When Will the Reservoirs Run Dry? The Looming Water Crisis in the Southwest

Lake Powell Summer 2004, 120’ low, ~ 10 maf remaining, 15 maf gone. B. Udall photo

April 15, 2010
Tucson, AZ

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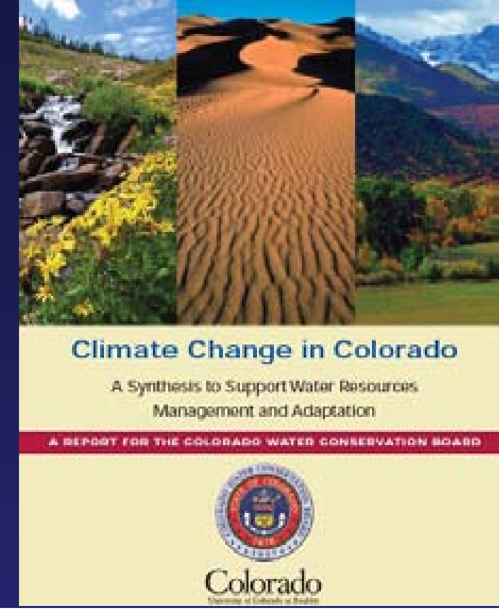
Outline

- Climate Change Studies
- Recent Climate
- Systemic Allocation Problems
- Science Issues
- Systemic Reservoir Risk
- Lessons from Australia
- Closing Thoughts

Colorado River Climate Change Studies over the Years

- Early Studies – Scenarios, About 1980
  - Stockton and Boggess, 1979
  - Revelle and Waggoner, 1983*
- Mid Studies, First Global Climate Model Use, 1990s
  - Nash and Gleick, 1991, 1993
  - McCabe and Wolock, 1999 (NAST)
  - IPCC, 2001
- More Recent Studies, Since 2004 – RANGE -5% to -45% BY 2050
  - Milly et al.,2005, “Global Patterns of trends in runoff”
  - Christensen and Lettenmaier, 2004, 2006
  - Hoerling and Eischeid, 2006, “Past Peak Water?”
  - Seager et al, 2007, “Imminent Transition to more arid climate state..”
  - IPCC, 2007 (Regional Assessments)
  - National Research Council Colorado River Report, 2007
  - McCabe and Wolock, 2007, “Warming may create substantial water shortages…”
  - Barnett and Pierce, 2008, “When will Lake Mead Go Dry?”
  - Barnett and Pierce, 2009, “Sustainable Water Deliveries From CR in changing climate
  - Rajagopalan, 2009, “Water Supply risk on the CR: Can management mitigate?”
  - Comments and Responses to B&P 2008

At Least 7 Colorado River Studies Since 2004...



….Runoff Declines Range from -6% to -45% by 2050
....Best guess now -10% to -20% by 2050

TABLE 5-1. Projected Changes in Colorado River Basin Runoff or Streamflow in the Mid-21st Century from Recent Studies

Study	*GCMs (runs)*	*Spatial Scale*	*Temperature*	*Precipitation*	*Year*	*Runoff (Flow)*	*Risk Estimate*
Christensen et al. 2004	1 (3)	VIC model grid (~8 mi)	+3.1°F	-6%	2040–69	-18%	Yes
Milly 2005, replotted by P.C.D. Milly	12 (24) (~100–300 mi)	GCM grids —	—		2041–60	-10 to -20% 96% model agreement	No
Hoerling and Eischeid 2006	18 (42)	NCDC Climate Division	+5.0°F	~0%	2035–60	-45%	No
Christensen and Lettenmaier 2007	11 (22)	VIC model grid (~8 mi)	+4.5°F (+1.8 to +5.0)	-1% (-21% to +13%)	2040–69	-6% (-40% to +18%)	Yes
Seager et al. 2007*	19 (49)	GCM grids (~100–300 mi)	—	—	2050	-16% (-8% to -25%)	No
McCabe and Wolock 2008	—	USGS HUC8 units (~25–65 mi)	Assumed +3.6°F	0%	—	-17 %	Yes
Barnett and Pierce 2008*	—	—	—	—	2057	Assumed -10% to -30%	Yes

