Integration of Hydrometeorological and Climate Information in Water Resources System Operation and Design

Soroosh Sorooshian

Center for Hydrometeorology and Remote Sensing

University of California Irvine

The Abdus Salam ICPT Conference on:

Water Resources in Developing Countries: Planning & Management under Climate Change Scenario

Trieste, Italy: Apr. 27th- May 8th 2009

Required Hydrometeorologic Predictions

Short Range – · – · – · – · – · – · – · – · – · – · – · – · – · – · –>Long Range

hours – – – –> days – – – –> weeks – – –> months – –> seasons – –> years – – – – – –> decades

Flash Flood Warning

Flash Flood Guidance

Headwater Guidance

Flood Forecast Guidance

Reservoir Inflow Forecasts

Spring Snow Melt Forecasts

Water Supply Volume

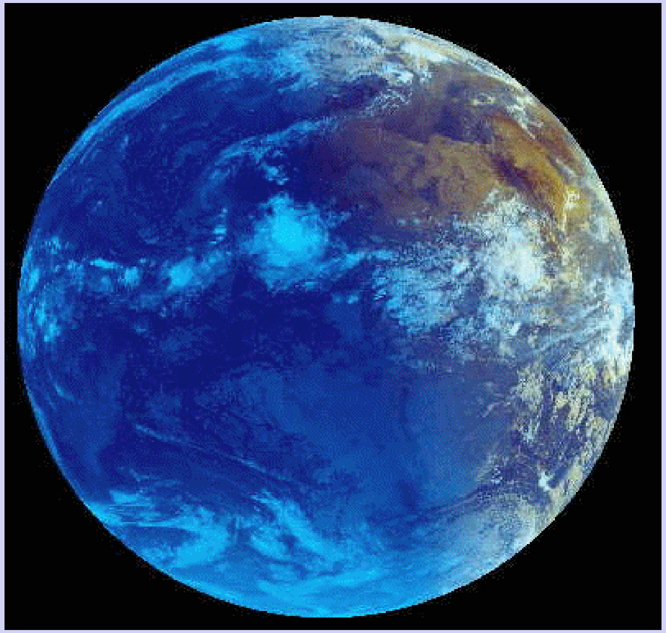
Short-range ***Mid-range*** ***Long-range***

Forecast Requirements

Climate, Hydrology and Water Resources

- ***How will Climate effect water Availability?***

- ***Can we predict the future changes which are responsive to "user" needs?***



What Do "Instrumental" Records Tell Us?

Center for Hydrometeorology and Remote Sensing, UCI
CHRS

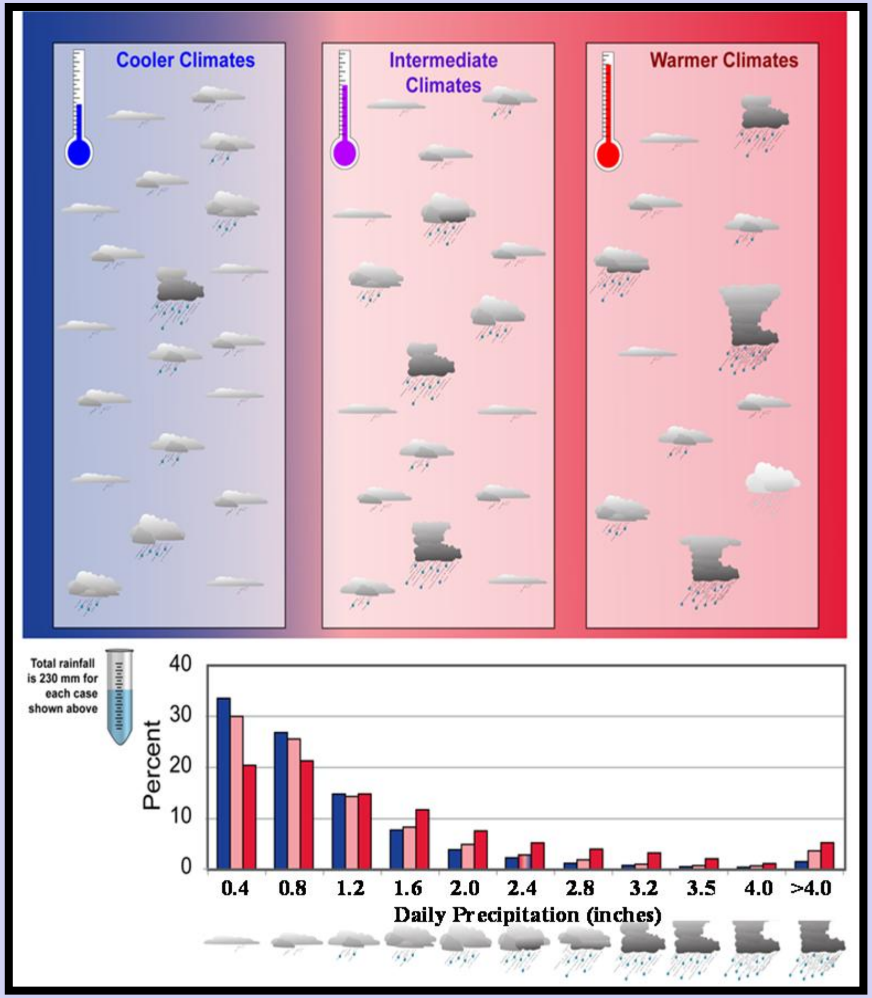
Changes in Precipitation: U.S.A

Facts from Observations

- From 1908-2002:
  - Total annual precipitation across the contiguous U.S. increased 7%
  - Heavy daily Precipitation events have increased by 20%

- Rainfall associated with warmer climates are more due to extreme events compared to colder climates

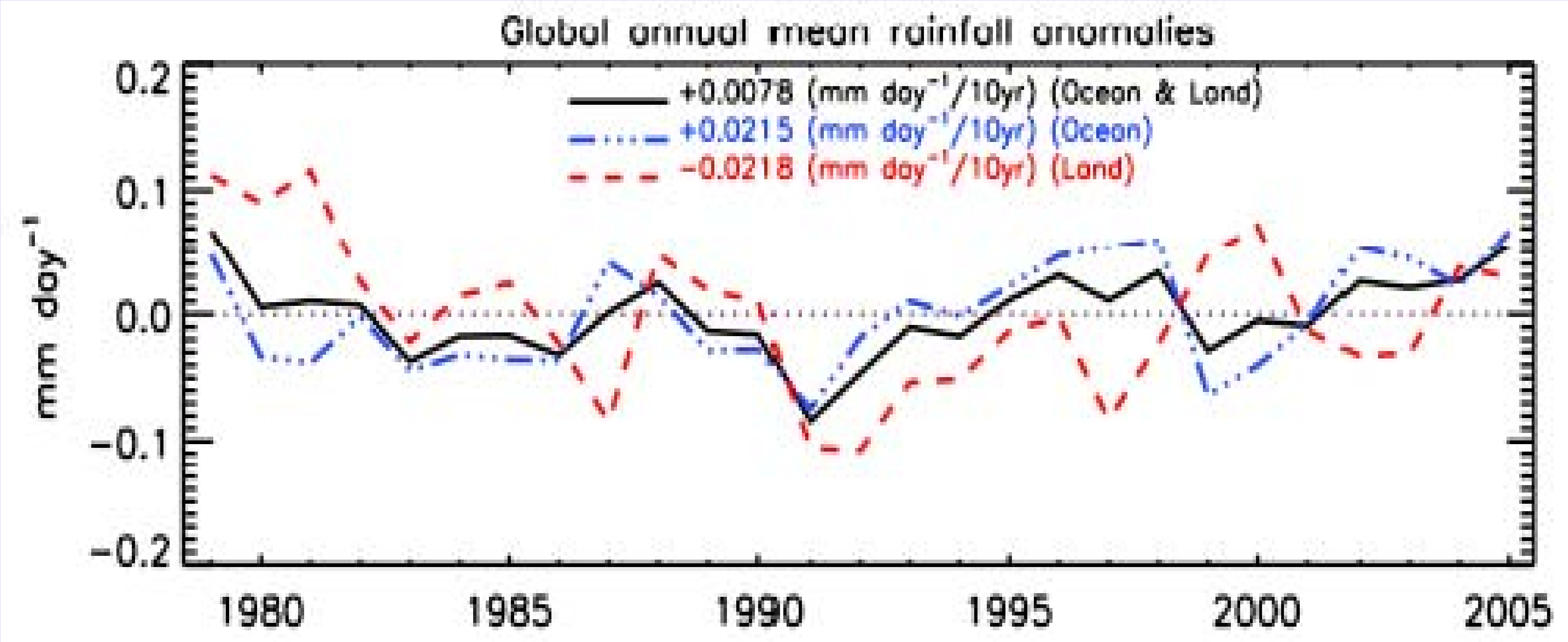
10
Confidence Index
0



Source: Tom Karl NCDC-NOAA 2007

Global Variations in Precipitation (1979-2005) 90N-90S

Global mean = 2.6 mm/d *(Ocean [2.8 mm/d] Land[2.1 mm/d])*



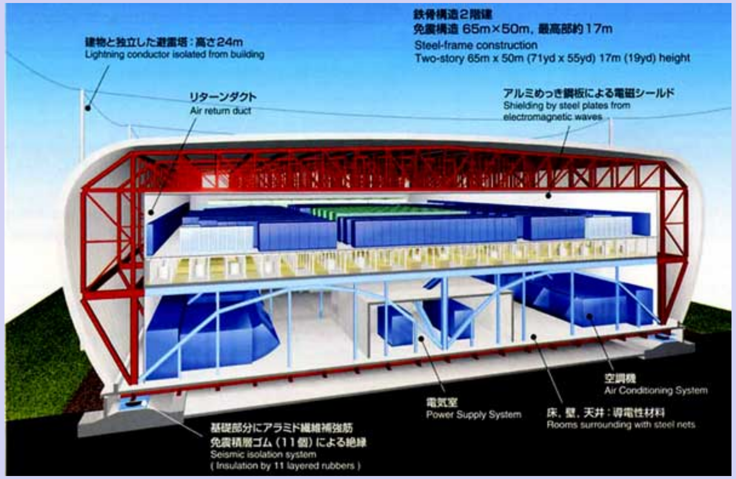
- ***Little or no linear change during period [biggest change is +2% over ocean]***
- ***Ocean and land precipitation tend to compensate***

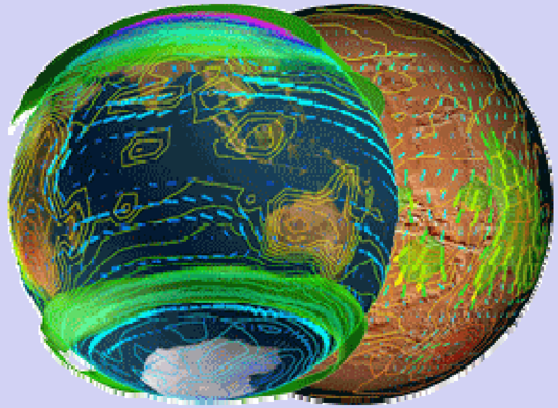
Adler et al. J. Hydromet.

Hydrologically-Relevant Climate Variables

What Do Climate Models Tell Us About the Future which May Be Useful for Water Resources Applications ?

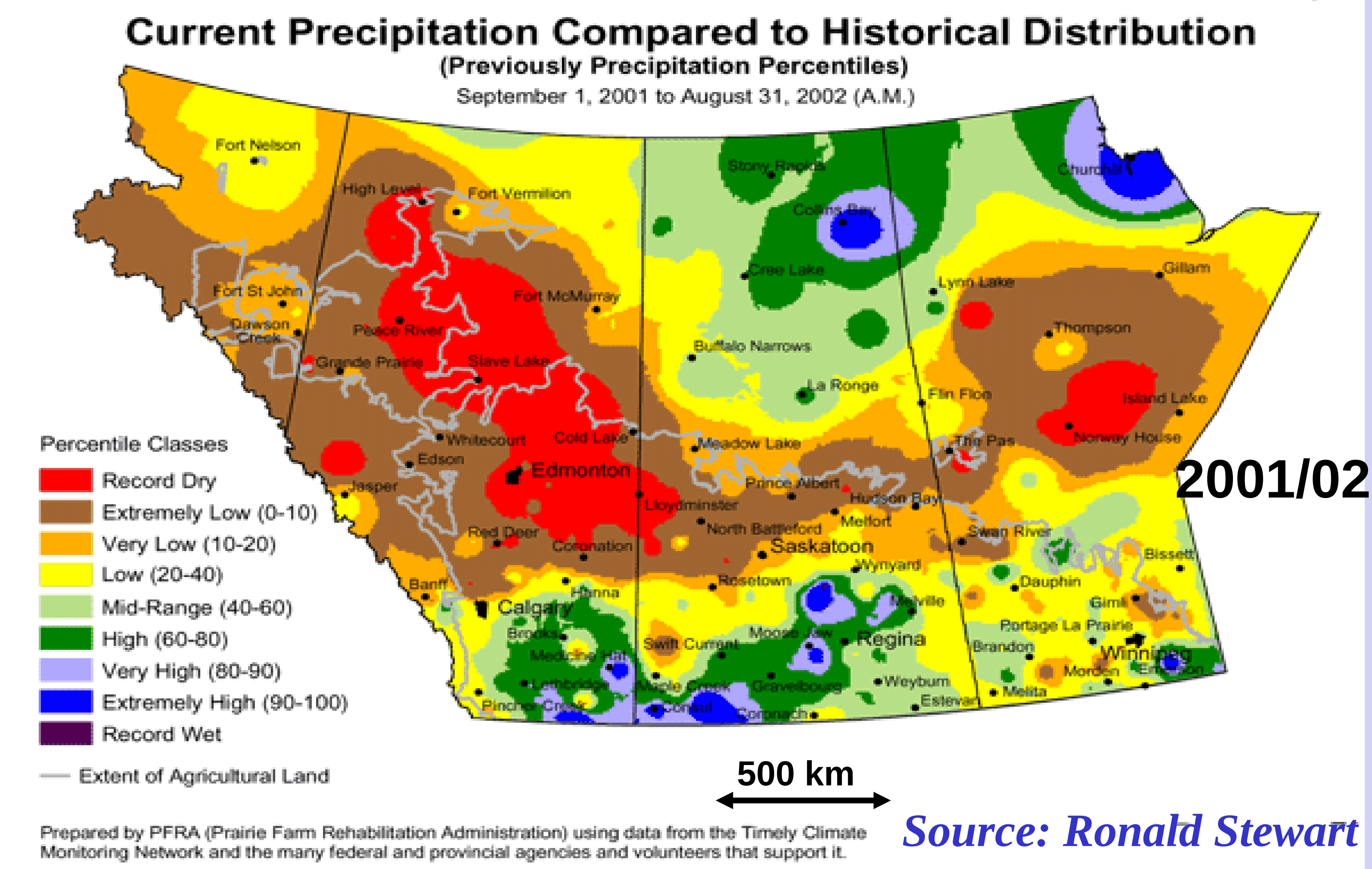
Climate Predictions into the Future!





