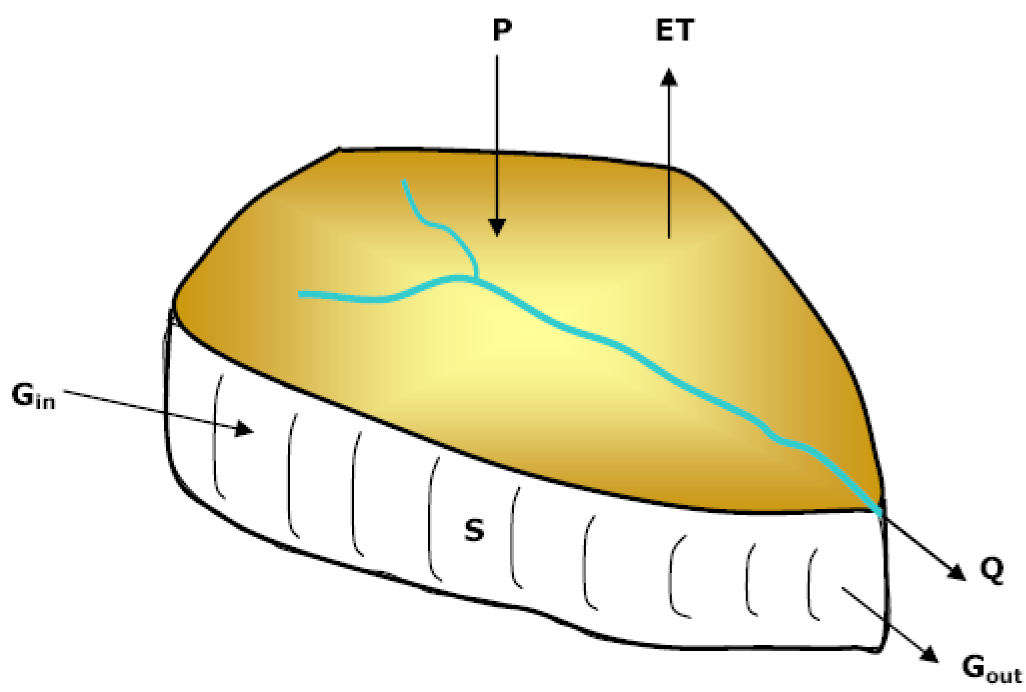
- Area that topographically appears to contribute all the water that flows through a given cross section of a stream. In other words, the area over which water flowing along the surface will eventually reach the stream, upstream of the cross-section.
- Horizontal projection of this area is the drainage 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

- P + Gin – (Q + ET + Gout) = $\Delta$S
- P precipitation
- Q runoff
- ET evapotranspiration
- G ground water in and out
- $\Delta$S storage change
- S = $\rho$ vol
- Assuming $\rho$ constant, S = vol [$L^3$]
- Usually normalized w.r.t drainage area, hence get [L].
- Equation expressed in mm/hr, or mm/day

# The Watershed: Water Balance




output

0 0

$$P + G_{in} - (Q + ET + G_{out}) = \Delta S \quad \Rightarrow \quad P - ET \approx Q + G_{out}$$

# Estimation of areal ET

- Assume $G_{in}$ and $G_{out}$ small
- Assume storage is negligible
- $m_{ET} = m_p - m_Q$
- Errors: model and measurement
- Accuracy of precipitation and streamflow
- Absolute and relative uncertainty
- Independent errors $\sigma^2_{x+y} = \sigma^2_x + \sigma^2_y$

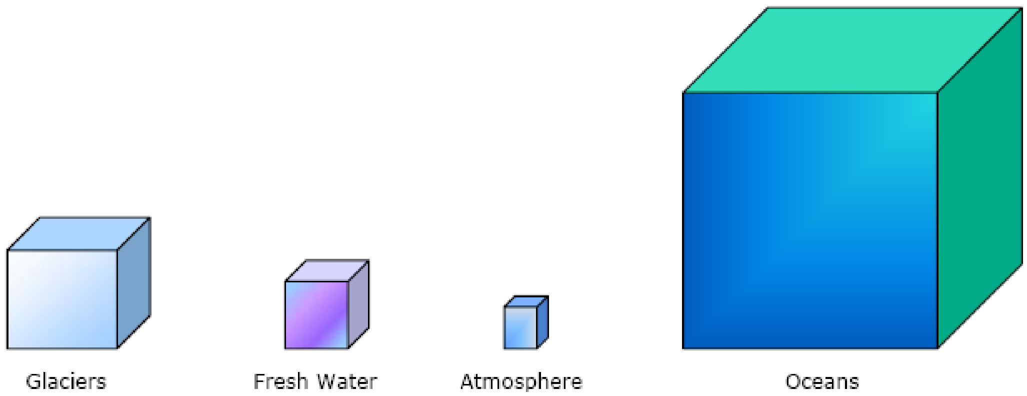
# Example of ET estimate (2-1)