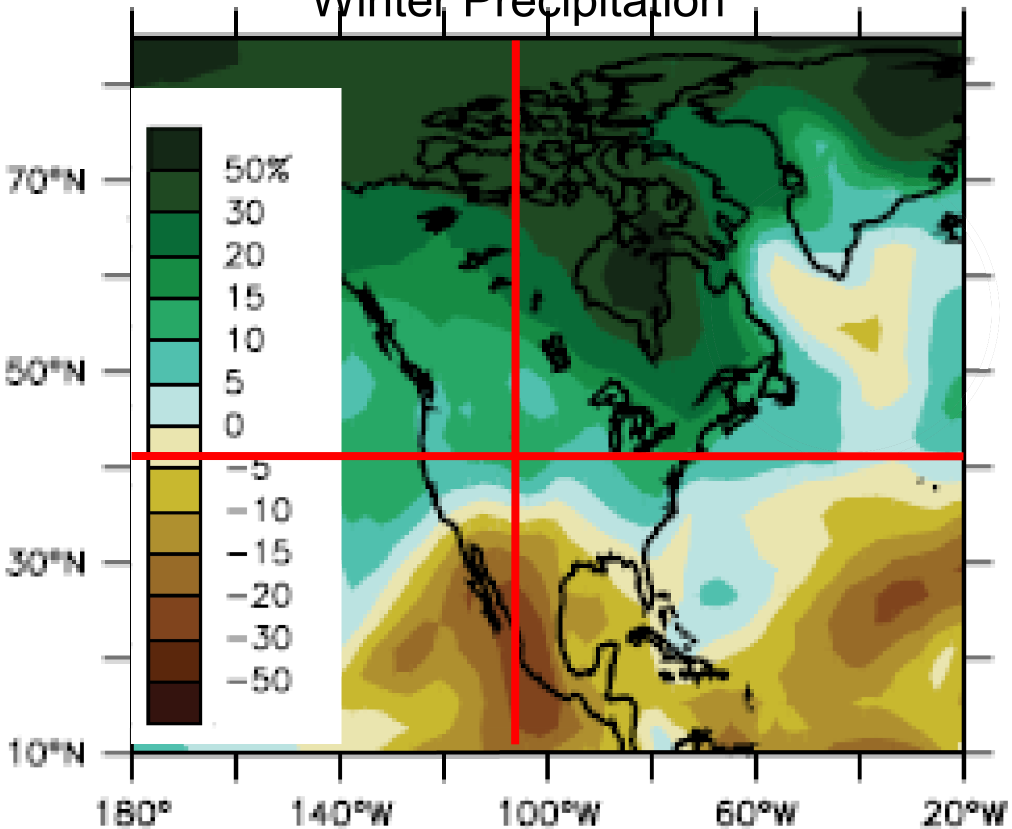
Values and ranges (where available) were extracted from the text and figures of the references shown. Columns provide the number of climate models and individual model runs used to drive the hydrology models, the spatial scale of the hydrology, the temperature and precipitation changes that drive the runoff projections, and whether or not the study quantified the risk these changes pose to water supply (e.g., the risk of a compact call or of significantly depleting reservoir storage).