Seasonal and Inter-Annual Time-Scales

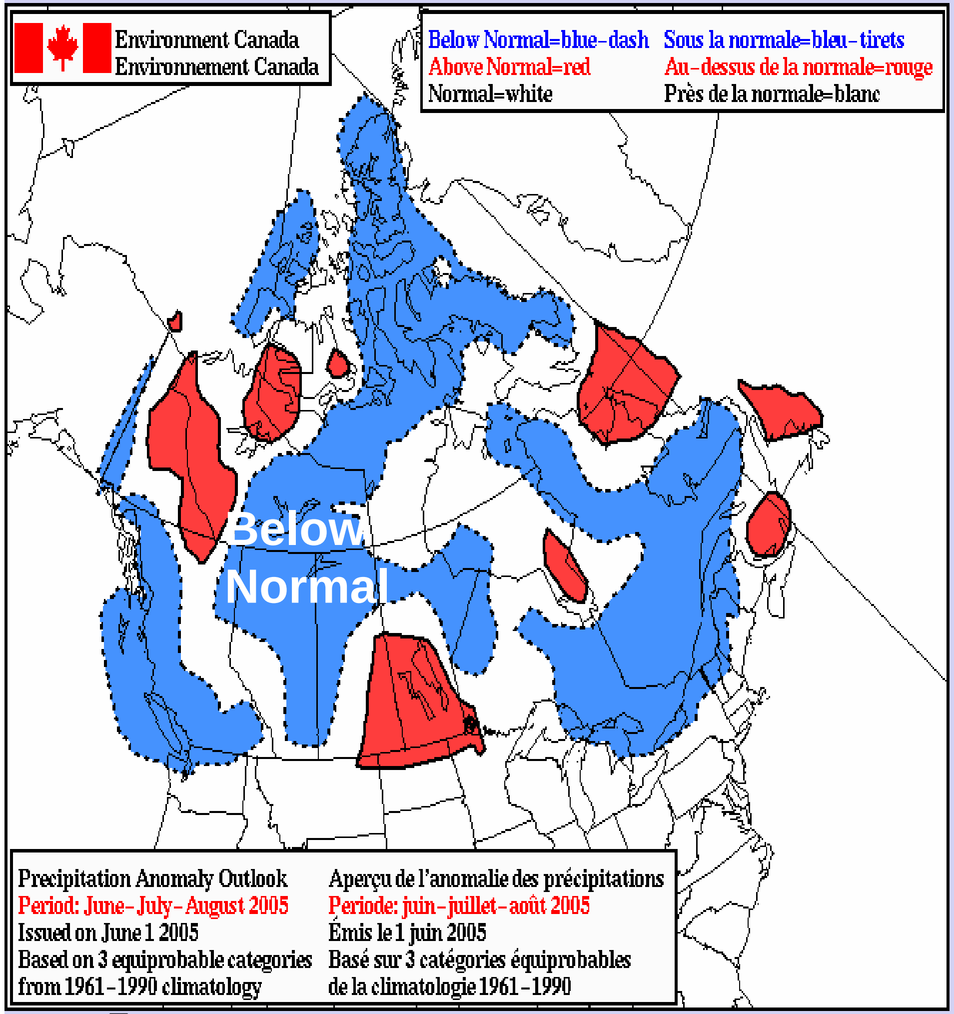
Canadian Prairie drought 1999-2005



Source: Ronald Stewart

SEASONAL PREDICTIONS: Summer of 2005 - Canada

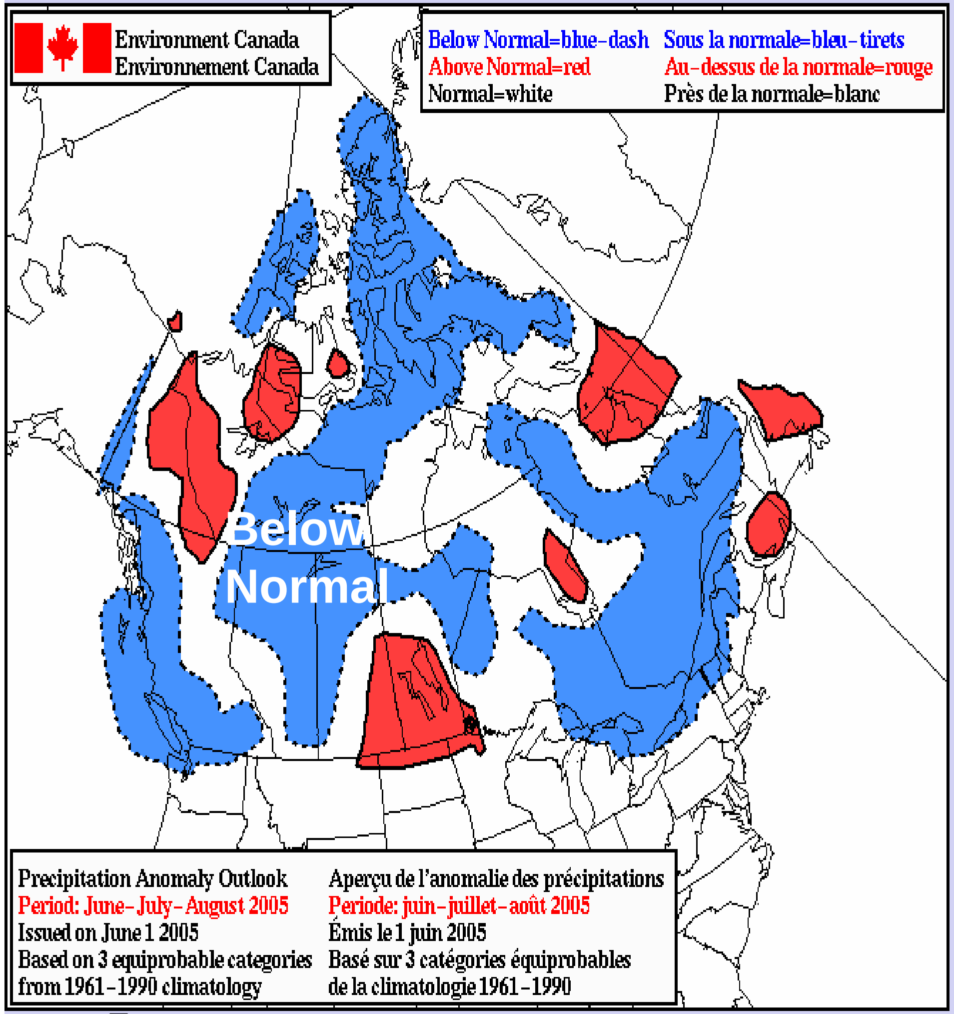
PREDICTION



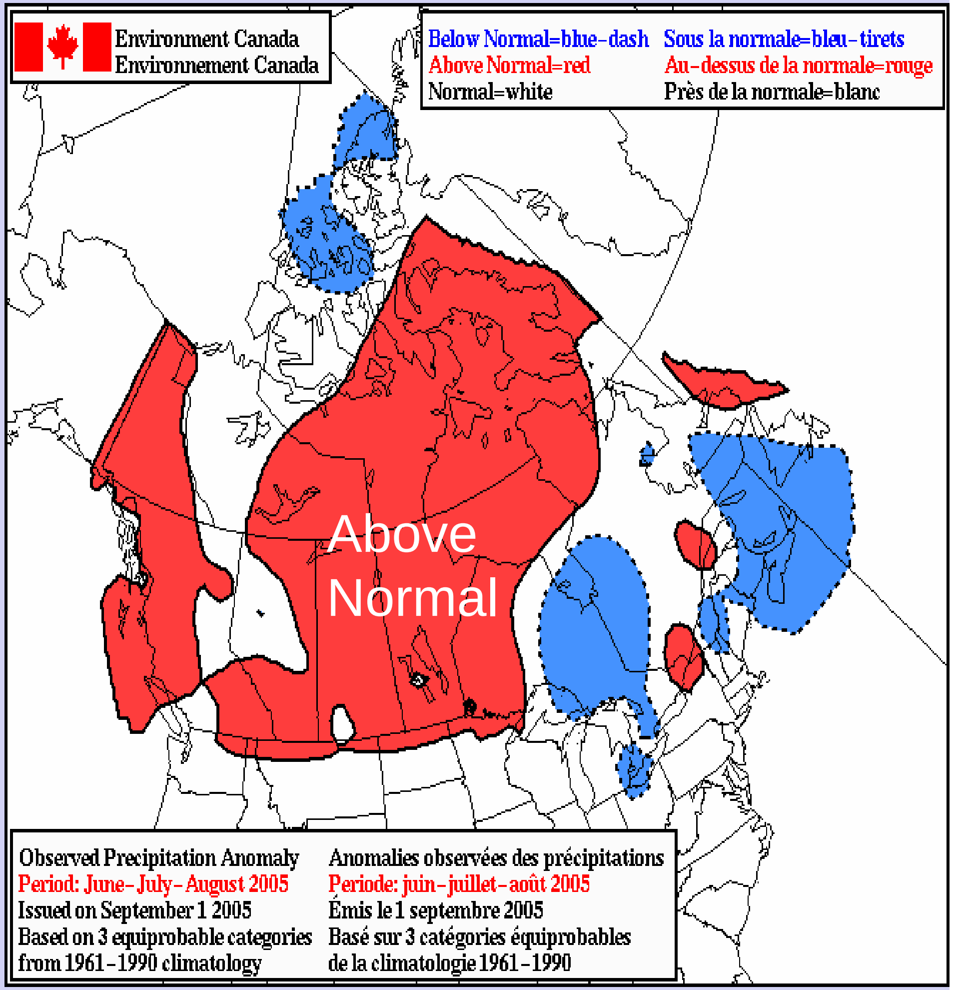
Source: Ronald Stewart

SEASONAL PREDICTIONS: Summer of 2005 - Canada

PREDICTION



OBSERVATION

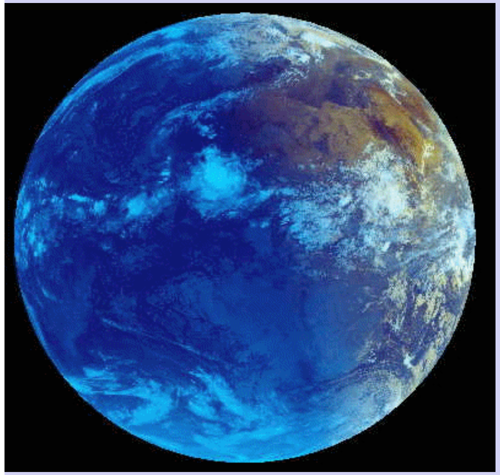


Source: Ronald Stewart


(flooding at the end of the drought)
St. Jean de Baptiste, Manitoba
July 2005
Source: Ronald Stewart

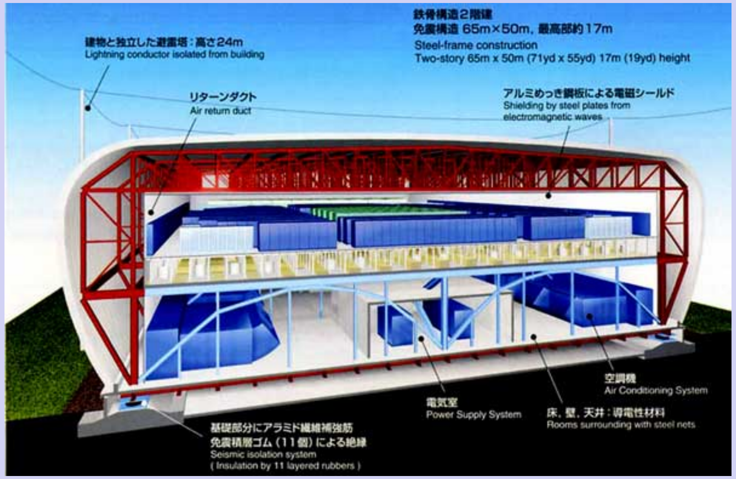
Recent Assessment of Seasonal Climate Forecasts

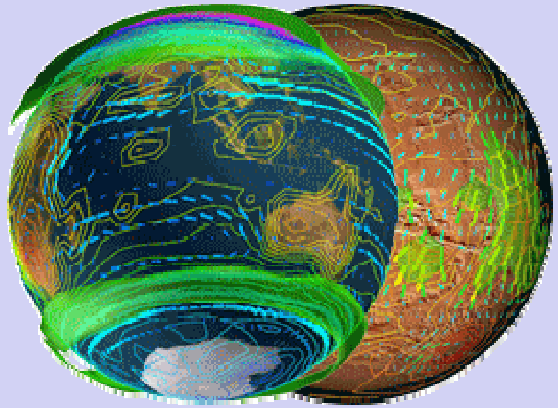
Quoting from Science, Vol. 321, 15th August 2008