- NH Oyster river
- Average preci 1066mm/year, uncertain 10% (at 95% level)
- Average drainage 551 mm/year, 5% uncertain
- ET = 1066 – 551 mm/year = 515 mm/yr
- Uncertainty = SQRT {(1066*.1)**2 + (551*.05)**2} = 55.1 mm/yr
- Relative uncertainty = 2 (55.1/515) = 0.214
- Pr $\{405 < \mu_{ET} < 625\} = .95$

# How much water is there?

| Component | USGS | UNESCO (1990) |
|---|---|---|
| Oceans | 97.09% | 93.93% |
| Glaciers | 1.99% | 1.65% |
| Groundwater | 0.62% | 4.12% |
| Atmosphere | 0.29% | 0.001% |
| Lakes | 0.012% | 0.016% |
| Soil moisture | 0.004% | 0.005% |
| Rivers | 0.0001% | 0.0001% |
| Total | 100% | 99.72% |

# Global Water Balance




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

**Estimate of the World Water Balance**

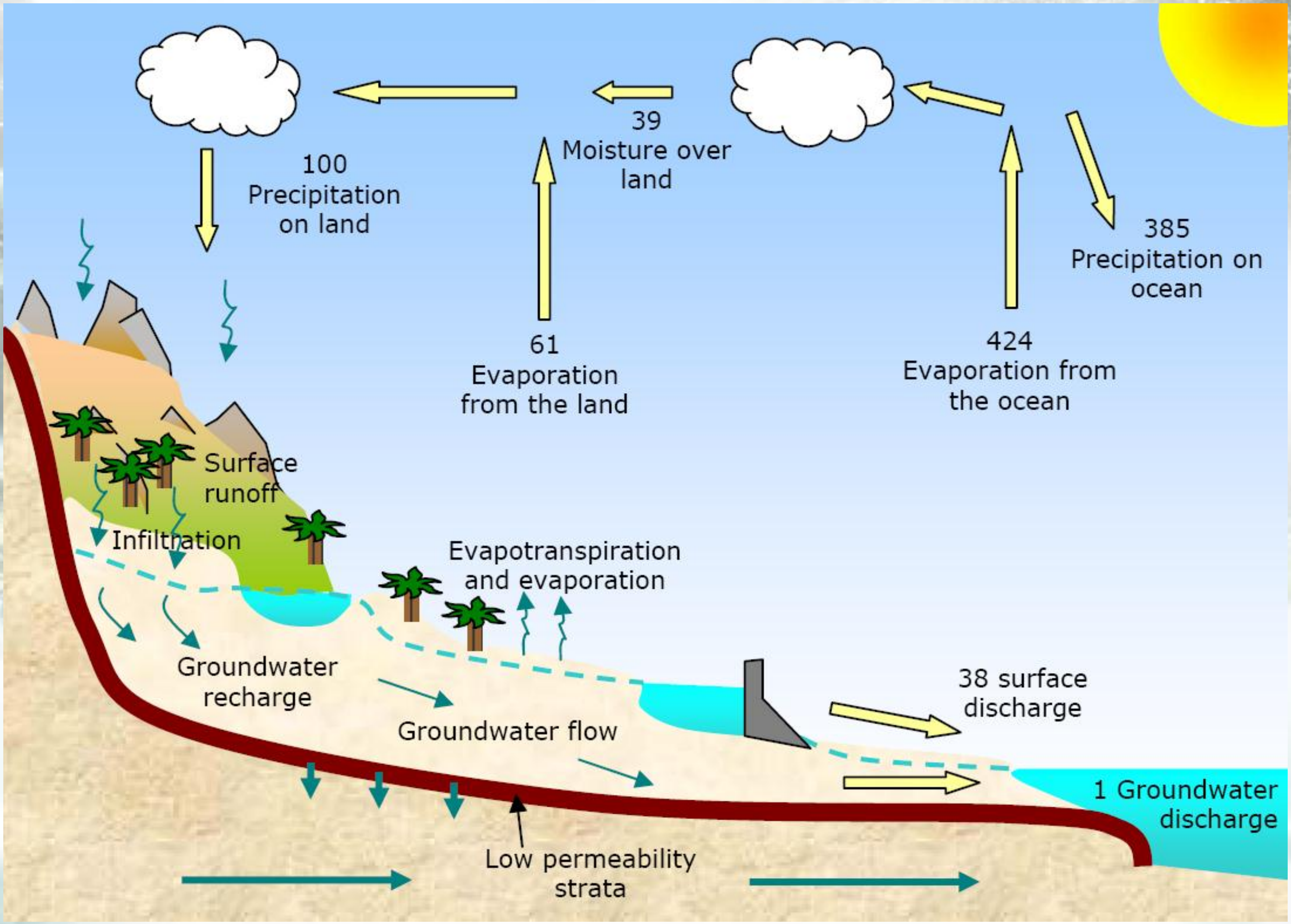
| Parameter | Surface area ($km^2$) X $10^6$ | Volume (km3) X $10^6$ | Volume % | Equivalent depth (m) | Residence Time |
|---|---|---|---|---|---|
| Oceans and seas | 361 | 1370 | 94 | 2500 | ~4000 years |
| Lakes and reservoirs | 1.55 | 0.13 | <0.01 | 0.25 | ~10 years |
| Swamps | <0.1 | <0.01 | <0.01 | 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 $km^3$/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