Precip and Temp at 2100 A1B –

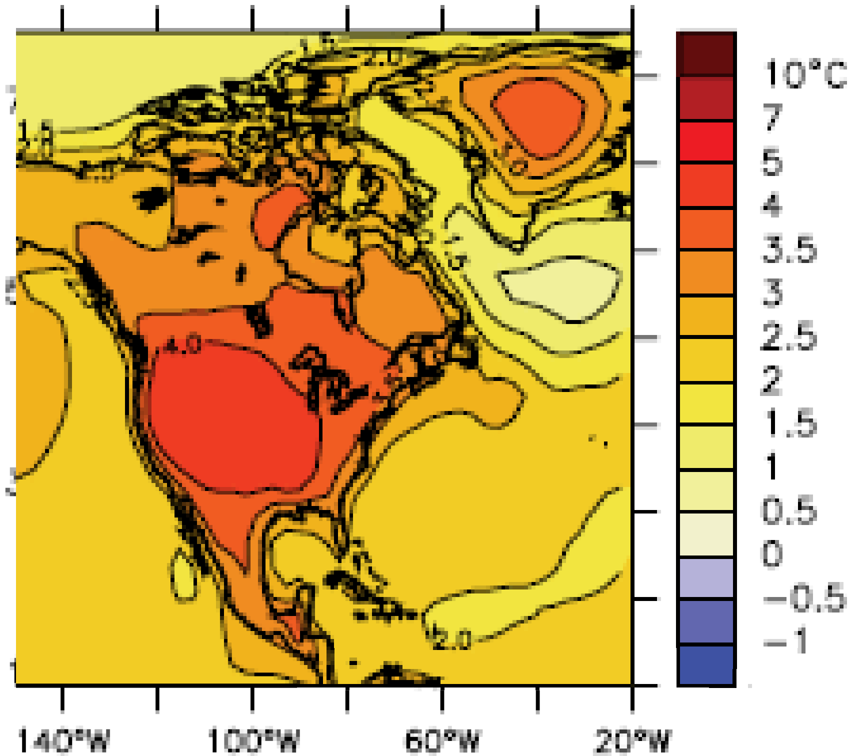
7F = 3-4C Rise

Precip

Winter Precipitation



Summer Temperatures