- *" of the dozens of forecast techniques proffered by government, academic, private-sector climatologists, all but two are virtually useless, according to a new study"* *Livezey &Timofeyeva - BAMS, June 2008.*
- *"About the only time forecasts had any success predicting precipitation was for winters with an El Nino or a La Nina"*

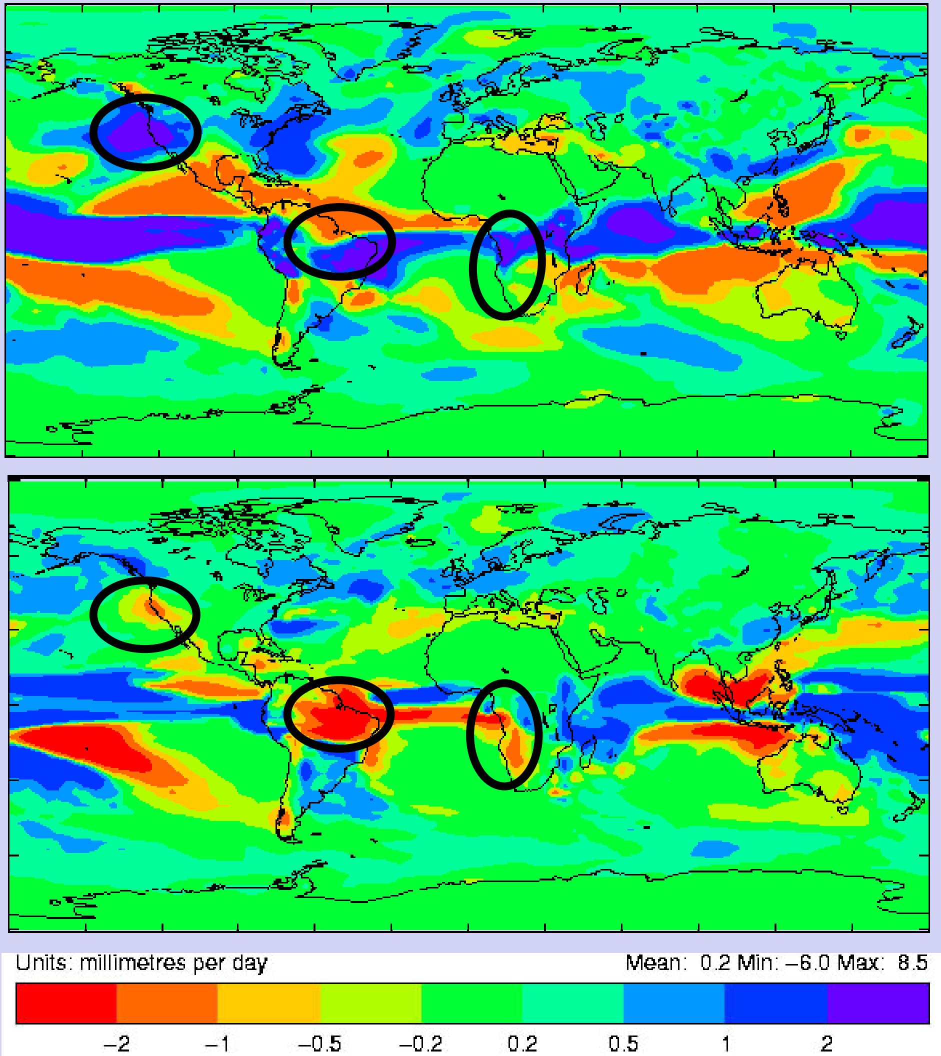
Climate Predictions into the Future!





Some Results from Long Time-Scales

Climate model Predictions about the future? → globally



DJF Precipitation Changes
CM2 - Old model

CM3 - Updated model

Significant differences in regional outcomes!

Source: Hadley Center (Climate Change Projections)

A Dryer Future for Southwest US?

Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America

Richard Seager,[1*] Mingfang Ting,[1] Isaac Held,[2,3] Yochanan Kushnir,[1] Jian Lu,[4] Gabriel Vecchi,[2] Huei-Ping Huang,[1] Nili Harnik,[5] Ants Leetmaa,[2] Ngar-Cheung Lau,[2,3] Cuihua Li,[1] Jennifer Velez,[1] Naomi Naik[1]

How anthropogenic climate change will affect hydroclimate in the arid regions of southwestern North America has implications for the allocation of water resources and the course of regional development. Here we show that there is a broad consensus among climate models that this region will dry in the 21st century and that the transition to a more arid climate should already be under way. If these models are correct, the levels of aridity of the recent multiyear drought or the Dust Bowl and the 1950s droughts will become the new climatology of the American Southwest within a time frame of years to decades.

The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) reported that the average of all the participating models showed a general decrease in rainfall in the subtropics during the 21st century, although there was also considerable disagreement among the models (*1*). Subtropical drying accompanying rising CO_2 was also found in the models participating in the second Coupled Model Intercomparison Project (*2*). We examined future subtropical drying by analyzing the time history of precipitation in 19 climate models participating in the Fourth Assessment Report (AR4) of the IPCC (*3*). The future climate projections followed the A1B emissions scenario (*4*), in which CO_2 emissions increase until about 2050 and decrease modestly thereafter, leading to a CO_2 concentration of 720 parts per million in 2100. We also analyzed the simulations by these models for the 1860–2000 period, in which the models were forced by the known history of trace gases and estimated changes in solar irradiance, volcanic and anthropogenic aerosols, and land use (with some variation among the models). These simulations provided initial conditions for the 21st-century climate projections. For each model,

precipitation minus the evaporation ($P - E$), averaged over this region for the period common to all of the models (1900–2098). The median, 25th, and 75th percentiles of the model $P - E$ distribution and the median of P and E are shown. For cases in which there were multiple simulations with a single model, data from these simulations were averaged together before computing the distribution. $P - E$ equals the moisture convergence by the atmospheric flow and (over land) the amount of water that goes into runoff.

In the multimodel ensemble mean, there is a transition to a sustained drier climate that begins in the late 20th and early 21st centuries. In the ensemble mean, both P and E decrease, but the former decreases by a larger amount. $P - E$ is primarily reduced in winter, when P decreases and E is unchanged or modestly increased, whereas in summer, both P and E decrease. The annual mean reduction in P for this region, calculated from rain gauge data within the Global Historical Climatology Network, was 0.09 mm/day between 1932 and 1939 (the Dust Bowl drought) and 0.13 mm/day between 1948 and 1957 (the 1950s Southwest drought). The ensemble median reduction in P that drives the reduction in $P - E$ reaches 0.1 mm/day in midcentury, and one quarter of the models reach this amount in the early part of the current century.

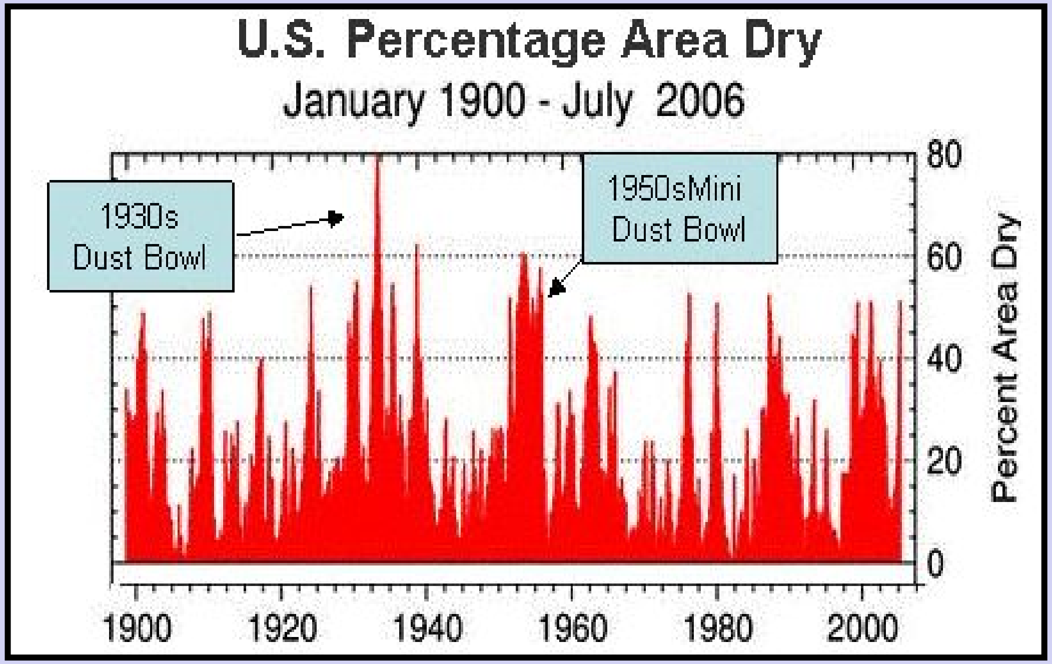
The annual mean $P - E$ difference between 20-year periods in the 21st century and the 1950–2000 climatology for the 19 models are shown in Fig. 2. Almost all models have a drying trend in the American Southwest, and they con-

If these models are correct,

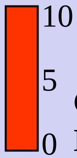
Observed changes: Drought

Drought activity during the 20th and early 21st Century

- **U.S. droughts show pronounced multi-year to multi-decadal variability, but no convincing evidence for long-term trends toward more or fewer events.**



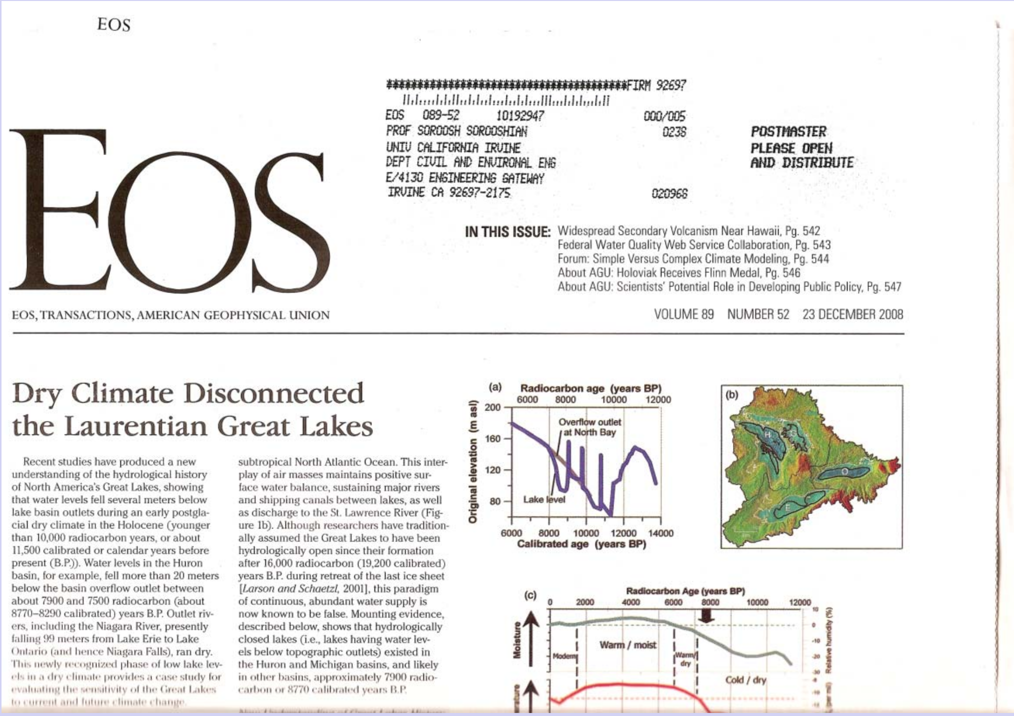
Based on Palmer Drought Index
Moderate to Extreme Drought



Confidence Index

Source: Tom Karl NCDC-NOAA 2007

Recent Articles About the efficacy of climate models



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Dry Climate Disconnected the Laurentian Great Lakes

Recent studies have produced a new understanding of the hydrological history of North America's Great Lakes, showing that water levels fell several meters below lake basin outlets during an early postglacial dry climate in the Holocene (younger than 10,000 radiocarbon years, or about 11,500 calibrated or calendar years before present (B.P.)). Water levels in the Huron basin, for example, fell more than 20 meters below the basin overflow outlet between about 7900 and 7500 radiocarbon (about 8770–8290 calibrated) years B.P. Outlet rivers, including the Niagara River, presently falling 99 meters from Lake Erie to Lake Ontario (and hence Niagara Falls), ran dry. This newly recognized phase of low lake levels in a dry climate provides a case study for evaluating the sensitivity of the Great Lakes to current and future climate change.

subtropical North Atlantic Ocean. This interplay of air masses maintains positive surface water balance, sustaining major rivers and shipping canals between lakes, as well as discharge to the St. Lawrence River (Figure 1b). Although researchers have traditionally assumed the Great Lakes to have been hydrologically open since their formation after 16,000 radiocarbon (19,200 calibrated) years B.P. during retreat of the last ice sheet [*Larson and Schaetzl*, 2001], this paradigm of continuous, abundant water supply is now known to be false. Mounting evidence, described below, shows that hydrologically closed lakes (i.e., lakes having water levels below topographic outlets) existed in the Huron and Michigan basins, and likely in other basins, approximately 7900 radiocarbon or 8770 calibrated years B.P.

Recent Articles About the efficacy of climate models

FORUM

Simple Versus Complex Climate Modeling

This Forum is based on my own personal experience with the climate and paleoclimate community during the past several years. This experience includes having read numerous articles and having witnessed numerous interdisciplinary discussions at various conferences. A theme I have frequently encountered is the sense that the resolution of modern state-of-the-art global climate models is so high that—when compared with simple models—their results represent the "absolute truth." It seems that through genuine efforts to improve aspects of numerical modeling, the point that they are still models and not observational data is occasionally forgotten.

The main message of this Forum is to point out that regardless of how high the resolution of numerical climate models is, and regard-

Still worse, some global numerical climate modelers hold the view that their models' results are always correct unless the process in question is a subgrid process. Because subgrid processes, such as mixing, govern the entire flow field and get integrated over many grid points, there are counterexamples where the model dynamics are totally wrong even when it is "merely" the subgrid processes that are wrong [see, e.g., *Nof et al.*, 2007].