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

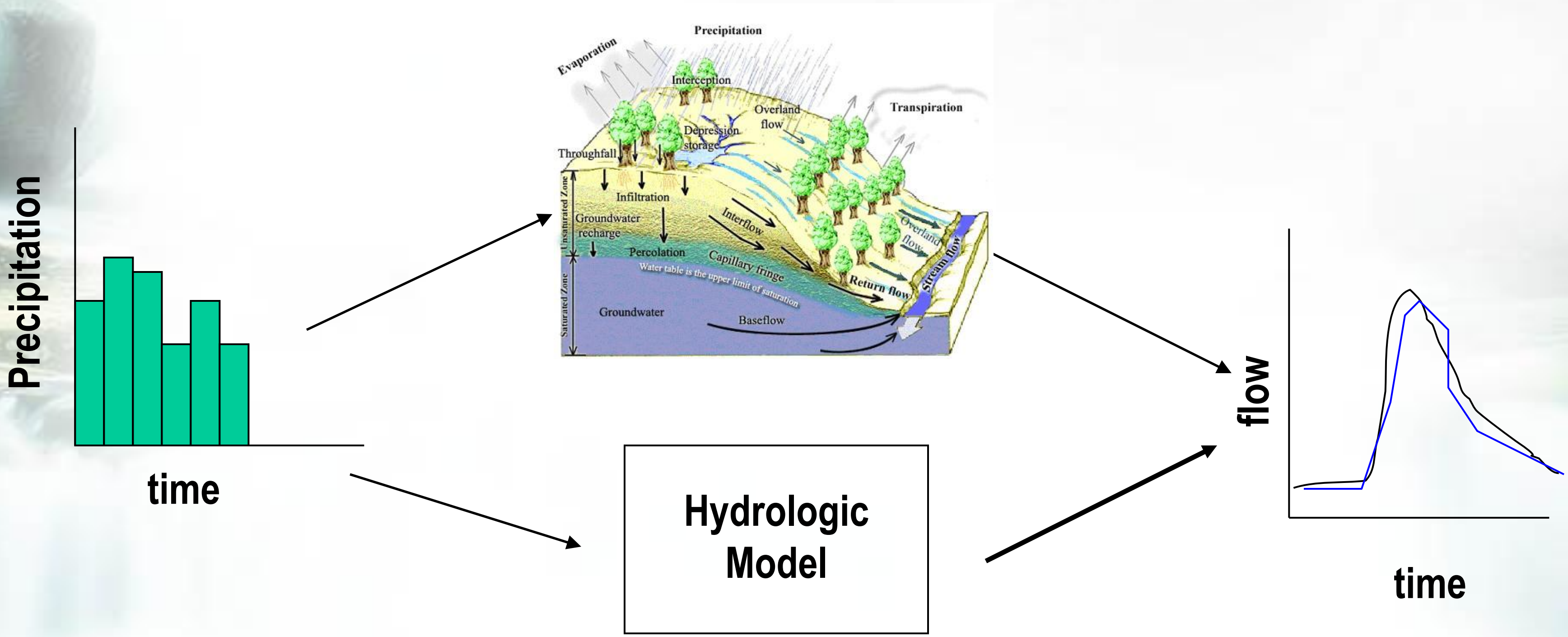


# Space/time variability

- Continuous series – samples
- Expectation, Mean, standard deviation, median, extremes (max/min), percentile, coefficient of variation (CV)
- Flow duration curves (FDC) flow rate (q) vs. cumulative distribution (Q)
- Exceedence probability E $P_Q(q_p) = 1 - F_Q(q_p) = \Pr\{Q>q_p\}$