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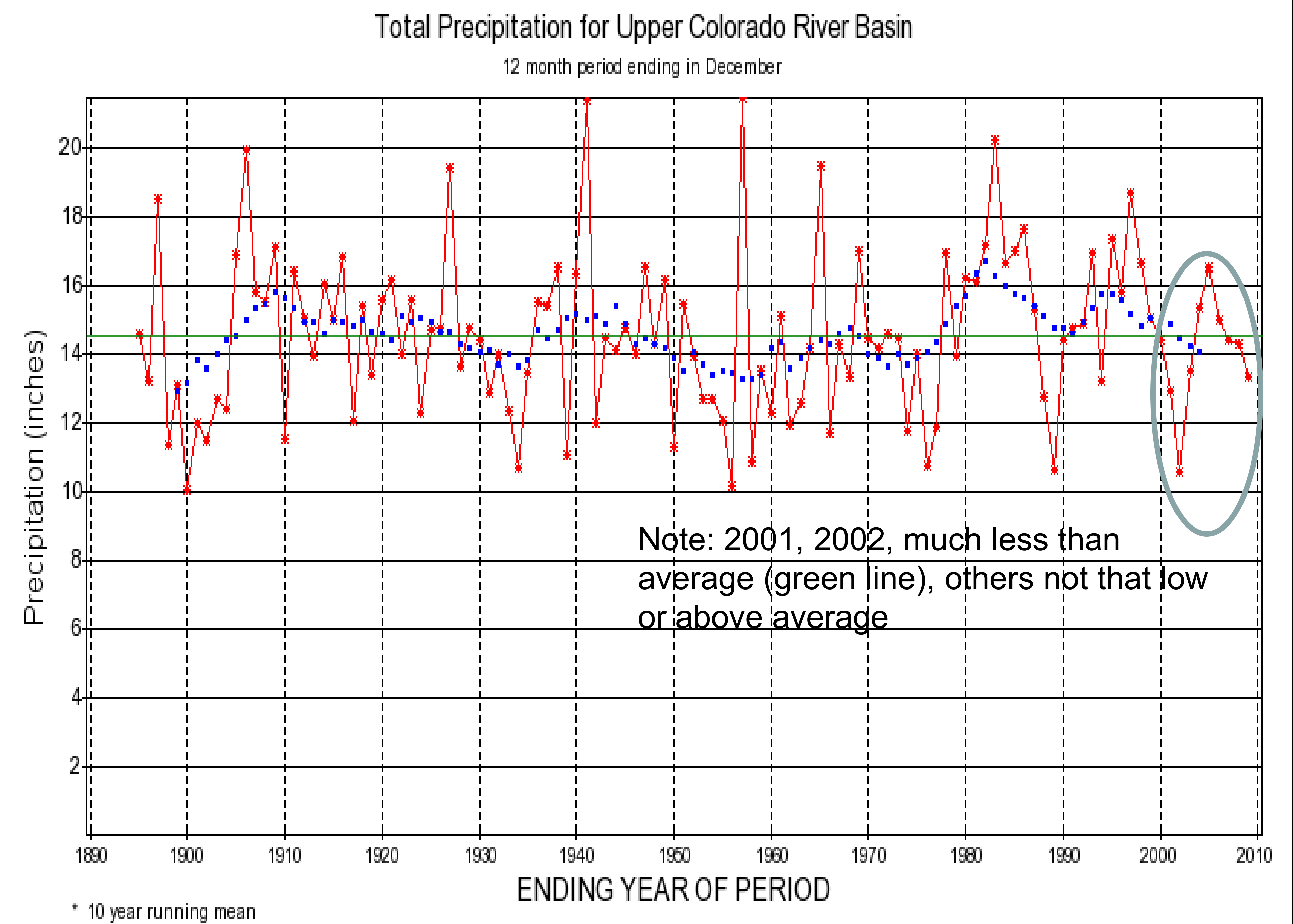
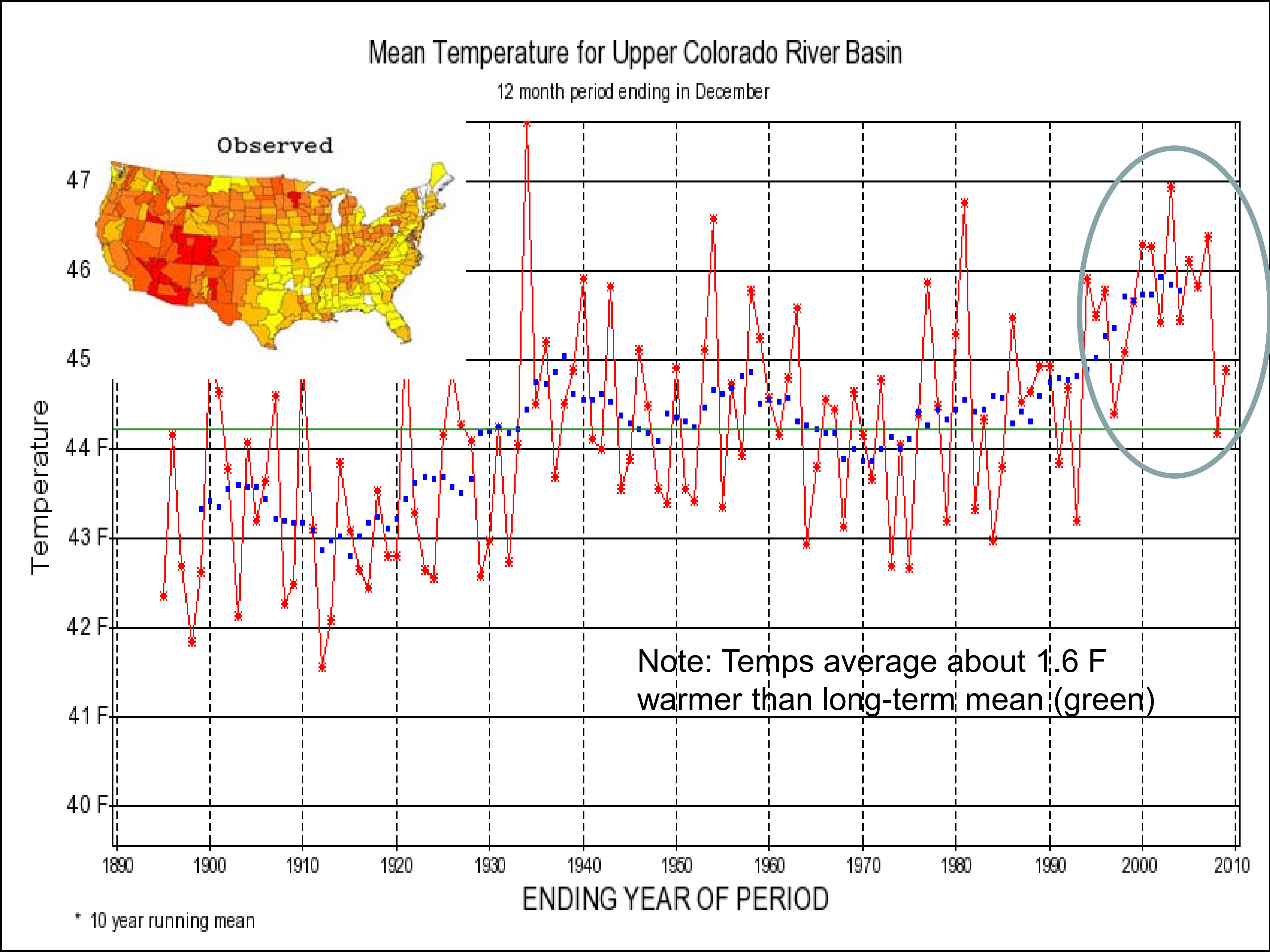
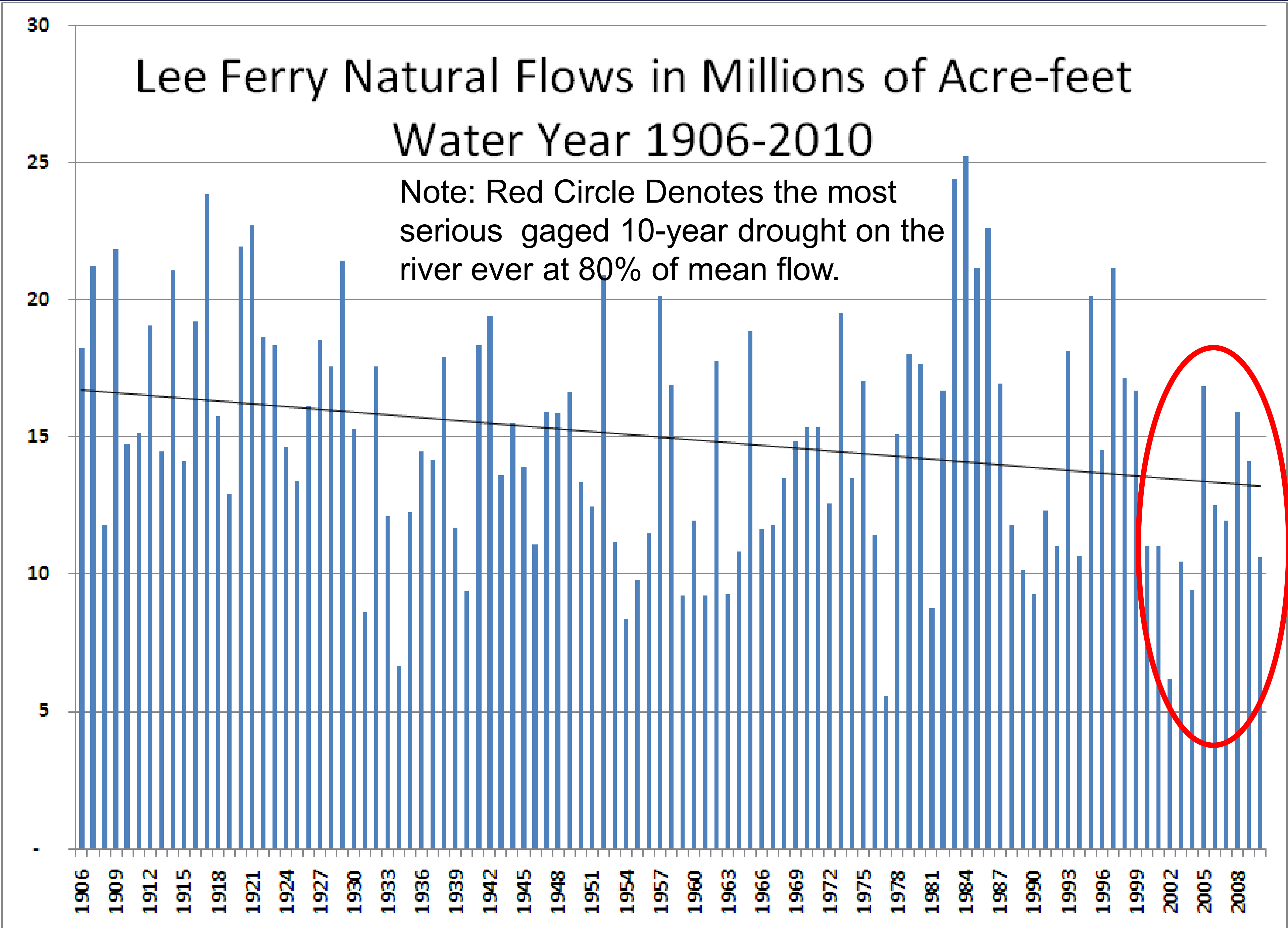