For instance, regarding the Atlantic Meridional Overturning Cell, it is very probable that the only aspect that the global numerical models resolve adequately is the large-scale pressure gradient. Convection, overflows, eddies, and topography are all parts of subgrid atmospheric processes that

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ELSEVIER

Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951–2000

J.D. Milliman [a,*], K.L. Farnsworth [b,1], P.D. Jones [c], K.H. Xu [a], L.C. Smith [d]

[a] School of Marine Science, College of William and Mary, Gloucester Point, VA 23062, USA
[b] U.S. Geological Survey, Pacific Science Center, Coastal and Marine Geology Program, 400 Natural Bridges Drive, Santa Cruz, CA 95060, USA
[c] Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, UK
[d] Department of Geography, 1255 Bunche Hall, University of California-Los Angeles, CA 90095, USA

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ABSTRACT

During the last half of the 20th century, cumulative annual discharge from 137 representative rivers (watershed areas ranging from 0.3 to 6300×10^3 km^2) to the global ocean remained constant, although annual discharge from about one-third of these rivers changed by more than 30%. Discharge trends for many rivers reflected mostly changes in precipitation, primarily in response to short- and longer-term atmospheric–oceanic signals; with the notable exception of the Parana, Mississippi, Niger and Cunene rivers, few of these "normal" rivers experienced significant changes in either discharge or precipitation. Cumulative discharge from many mid-latitude rivers, in contrast, decreased by 60%, reflecting in large part impacts due to damming, irrigation and interbasin water transfers. A number of high-latitude and high-altitude rivers experienced increased discharge despite generally declining precipitation. Poorly constrained meteorological and hydrological data do not seem to explain fully these "excess" rivers; changed seasonality in discharge, decreased storage and/or decreased evapotranspiration also may play important roles.

Recent Articles About the efficacy of climate models

Hydrological Sciences–Journal–des Sciences Hydrologiques, 53(4) August 2008 671

RAPID COMMUNICATION

On the credibility of climate predictions

D. KOUTSOYIANNIS, A. EFSTRATIADIS, N. MAMASSIS & A. CHRISTOFIDES

Department of Water Resources, Faculty of Civil Engineering, National Technical University of Athens, Heroon Polytechneiou 5, GR-157 80 Zographou, Greece

dk@itia.ntua.gr

Abstract Geographically distributed predictions of future climate, obtained through climate models, are widely used in hydrology and many other disciplines, typically without assessing their reliability. Here we compare the output of various models to temperature and precipitation observations from eight stations with long (over 100 years) records from around the globe. The results show that models perform poorly, even at a climatic (30-year) scale. Thus local model projections cannot be credible, whereas a common argument that models can perform better at larger spatial scales is unsupported.

Key words climate models; general circulation models; falsifiability; climate change; Hurst-Kolmogorov climate

NEWS OF THE WEEK

CLIMATE PREDICTION

Seasonal-Climate Forecasts Improving Ever So Slowly

Farmers, ski-resort operators, and heating-oil suppliers would very much like to know what the coming winter will be like. If a strong El Niño were brewing in the tropical Pacific, at least some of them would be in luck. The official United States winter forecast could warn them, with considerable reliability, that the Southeast and the Gulf Coast will be cooler and wetter than normal. But without an El Niño or its counterpart, La Niña, next winter's weather is pretty much anybody's guess.

Of the dozens of forecasting techniques proffered by government, academic, and private-sector climatologists, all but two are virtually worthless, according to a new study. "There are seasons, places, and situations in which skill is very, very good," says climatologist and study co-author Robert Livezey, recently retired from the National Weather Service (NWS). But even many people in the field "don't appreciate how little there is to work with. There is really no evidence here that there are any other silver bullets" waiting to be found.

Since 1946, NWS forecasters have been trying to forecast the average temperature and precipitation across the lower 48 states a month ahead, and more recently season by season up to a year ahead. At NWS's Climate Prediction Center (CPC) in Camp Springs, Maryland, where Livezey oversaw seasonal forecasting in the late 1990s, the trick has generally been to identify some element of recent or current climate—say, the presence of El Niño—that can influence future climate. If they couldn't find one, researchers could fashion a forecast "tool"—such as a collection of past time periods when the climate system resembled the current situation—that when tested on past seasons gave some inkling of future seasons. They would then subjectively choose which techniques to combine and how to combine them in order to predict whether temperature and precipitation would be above, near, or below normal in some 3-month period in a particular region.

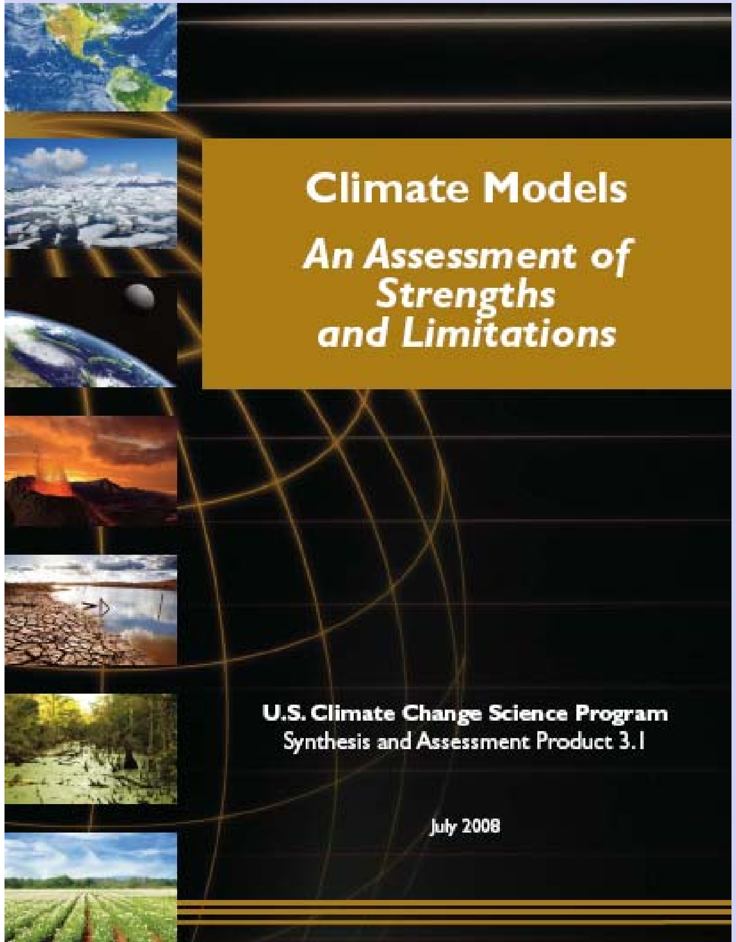
The CPC approach has shown very modest though increasing skill at CPC, Livezey and climatologist Marina Timofeyeva of NWS in Silver Spring, Maryland, report in the June issue of the *Bulletin of the American Meteorological Society*. They worked up a scorecard for CPC forecasts made from 1994 to 2004, comparing the success rates for different seasons, regions, and periods when a strong El Niño or La Niña was present or absent.

About the only time forecasters had any success predicting precipitation was for winters with an El Niño or a La Niña, Livezey and Timofeyeva found. Using a scale in which mere chance is 0% and perfection is 100%, in those winters they estimate "unprecedented" skill—50% to more than 85%—along the southern tier states and up the West Coast about half a year into the future. Even so, the overall skill score for precipitation was just 3%.

Temperature forecasts fared better, with an overall skill score of 13%, up from a score of 8% for the previous decade. El Niño and La Niña helped out again during winter, raising skill to more than 85% across much of the eastern United States out to more than 8 months. But CPC also had substantial success predicting temperature out to a year in the American

Recent Assessment of Climate Models

How Accurate Are Global Climate Models?



- "Regional trends in extreme events are not always captured by current models, but it is difficult to assess the significance of these discrepancies and to distinguish between model deficiencies and natural variability."

What is the Message?

- ***Presently, the accuracy of regional-scale climate model predictions fall short of meeting the requirements of water resources planning.***

- ***Hardly used for operational Purposes and unwise to push their use while highly uncertain.***

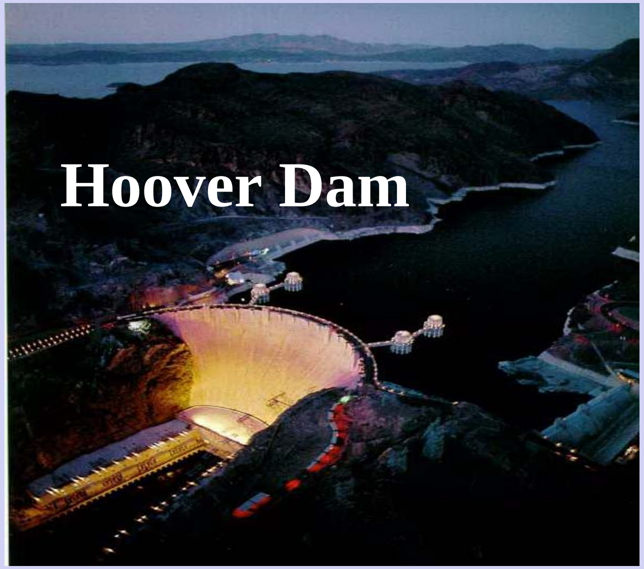
Therefore, Factoring in Resiliency in water resources systems design and planning is still the safest approach!

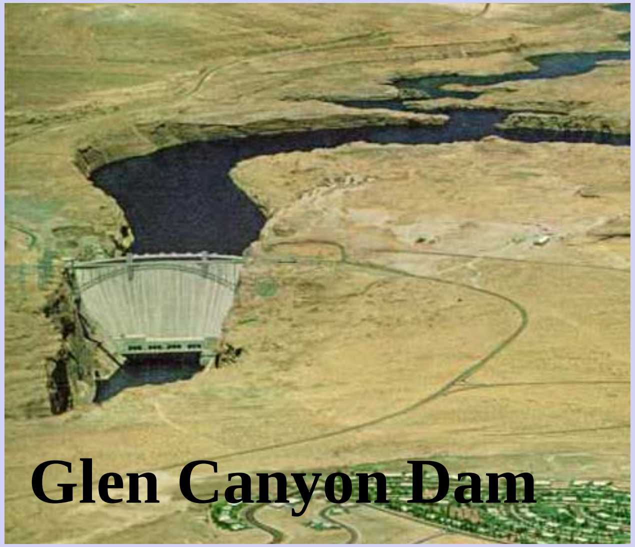
Back to Operational and Design Practices in Water Resources Planning

Factoring in Climate

Engineering Approach:
Build and operate infrastructures
to
Control, Store & Deliver water
for Multi-Purpose Uses