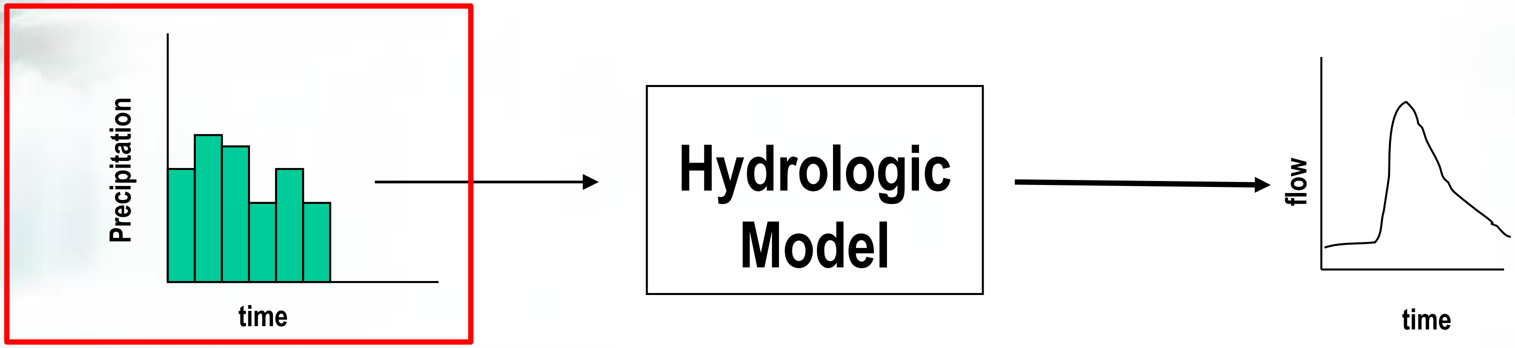
# Hydrograph Modeling

- Goal: Simulate the shape of a hydrograph given a known or designed water input (rain or snowmelt)



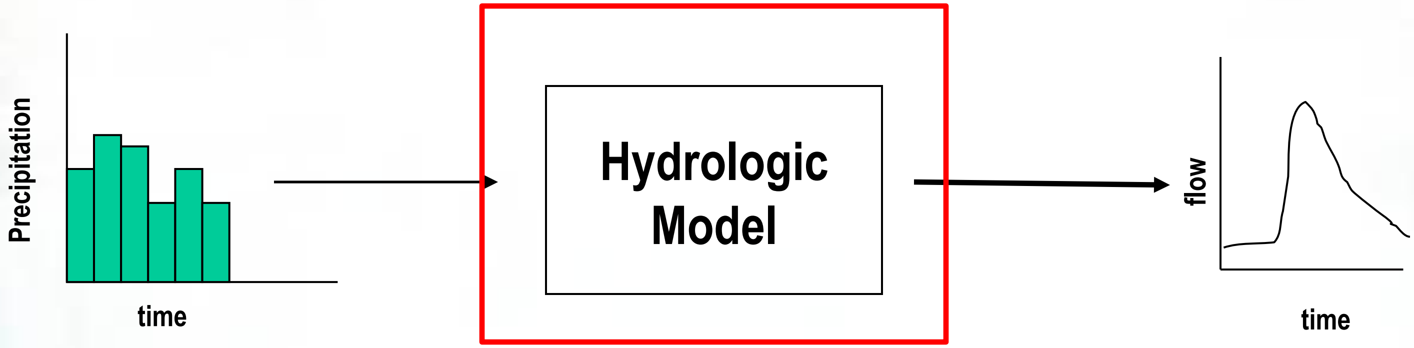
# Hydrograph Modeling: The input signal

- Hyetograph can be
  - A future “design” event
    - What happens in response to a rainstorm of a hypothetical magnitude and duration
      - See http://hdsc.nws.noaa.gov/hdsc/pfds/
  - A past storm
    - Simulate what happened in the past
    - Can serve as a calibration data set



# Hydrograph Modeling: The Model

- What do we do with the input signal?
  - We mathematically manipulate the signal in a way that represents how the watershed actually manipulates the water
    - Q = f(P, landscape properties)



# Hydrograph Modeling

- What is a model?
- What is the purpose of a model?
- Types of Models
  - Physical
    - http://uwrl.usu.edu/facilities/hydraulics/projects/projects.html
  - Analog
    - Ohm's law analogous to Darcy's law
  - **Mathematical**
    - **Equations to represent hydrologic process**