Total Precipitation for Upper Colorado River Basin
12 month period ending in December
Precipitation (inches)
20
18
16
14
12
10
8
6
4
2
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
ENDING YEAR OF PERIOD
* 10 year running mean
Note: 2001, 2002, much less than average (green line), others not that low or above average


Mean Temperature for Upper Colorado River Basin
12 month period ending in December
Observed
Temperature
47
46
45
44 F
43 F
42 F
41 F
40 F
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
ENDING YEAR OF PERIOD
* 10 year running mean
Note: Temps average about 1.6 F warmer than long-term mean (green)



Lee Ferry Natural Flows in Millions of Acre-feet
Water Year 1906-2010
Note: Red Circle Denotes the most serious gaged 10-year drought on the river ever at 80% of mean flow.
30
25
20
15
10
5
-
1906
1909
1912
1915
1918
1921
1924
1927
1930
1933
1936
1939
1942
1945
1948
1951
1954
1957
1960
1963
1966
1969
1972
1975
1978
1981
1984
1987
1990
1993
1996
1999
2002
2005
2008

Colorado River Ten-Year Droughts Since 1906 at Lees Ferry

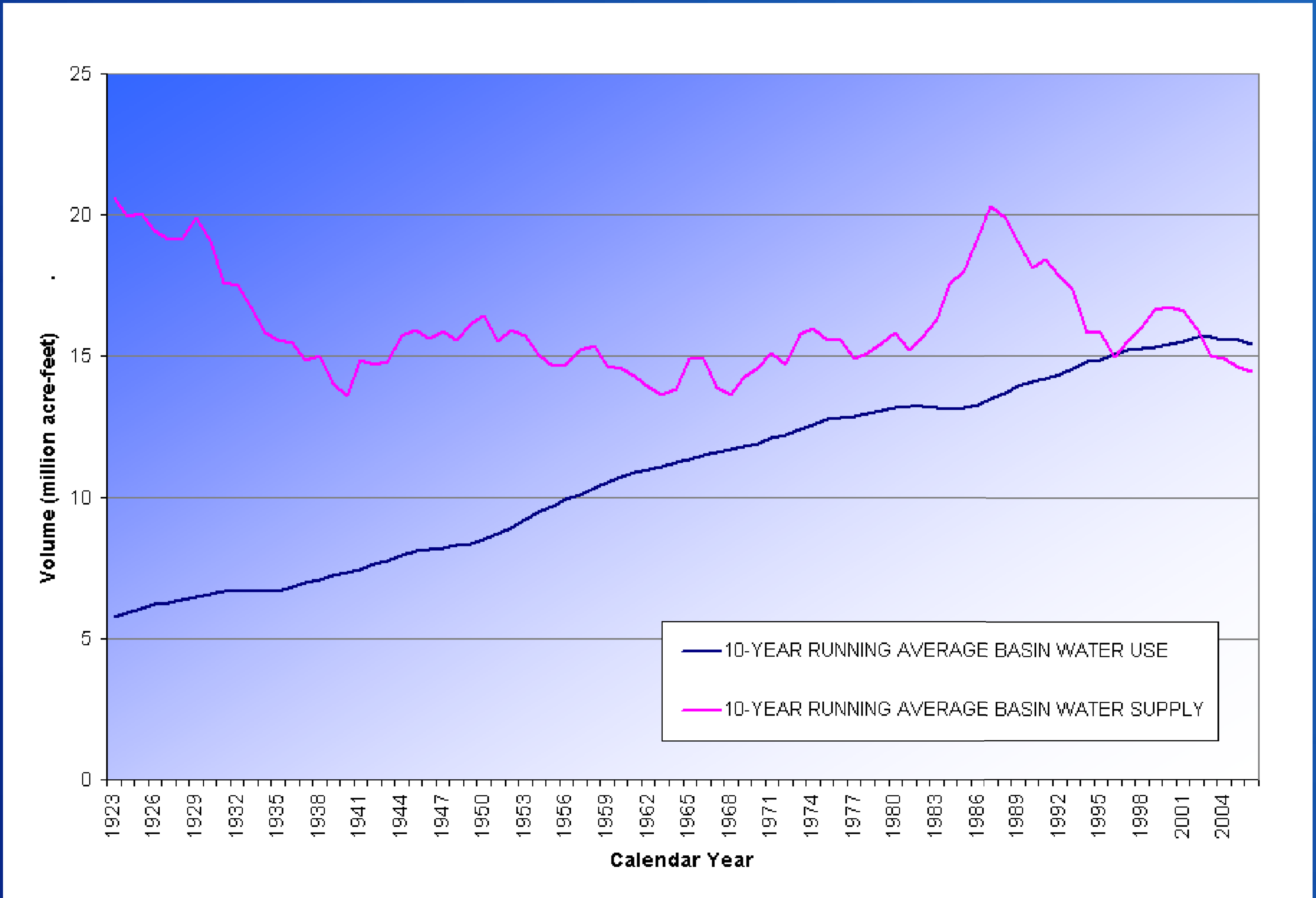
Take Home Message: This is by far the most serious 10-year drought in the historic record