A Century of Water Resources Development: ***Engineering success!***



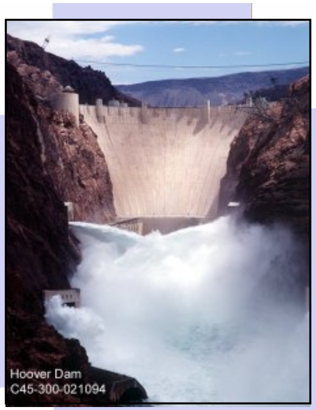


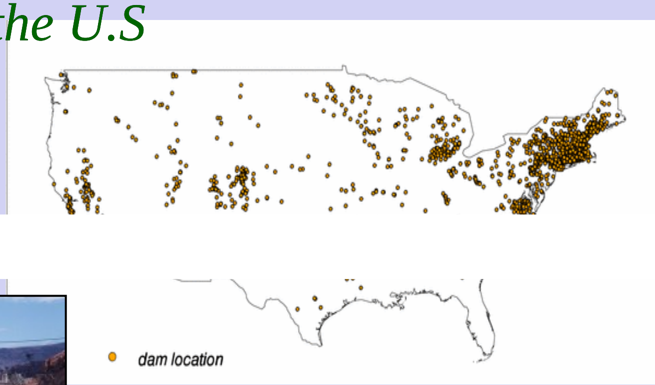
Central Arizona Project Aqueduct

Impact of Dam & Reservoir Construction

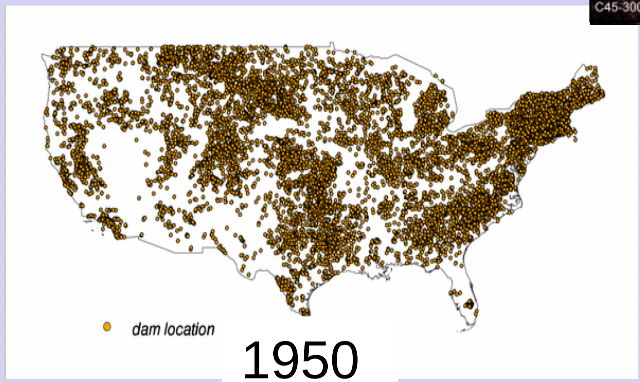
More than 70,000 Dams in the U.S

1800

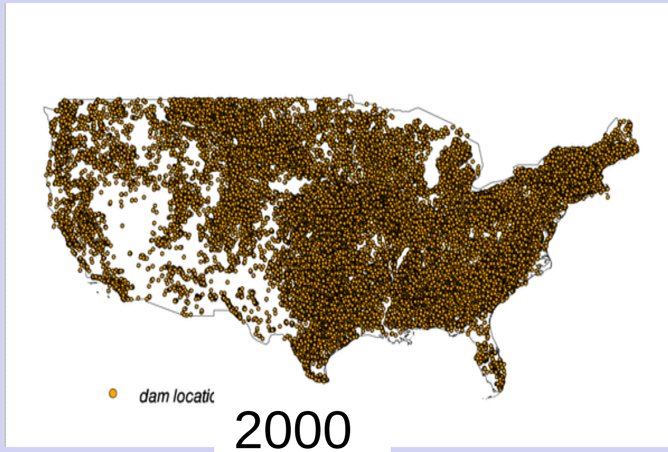




1900



1950



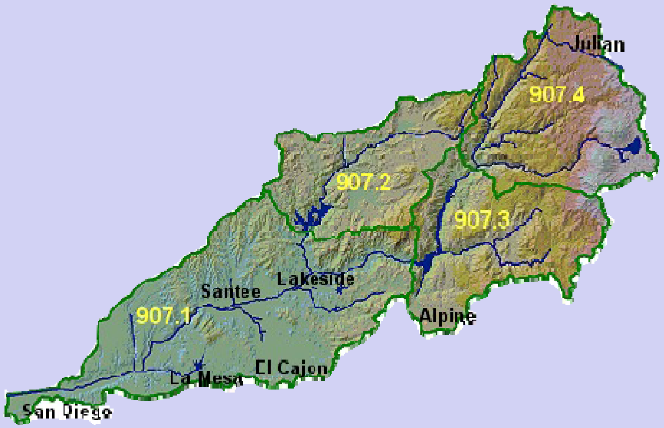
2000

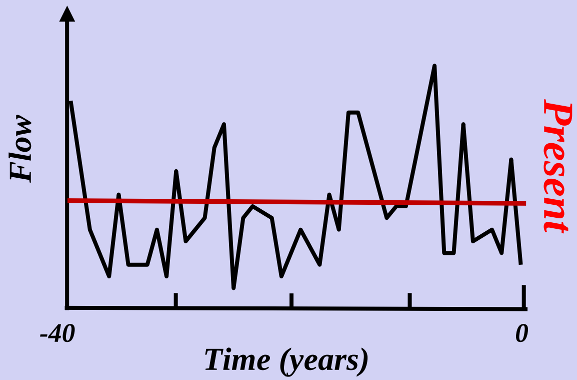
Provided by: C. J. Vörösmarty

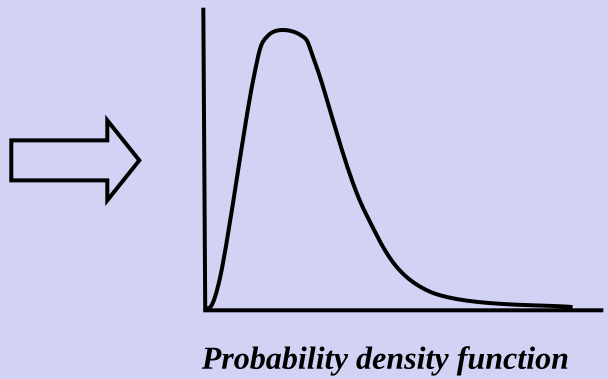
Addressing " Climate Extremes" in Water Resources Planning:

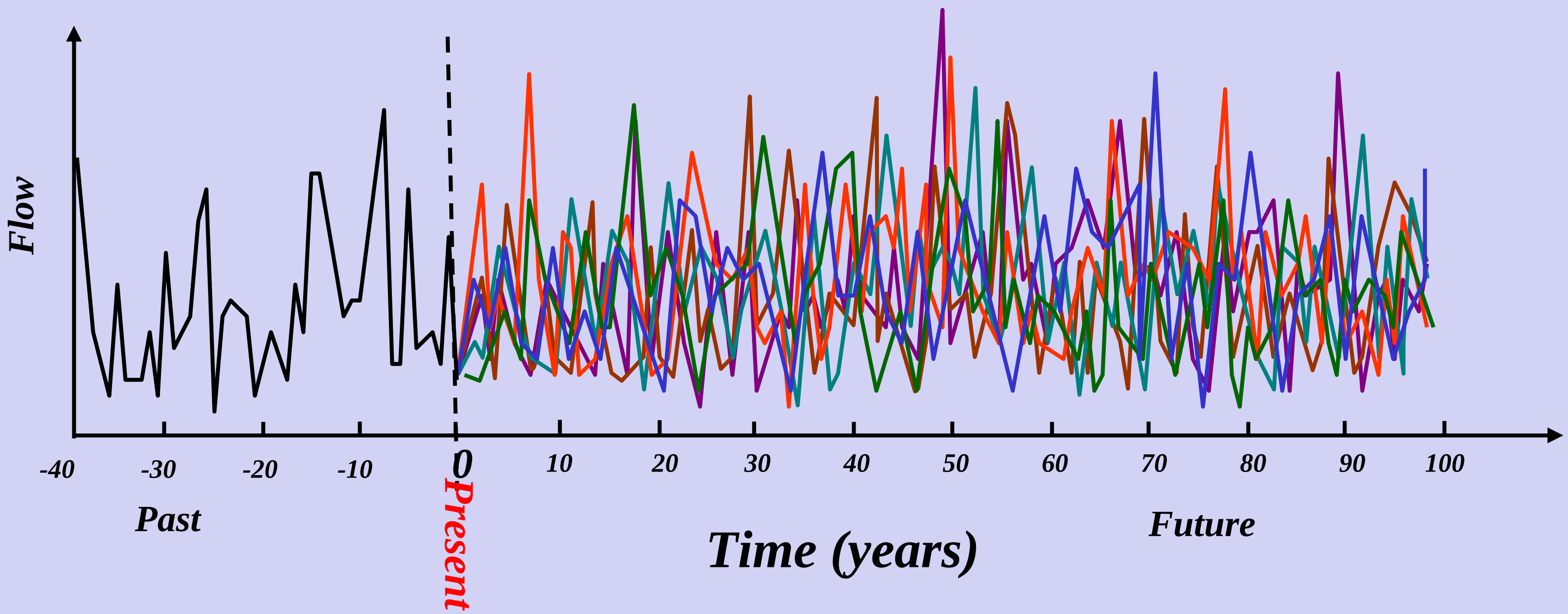
Stochastic Hydrology

Statistical Hydrology: "synthetic" streamflow Generation





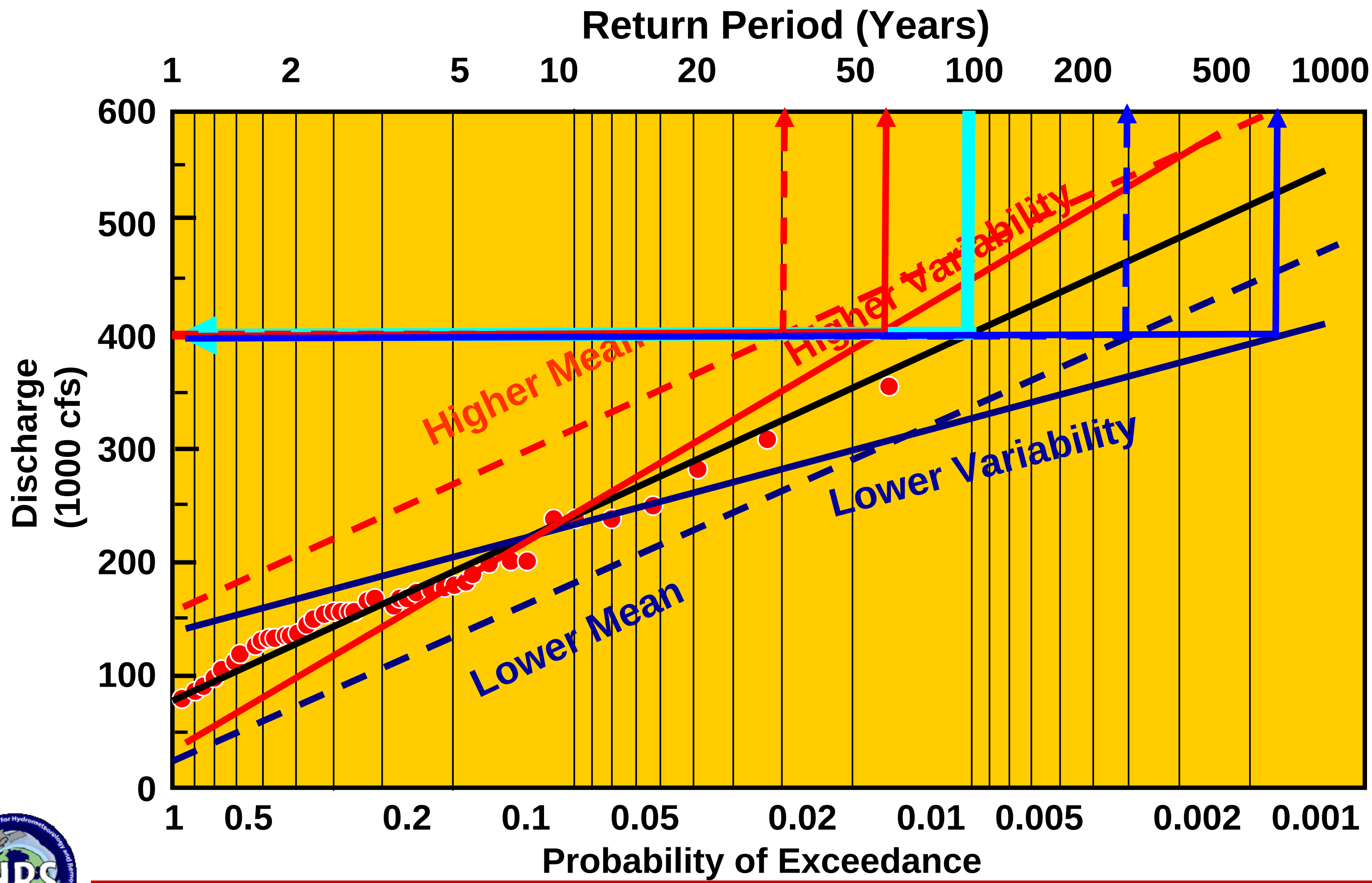




Potential Hydrologic Scenarios

1. Precipitation and Runoff Trends
   (e.g. increase/decrease)

2. Hydrologic Variability
   (e.g. magnitude/severity/duration)



Impact of Nonstationarity on Water Resources

POLICYFORUM

CLIMATE CHANGE

Stationarity Is Dead: Whither Water Management?

Climate change undermines a basic assumption that historically has facilitated management of water supplies, demands, and risks.

P. C. D. Milly,[1]* Julio Betancourt,[2] Malin Falkenmark,[3] Robert M. Hirsch,[4] Zbigniew W. Kundzewicz,[5] Dennis P. Lettenmaier,[6] Ronald J. Stouffer[7]

Systems for management of water throughout the developed world have been designed and operated under the assumption of stationarity. Stationarity—the idea that natural systems fluctuate within an unchanging envelope of variability—is a foundational concept that permeates training and practice in water-resource engineering. It implies that any variable (e.g., annual streamflow or annual flood peak) has a time-invariant (or 1-year–periodic) probability density function (pdf), whose properties can be estimated from the instrument record. Under stationarity, pdf estimation errors are acknowledged, but have been assumed to be reducible by additional observations, more efficient estimators, or regional or paleohydrologic data. The pdfs, in turn, are used to evaluate and manage risks to water supplies, waterworks, and floodplains; annual global investment in water infrastructure exceeds U.S.$500 billion (*1*).

The stationarity assumption has long been compromised by human disturbances in river basins. Flood risk, water supply, and water quality are affected by water infrastructure, channel modifications, drainage works, and land-cover and land-use change. Two other (sometimes indistinguishable) challenges to stationarity have been externally forced, natural climate changes and low-frequency, internal variability (e.g., the Atlantic multidecadal oscillation) enhanced by the slow dynamics of the oceans and ice sheets (*2*, *3*). Planners have tools to adjust their analyses for known human disturbances within river basins, and justifiably or not, they generally have considered natural change and variability to be sufficiently small to allow stationarity-based design.

[1]U.S. Geological Survey (USGS), c/o National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory, Princeton, NJ 08540, USA. [2]USGS, Tucson, AZ 85745, USA. [3]Stockholm International Water Institute, SE 11151 Stockholm, Sweden. [4]USGS, Reston, VA 20192, USA. [5]Research Centre for Agriculture and Forest Environment, Polish Academy of Sciences, Poznań, Poland, and Potsdam Institute for Climate Impact Research, Potsdam, Germany. [6]University of Washington, Seattle, WA 98195, USA. [7]NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ 08540, USA.

*Author for correspondence. E-mail: cmilly@usgs.gov.

An uncertain future challenges water planners.

In view of the magnitude and ubiquity of the hydroclimatic change apparently now under way, however, we assert that stationarity is dead and should no longer serve as a central, default assumption in water-resource risk assessment and planning. Finding a suitable successor is crucial for human adaptation to changing climate.

How did stationarity die? Stationarity is dead because substantial anthropogenic change of Earth's climate is altering the means and extremes of precipitation, evapotranspiration, and rates of discharge of rivers (*4*, *5*) (see figure, above). Warming augments atmospheric humidity and water transport. This increases precipitation, and possibly flood risk, where prevailing atmospheric water-vapor fluxes converge (*6*). Rising sea level induces gradually heightened risk of contamination of coastal freshwater supplies. Glacial meltwater temporarily enhances water availability, but glacier and snow-pack losses diminish natural seasonal and interannual storage (*7*).

Anthropogenic climate warming appears to be driving a poleward expansion of the subtropical dry zone (*8*), thereby reducing runoff in some regions. Together, circulatory and thermodynamic responses largely explain the picture of regional gainers and losers of sustainable freshwater availability that has emerged from climate models (see figure, p. 574).

Why now? That anthropogenic climate change affects the water cycle (*9*) and water supply (*10*) is not a new finding. Nevertheless, sensible objections to discarding stationarity have been raised. For a time, hydroclimate had not demonstrably exited the envelope of natural variability and/or the effective range of optimally operated infrastructure (*11*, *12*). Accounting for the substantial uncertainties of climatic parameters estimated from short records (*13*) effectively hedged against small climate changes. Additionally, climate projections were not considered credible (*12*, *14*).