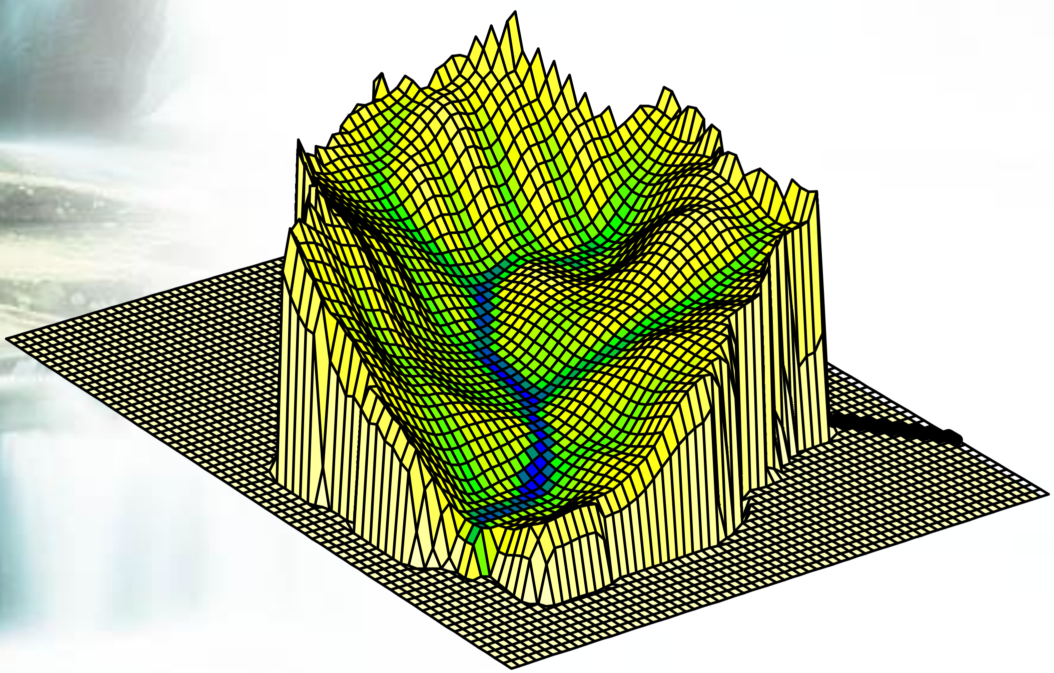
# Types of Mathematical Models

- Process representation
  - Physically Based
    - Derived from equations representing actual physics of process
    - i.e. energy balance snowmelt models
  - Conceptual
    - Short cuts full physics to capture essential processes
      - Linear reservoir model
  - Empirical/Regression
    - i.e temperature index snowmelt model
  - Stochastic
    - Evaluates historical time series, based on probability
- Spatial representation
  - Lumped
  - Distributed

# Hydrograph Modeling

- Physically Based, distributed

Physics-based equations for each process
in each grid cell



See dhsvm.pdf

Kelleners et al., 2009

Pros and cons?