Rank	% Average	10-Year Total	Start Yr	End Year
1	79.7%	119,081,504	2001	2010
2	80.0%	119,483,455	2000	2009
3	81.7%	122,048,340	1999	2008
4	82.5%	123,302,369	1998	2007
5	83.1%	124,090,505	1959	1968
6	83.1%	124,212,410	1954	1963
7	83.6%	124,880,374	1931	1940
8	84.4%	126,156,961	1953	1962
9	84.8%	126,645,471	1955	1964
10	85.3%	127,482,205	1958	1967

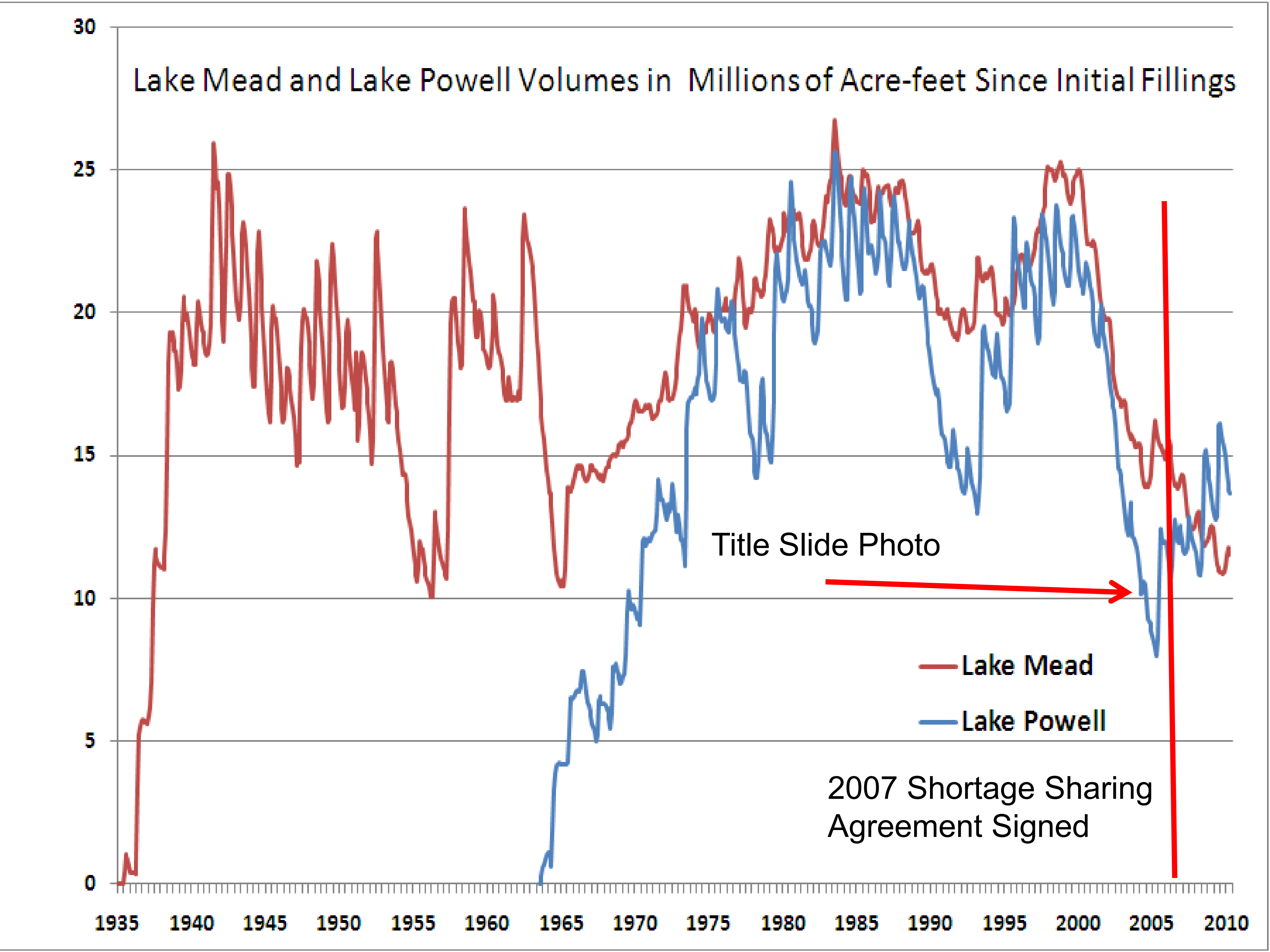
Lee Ferry Flow in Acre-feet By Year Since 2000 as % of Average