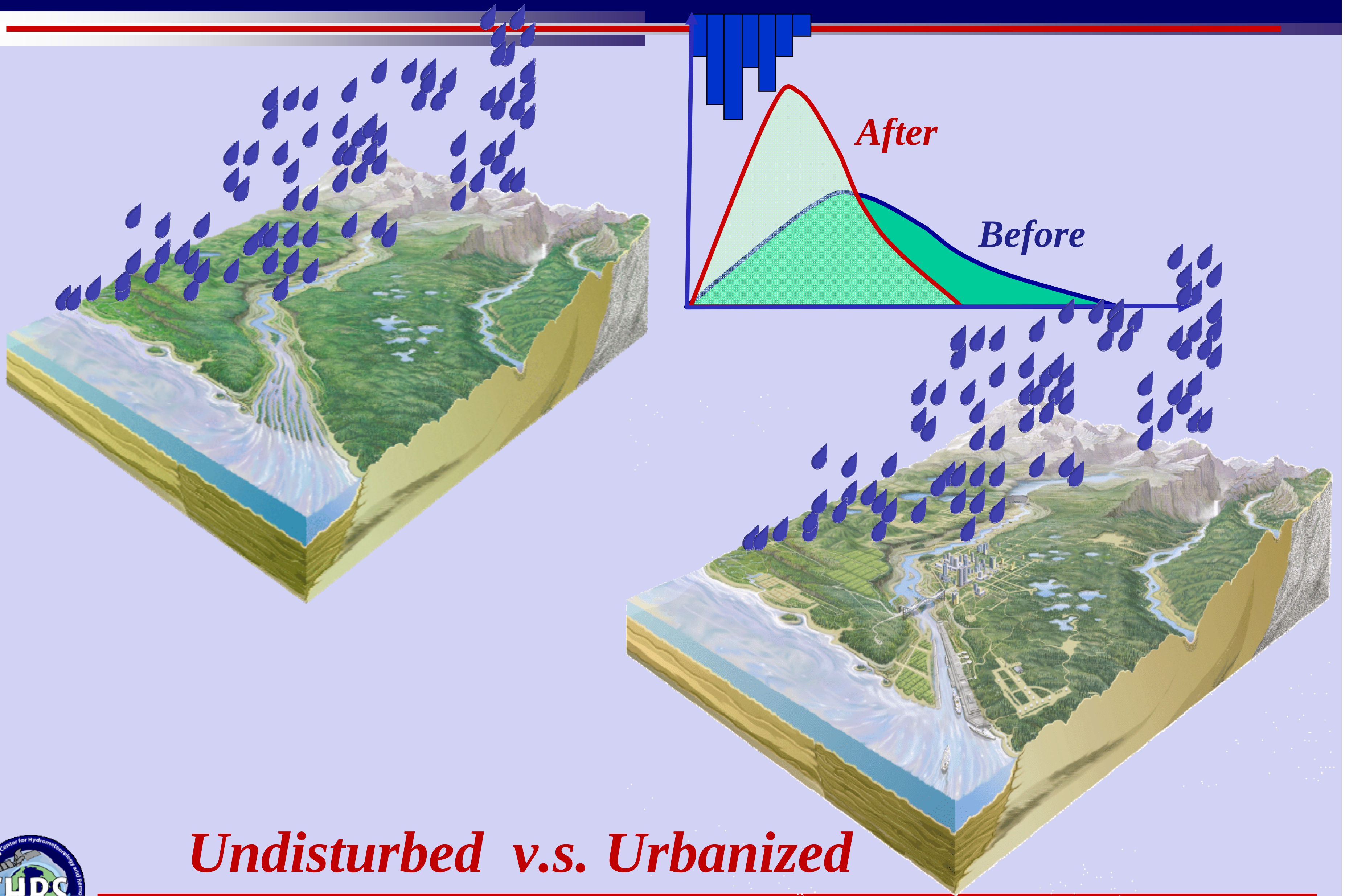
Recent developments have led us to the opinion that the time has come to move beyond the wait-and-see approach. Projections of runoff changes are bolstered by the recently demonstrated retrodictive skill of climate models. The global pattern of observed annual streamflow trends is unlikely to have arisen from unforced variability and is consistent with modeled response to climate forcing (*15*). Paleohydrologic studies suggest that small changes in mean climate might produce large changes in extremes (*16*), although attempts to detect a recent change in global flood frequency have been equivocal (*17*, *18*). Projected changes in runoff during the multidecade lifetime of major water infrastructure projects begun now are large enough to push hydroclimate beyond the range of historical behaviors (*19*). Some regions have little infrastructure to buffer the impacts of change.

Stationarity cannot be revived. Even with aggressive mitigation, continued warming is very likely, given the residence time of atmospheric CO_2 and the thermal inertia of the Earth system (*4*, *20*).

A successor. We need to find ways to identify nonstationary probabilistic models of relevant environmental variables and to use those models to optimize water systems. The challenge is daunting. Patterns of change are complex; uncertainties are large; and the knowledge base changes rapidly.

Under the rational planning framework advanced by the Harvard Water Program (*21*, *22*), the assumption of stationarity was

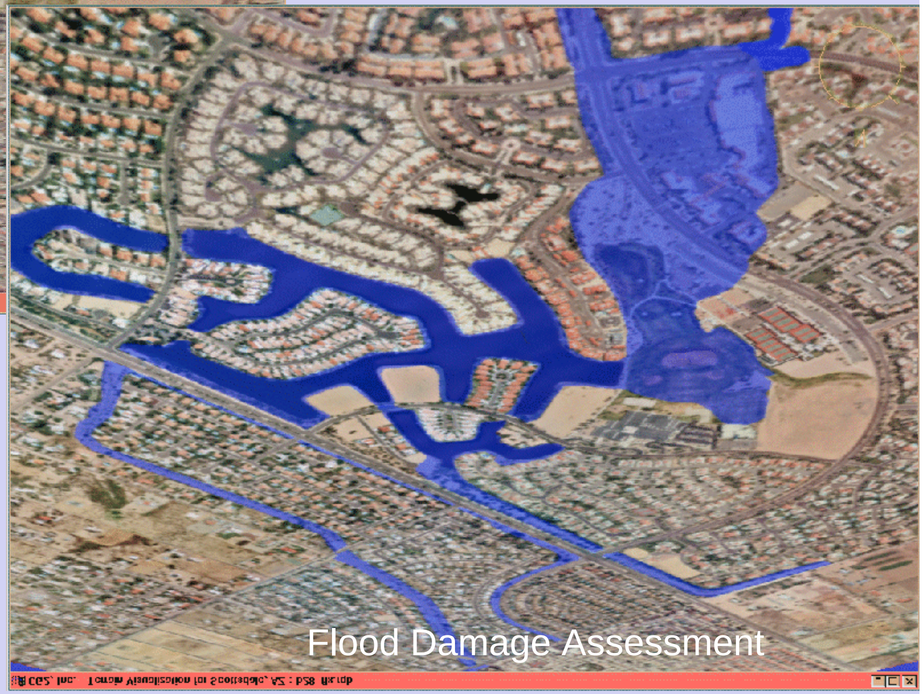
Increase in Runoff not always due to Increase in Precip.



Undisturbed v.s. Urbanized

What is the Big Deal About Characterizing the Long-Term Uncertainties in Hydro-Climate Variables?

Flood Plain Mapping and Zoning



Highway Culvert Design

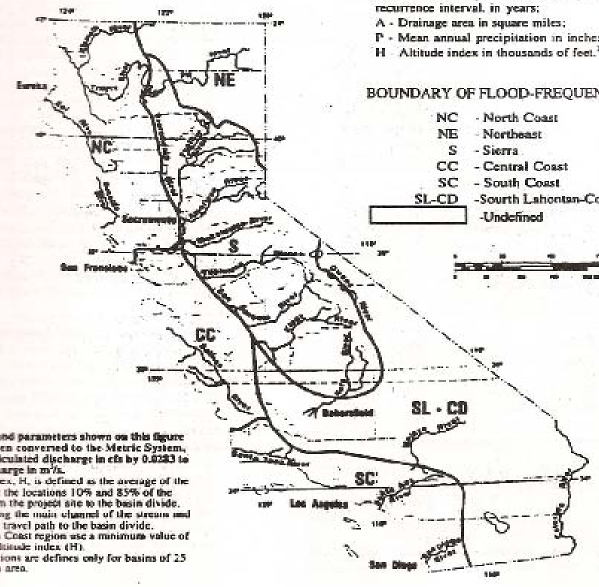



A Page From the CalTran Highway Design Manual

Figure 819.2C
Regional Flood-Frequency Equations

NORTH COAST REGION[1]		NORTHEAST REGION[1]		SOUTH LAHONTAN-COLORADO DESERT REGION[4]	
Q_2	$=3.52\ A^{0.90}\ P^{0.89}\ H^{-0.47}$	Q_2	$=22\ A^{0.40}$	Q_2	$=7.3\ A^{0.30}$
Q_5	$=5.04\ A^{0.89}\ P^{0.91}\ H^{-0.35}$	Q_5	$=46\ A^{0.45}$	Q_5	$=53.0\ A^{0.44}$
Q_{10}	$=6.21\ A^{0.88}\ P^{0.93}\ H^{-0.27}$	Q_{10}	$=61\ A^{0.49}$	Q_{10}	$=150\ A^{0.53}$
Q_{25}	$=7.64\ A^{0.87}\ P^{0.94}\ H^{-0.17}$	Q_{25}	$=84\ A^{0.54}$	Q_{25}	$=410.0\ A^{0.63}$
Q_{50}	$=8.57\ A^{0.87}\ P^{0.96}\ H^{-0.08}$	Q_{50}	$=103\ A^{0.57}$	Q_{50}	$=700.0\ A^{0.68}$
Q_{100}	$=9.23\ A^{0.87}\ P^{0.97}$	Q_{100}	$=125\ A^{0.59}$	Q_{100}	$=1080.0\ A^{0.71}$
SIERRA REGION		**CENTRAL COAST REGION**		**SOUTH COAST REGION**	
Q_2	$=0.24\ A^{0.88}\ P^{1.58}\ H^{-0.80}$	Q_2	$=0.0061\ A^{0.92}\ P^{2.54}\ H^{-1.10}$	Q_2	$=0.14\ A^{0.72}\ P^{1.62}$
Q_5	$=1.20\ A^{0.82}\ P^{1.37}\ H^{-0.64}$	Q_5	$=0.118\ A^{0.91}\ P^{1.95}\ H^{-0.79}$	Q_5	$=0.40\ A^{0.77}\ P^{1.69}$
Q_{10}	$=2.63\ A^{0.80}\ P^{1.25}\ H^{-0.58}$	Q_{10}	$=0.583\ A^{0.90}\ P^{1.61}\ H^{-0.64}$	Q_{10}	$=0.63\ A^{0.79}\ P^{1.75}$
Q_{25}	$=6.55\ A^{0.79}\ P^{1.12}\ H^{-0.52}$	Q_{25}	$=2.91\ A^{0.89}\ P^{1.26}\ H^{-0.50}$	Q_{25}	$=1.10\ A^{0.81}\ P^{1.81}$
Q_{50}	$=10.4\ A^{0.78}\ P^{1.06}\ H^{-0.48}$	Q_{50}	$=8.20\ A^{0.89}\ P^{1.03}\ H^{-0.41}$	Q_{50}	$=1.50\ A^{0.82}\ P^{1.85}$
Q_{100}	$=15.7\ A^{0.77}\ P^{1.02}\ H^{-0.43}$	Q_{100}	$=19.7\ A^{0.88}\ P^{0.84}\ H^{-0.33}$	Q_{100}	$=1.95\ A^{0.83}\ P^{1.87}$

Q - Peak discharge in CFS, subscript indicates recurrence interval, in years;
A - Drainage area in square miles;
P - Mean annual precipitation in inches;
H - Altitude index in thousands of feet.[2]

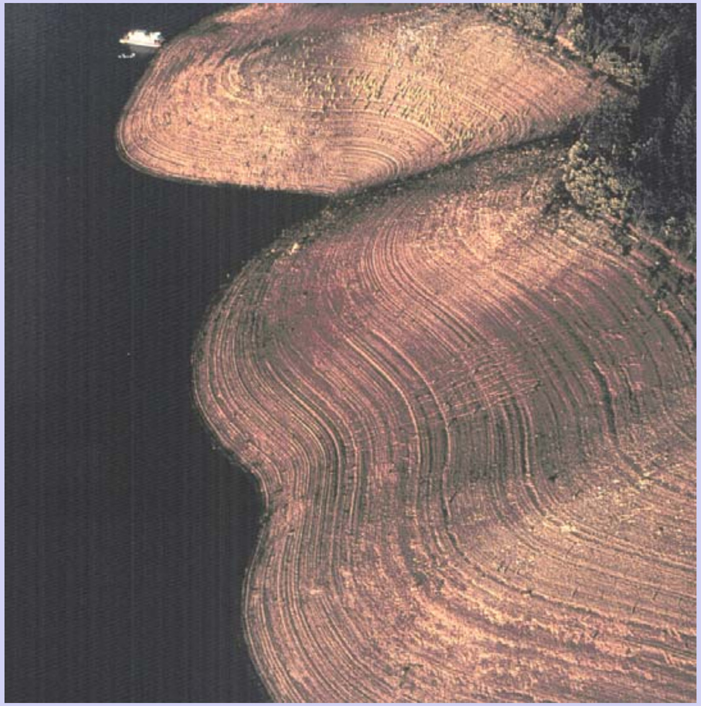


BOUNDARY OF FLOOD-FREQUENCY REGION

- NC - North Coast
- NE - Northeast
- S - Sierra
- CC - Central Coast
- SC - South Coast
- SL-CD - South Lahontan-Colorado
- Undefined

NOTES:
1. Equations and parameters shown on this figure have not been converted to the Metric System. Multiply calculated discharge in cfs by 0.0283 to obtain discharge in m³/s.
2. Altitude index, H, is defined as the average of the elevations at the locations 10% and 85% of the distance from the project site to the basin divide, measured along the main channel of the stream and the overland travel path to the basin divide.
3. In the North Coast region use a minimum value of 1.0 for the altitude index (H).
4. These equations are defines only for basins of 25 mi² of less in area.