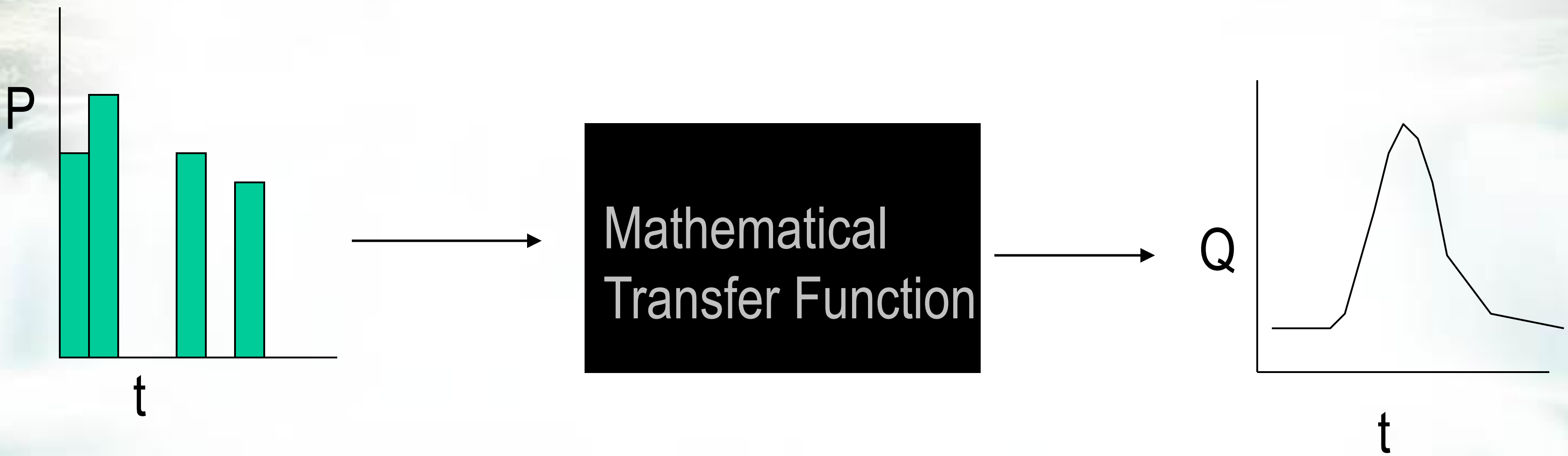
# Hydrologic Modeling: Systems Approach

A transfer function represents the lumped processes operating in a watershed

-Transforms numerical inputs through simplified paramters that “lump” processes to numerical outputs

-Modeled is calibrated to obtain proper parameters

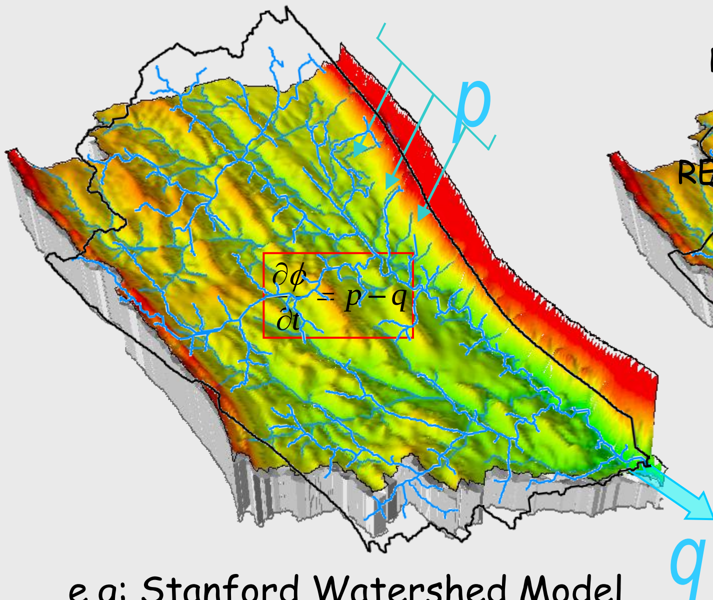
-Predictions at outlet only



# Integrated Hydrologic Models Are Used to Understand and Predict (Quantify) the Movement of Water

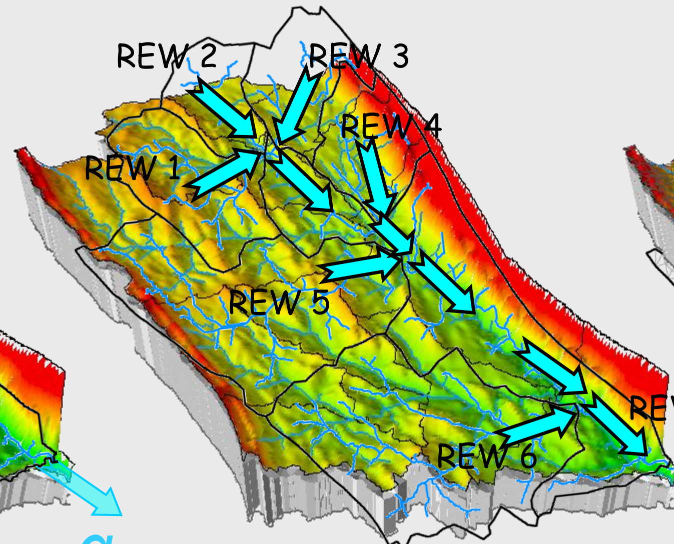
**How** ? Formalization of hydrologic process equations