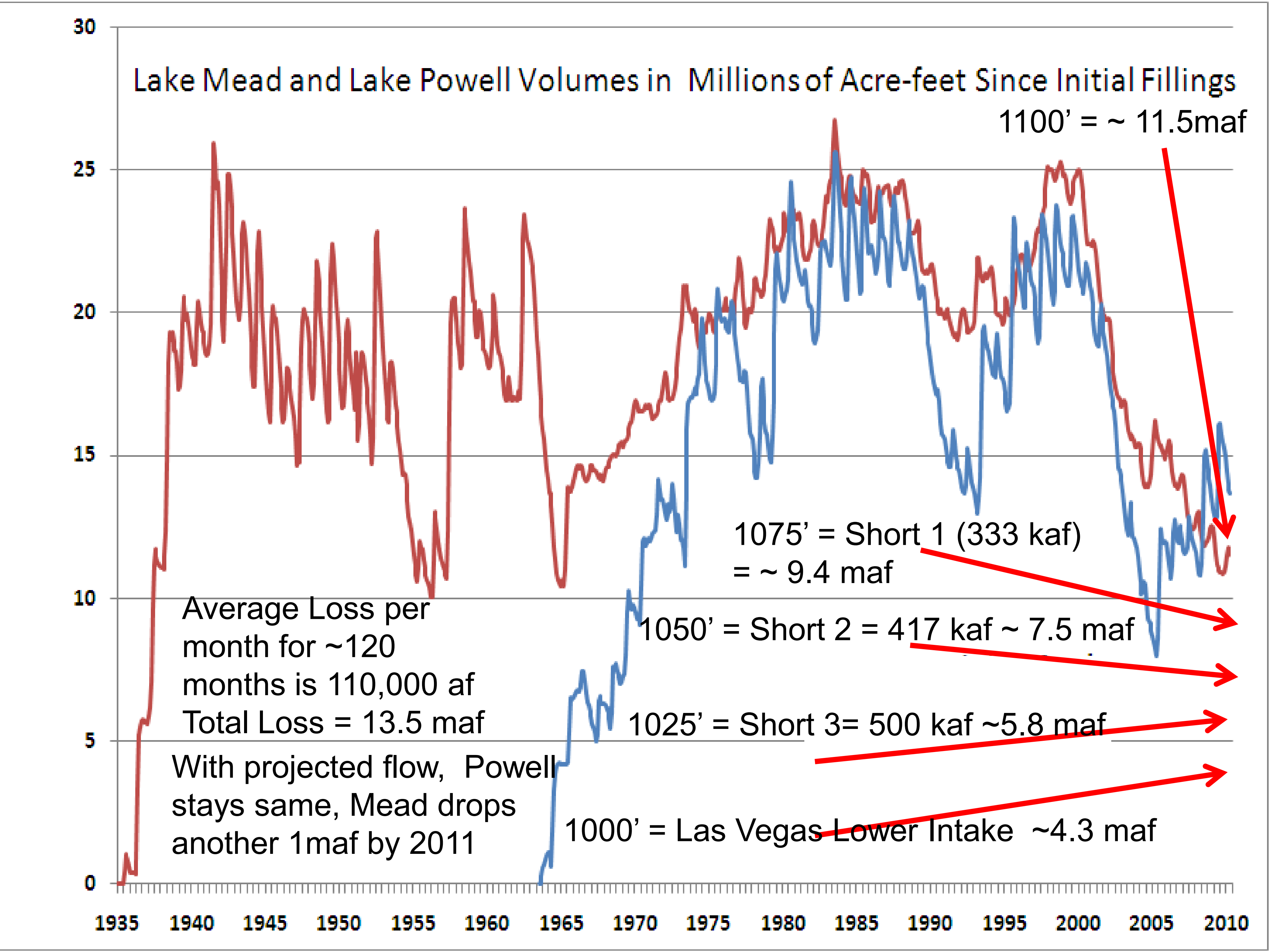
Year	Flow in AF	% Avg
2000	11,029,918	74%
2001	11,027,306	74%
2002	6,204,516	41%
2003	10,479,773	70%
2004	9,410,833	63%
2005	16,849,487	113%
2006	12,515,241	84%
2007	11,935,380	80%
2008	15,907,000	106%
2009	14,124,000	94%
2010	10,627,967	71%