How About Drought Frequency Analysis Methods?



Not to my Knowledge. No comprehensive program until recently.

Some of the Issues facing the Arid & Semi-Arid Regions:

Implications of Hydrologic Variability (Extremes) and Ecological changes

2 Precipitation Scenarios with different Temporal properties

Monthly Total

A

100 mm

Frequency 6.7%
Intensity 50.0 mm

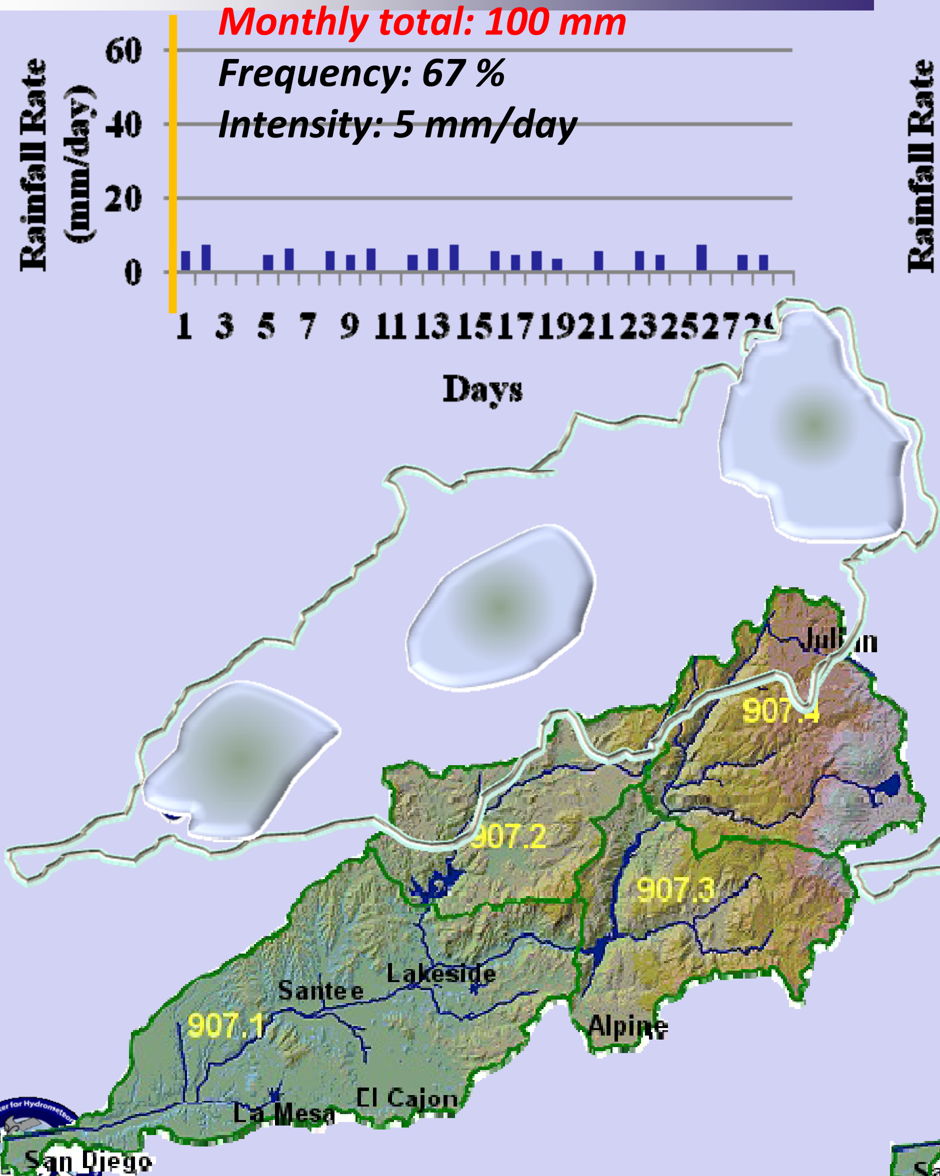
B

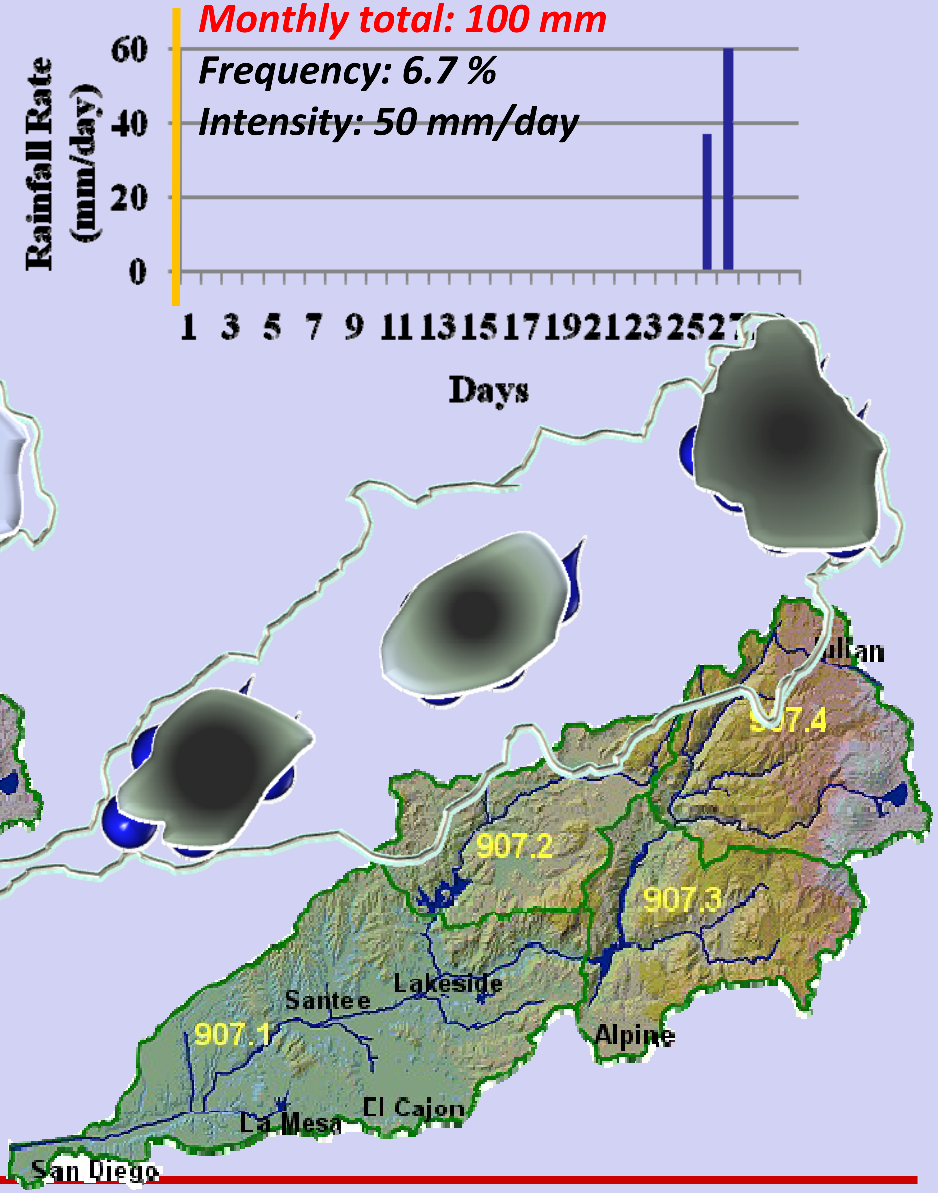
100 mm

Frequency 67%
Intensity 5.0 mm

Idea from: K. Trenberth, NCAR

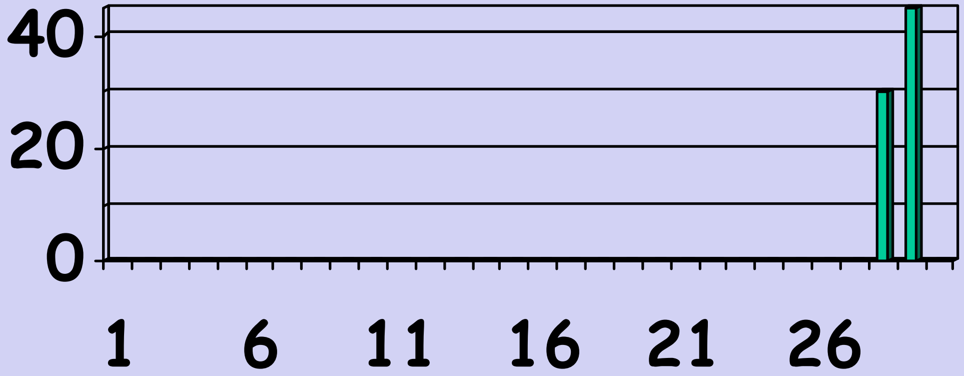
Importance of Temporal Scale : Daily Precip. at 2 stations