Lumped Model



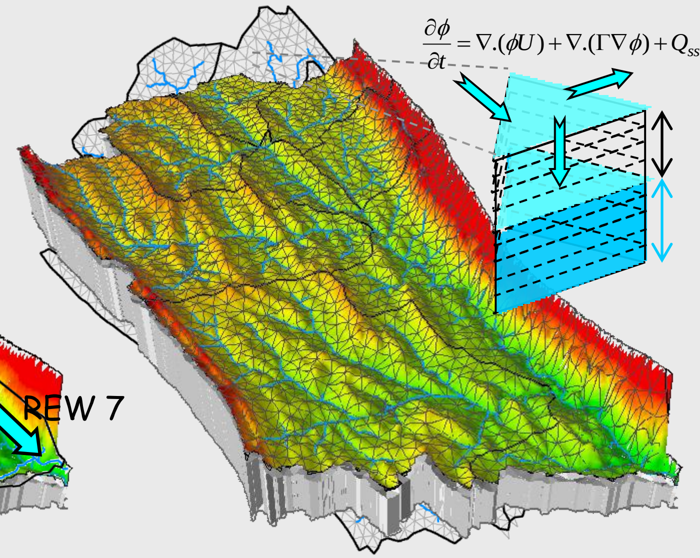

e.g: Stanford Watershed Model

Semi-Distributed Model




e.g: HSPF, LASCAM

Distributed Model




e.g: ModHMS, PIHM, FIHM, InHM

| | | |
|---|---|---|
| **Process Representation:** | **Parametric** | **Physics-Based** |
| **Predicted States Resolution:** | **Coarser** | **Fine** |
| **Data Requirement:** / **Computational Requirement:** | **Small** | **Large** |

# Syllabus

- Scope of the course
- Homework, grading, class project, etc.
- http://mason.gmu.edu/~phouser/hydrosphere

- **Global hydrological cycle** – spatial and temporal variations of water substances in the terrestrial, oceanic and atmospheric components of the global water system
- **Land phase** – the movement and transformation of water substances on and under land surfaces, their physical, chemical interactions, and biological processes that conduct or affect their movement
- **Ocean** – Major storage
- **Atmosphere** – Most active transfer agent

# HW #1

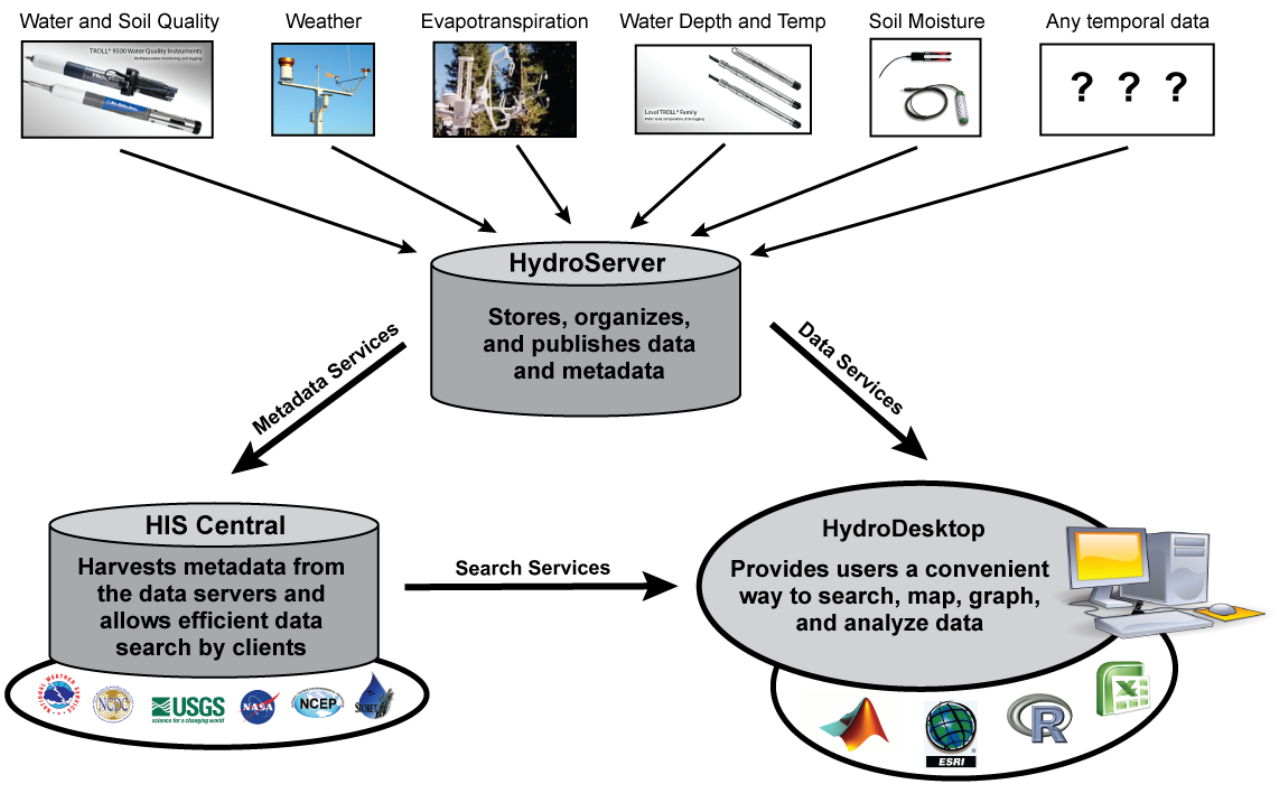
- Read Dingman Chapters 1-3
- Introduction to Hydrodesktop
- Assignment of presentations

# HIS – Hydrologic Information System

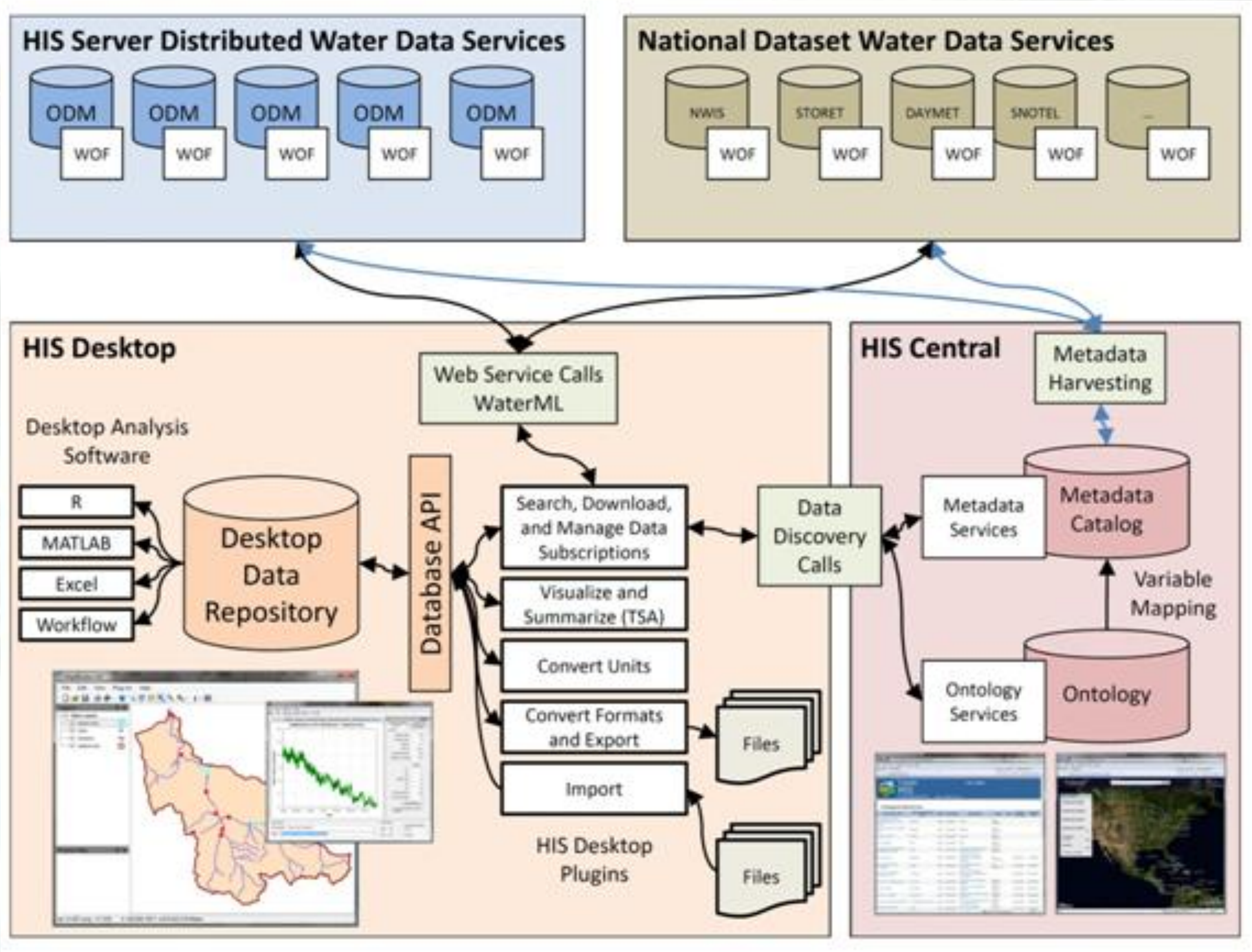
Hydrologic Information System (HIS) data storage and delivery tools:

- WaterML - language for sharing hydrologic data sets via web services
- HIS Server - a software tool set for delivering WaterML from a server

Support the consistent storage and delivery of hydrologic and other environmental observation data.



# HIS – Hydrologic Information System



# HIS – Hydrologic Information System