Importance of Temporal Scale : Daily Precip. at 2 stations

A



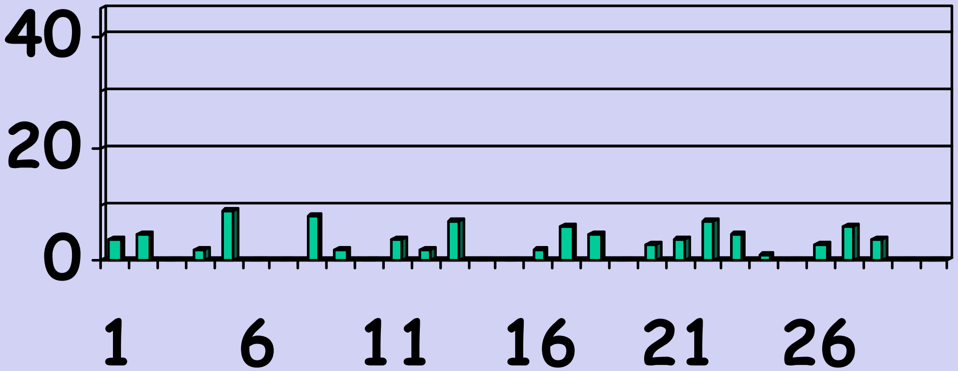
Monthly

Amount 100 mm

Frequency 6.7%
Intensity 50.0 mm

local Floods
Stream bed Recharge

B



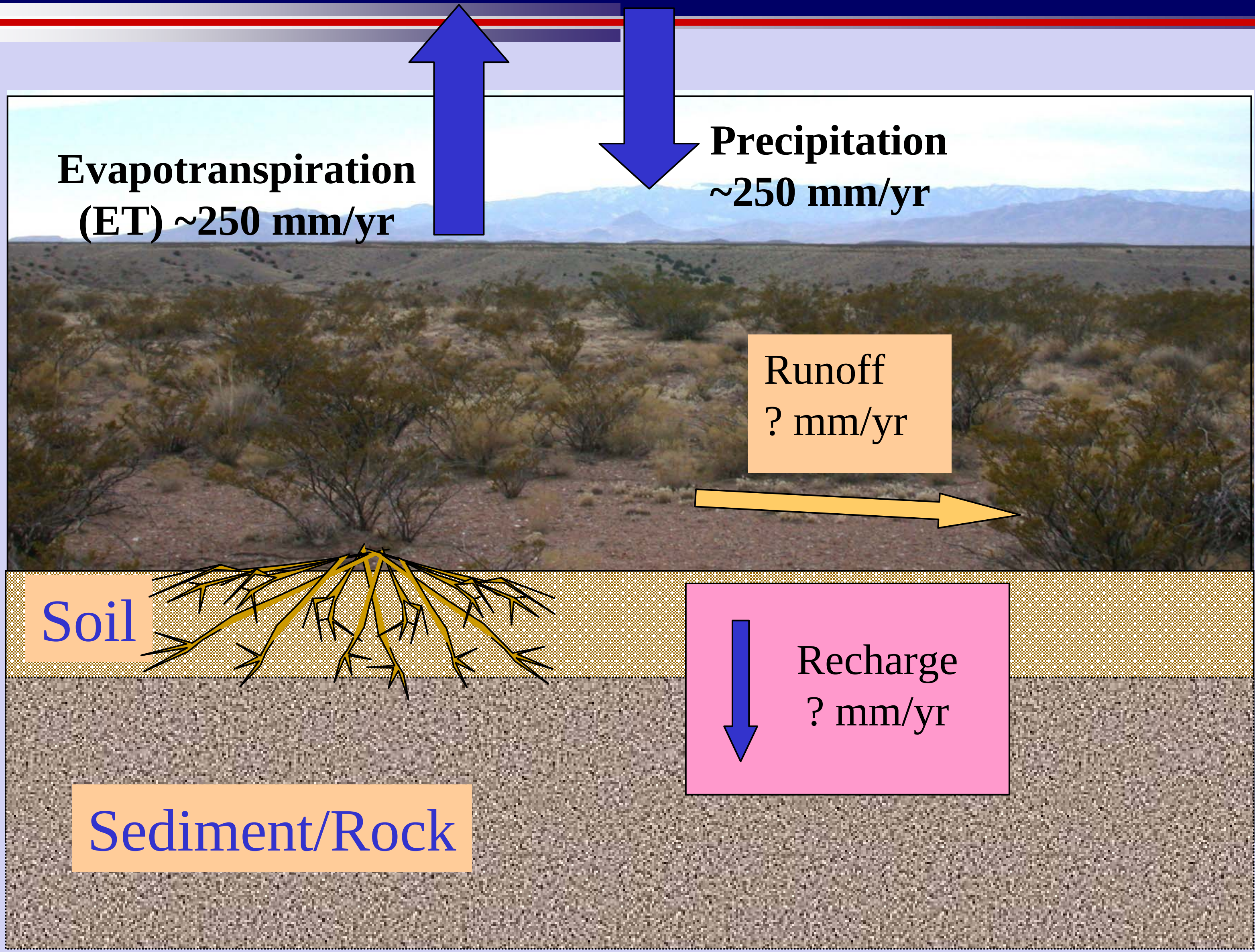
Amount 100 mm

Frequency 67%
Intensity 5.0 mm

soil moisture replenished
virtually no runoff

Idea from: K. Trenberth, NCAR

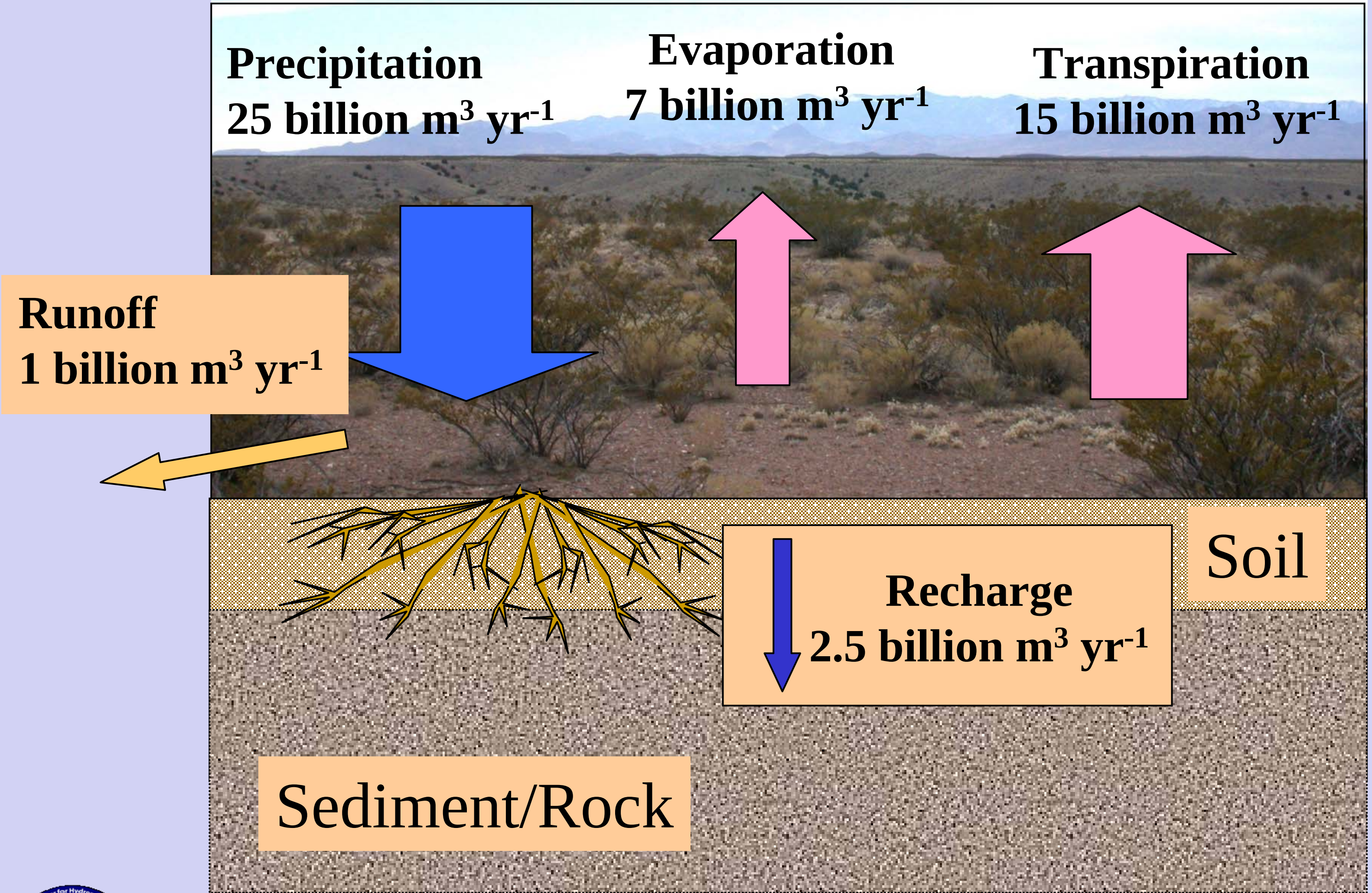
Water balance in Semi Arid Regions



Source: Eric Small, NMT now at CU Boulder

Where are the critical gaps in understanding?

Water balance of the Rio Grande basin in New Mexico



Data Source: West & Broadherst (1975)

Visualization: Eric Small, NMT now at CU Boulder

Vegetation change in the Southwestern US:

Semi-arid grasslands in
New Mexico and Arizona

are being replaced
by deep rooted shrubs.

Recharge through semiarid soils

- Groundwater recharge through semiarid soils is measured in ***mm per year***.

Table 1. Examples of diffuse recharge analyses from soil-water flux.

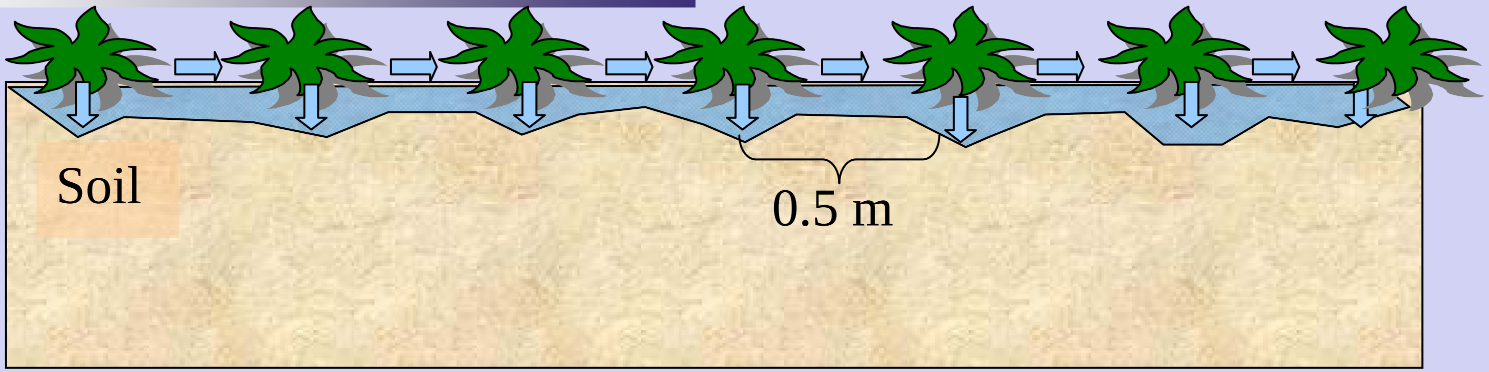
Site	Mean annual precipitation	Potential evapo-transpiration	Soil	Recharge	Reference
	mm/yr			mm/yr	
1. Socorro, NM	190	1780	Sandy alluvium	4.0–9.0	Stephens et al. (1991)
2. Socorro, NM	190	1780	Sandy alluvium	7.0–37	Stephens and Knowlton (1986)
3. Socorro, NM	190	1780	Sandy loam	2–2.6	Phillips et al. (1988)
4. Sunland Park, NM	200	1780	Medium sandy alluvium	0.05–1.9	Stephens & Associates (1992, unpublished data)
5. Las Cruces, NM	230	1780	Sandy loam	1.5–9.5	Phillips et al. (1988)
6. Hudspeth County, TX	280	1960	Gravel/clay loam	0.01–1	Scanlon et al. (1991)
7. Curry Co., NM	444	1156	Clayey and very fine sand (playa)	2.8	Stone (1986)
8. Curry Co., NM	444	1156	Fine to very fine sand (pasture)	0.2	Stone (1986)
9. Curry Co., NM	444	1156	Fine sand and caliche (dunes)	1.2	Stone (1986)
10. Hanford, WA	160	1400	Loamy sand, sand	0–100	Gee et al. (1989)
11. Beatty, NV	74	1900	Sand and gravel	0.036	Nichols et al. (1987)
12. South Australia	300	No report	Dune sand	14	Allison et al. (1985)
13. Saudi Arabia	70	2400	Dune sand	20	Dincer et al. (1974)
14. Eastern Botswana	447	1220	Sand, sandstone	0.5–6	Carlsson et al. (1989)
15. Southern Cyprus	390	1450	Fine sand	10–94	Kitching et al. (1980)
16. Central Sudan	225	No report	Sandstone	0.2–1.3	Darling et al. (1992)
17. Northeast Sudan	220	No report	Sandstone	<1	Darling et al. (1992)

(Stephens,1994)

- ***Only mm per year?!?!***
  Does it *really* matter?

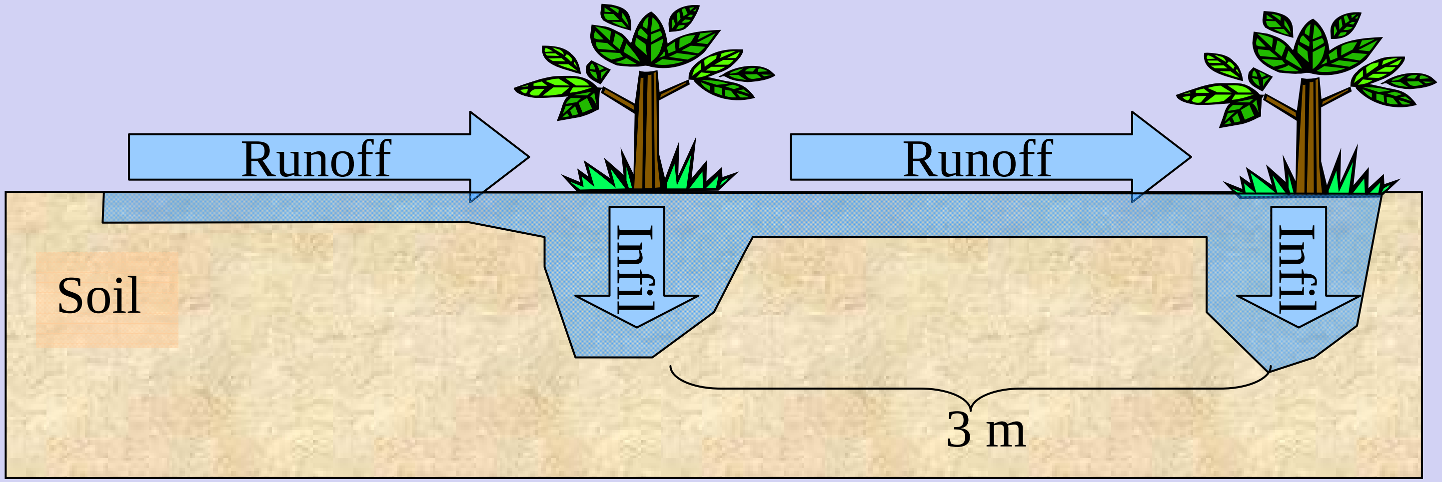
Slide contents from Walvoord & Phillips - NMT

Vegetation cover changes Impacts Infiltration



GRASSLAND

Original Recharge ~ 2 mm/yr

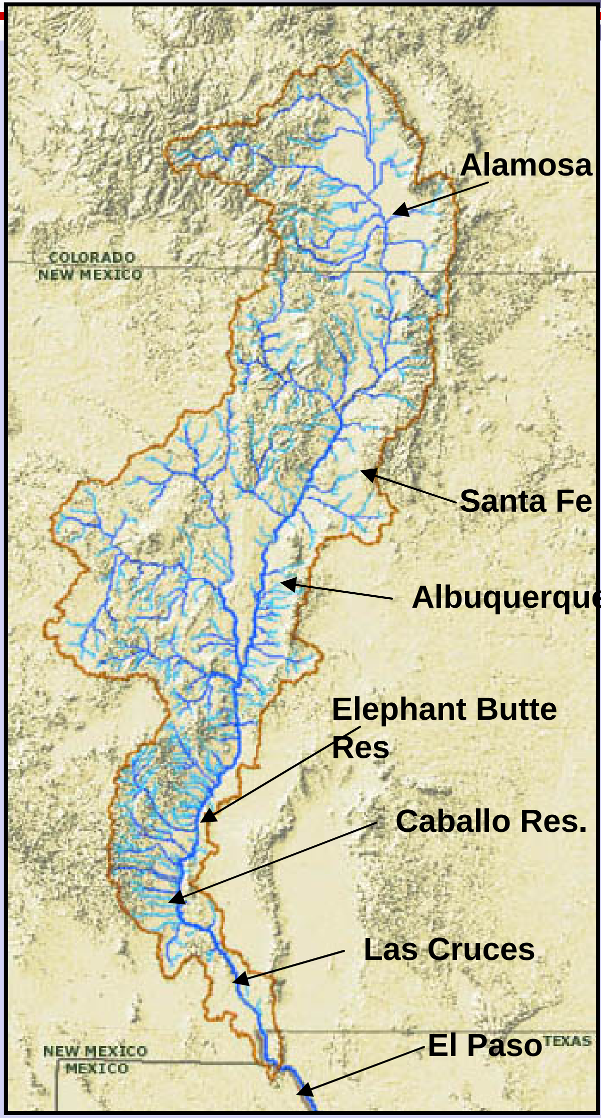


Revised Recharge rate ~ 0.02 mm/yr

SHRUBLAND

Source: Eric Small, NMT now at CU Boulder

Upper Rio Grande Basin – CO and NM



Map from C. Duffy

- Basin Area: 60,000 km^2
- Population: 1,200,000

Recharge ~ 2 mm/yr

Ground Water for 1.6 Million People

Recharge ~0.02 mm/yr

Ground Water for only 16,000 people

Slide contents from Walvoord & Phillips - NMT

What is the Message?

- ***Despite advances to date, predicting the future Hydro-Climate variables will remain a major challenge:***

- ***While investment in model development is fully justified, we must also improve the "engineering approaches" currently used in practice for operational and planning purposes.***

- ***Long-term and sustained observation programs are critical, especially for model verification. Without some degree of verifiability, hard to expect their use***


Thank You For Listening
The Rio Grande River, NM Photo: J. Sorooshian 2005