Colorado River Water Supply & Use



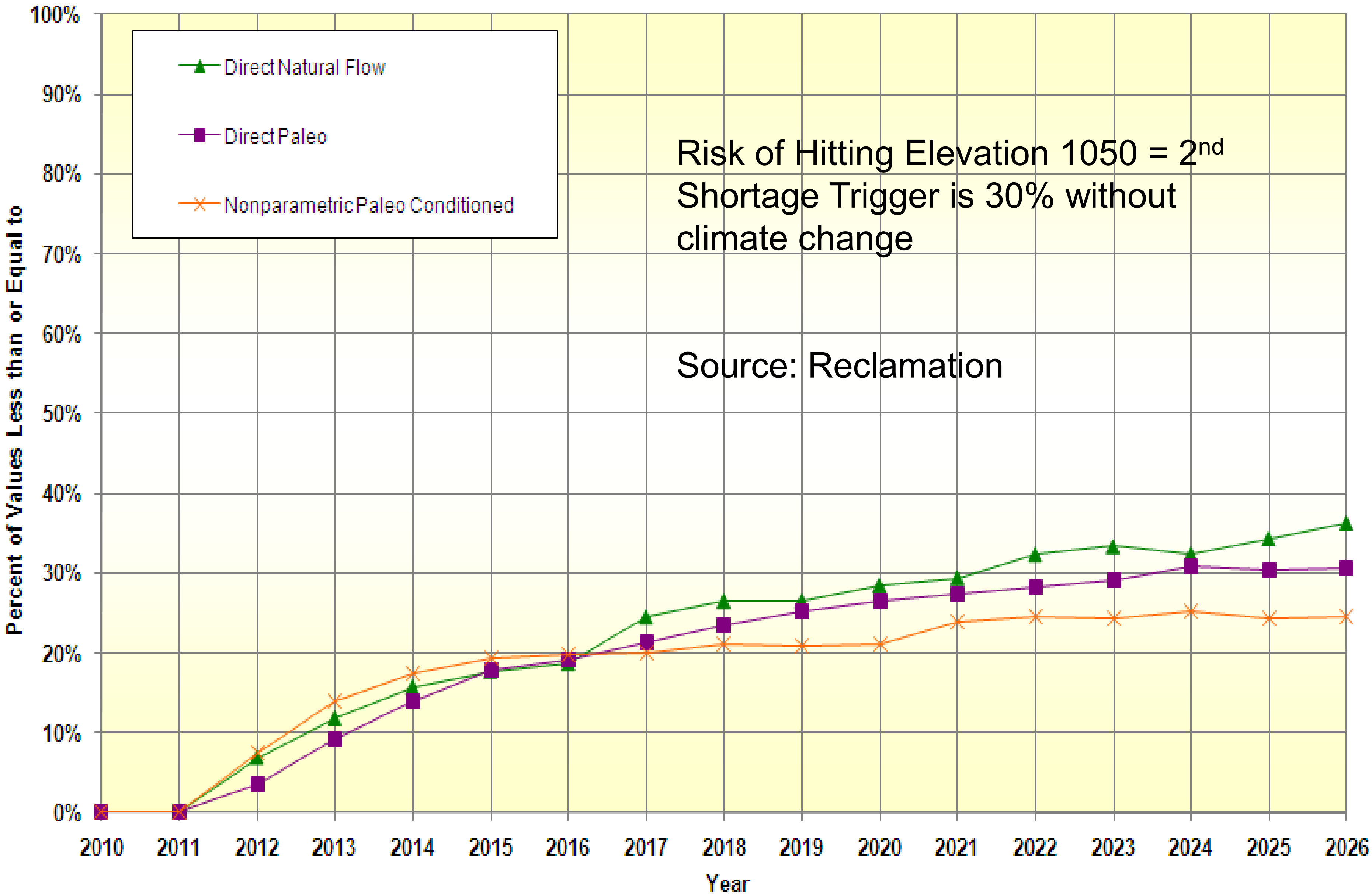
RECLAMATION


Lake Mead and Lake Powell Volumes in Millions of Acre-feet Since Initial Fillings
30
25
20
15
10
5
0
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Title Slide Photo
Lake Mead
Lake Powell
2007 Shortage Sharing Agreement Signed



Lake Mead and Lake Powell Volumes in Millions of Acre-feet Since Initial Fillings
1100' = ~ 11.5maf
1075' = Short 1 (333 kaf)
= ~ 9.4 maf
1050' = Short 2 = 417 kaf ~ 7.5 maf
1025' = Short 3= 500 kaf ~5.8 maf
1000' = Las Vegas Lower Intake ~4.3 maf
Average Loss per
month for ~120
months is 110,000 af
Total Loss = 13.5 maf
With projected flow, Powell
stays same, Mead drops
another 1maf by 2011
30
25
20
15
10
5
0
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010

Figure 6
Lake Mead End-of-July Water Elevations
Percent of Values Less than or Equal to Elevation 1,050 feet



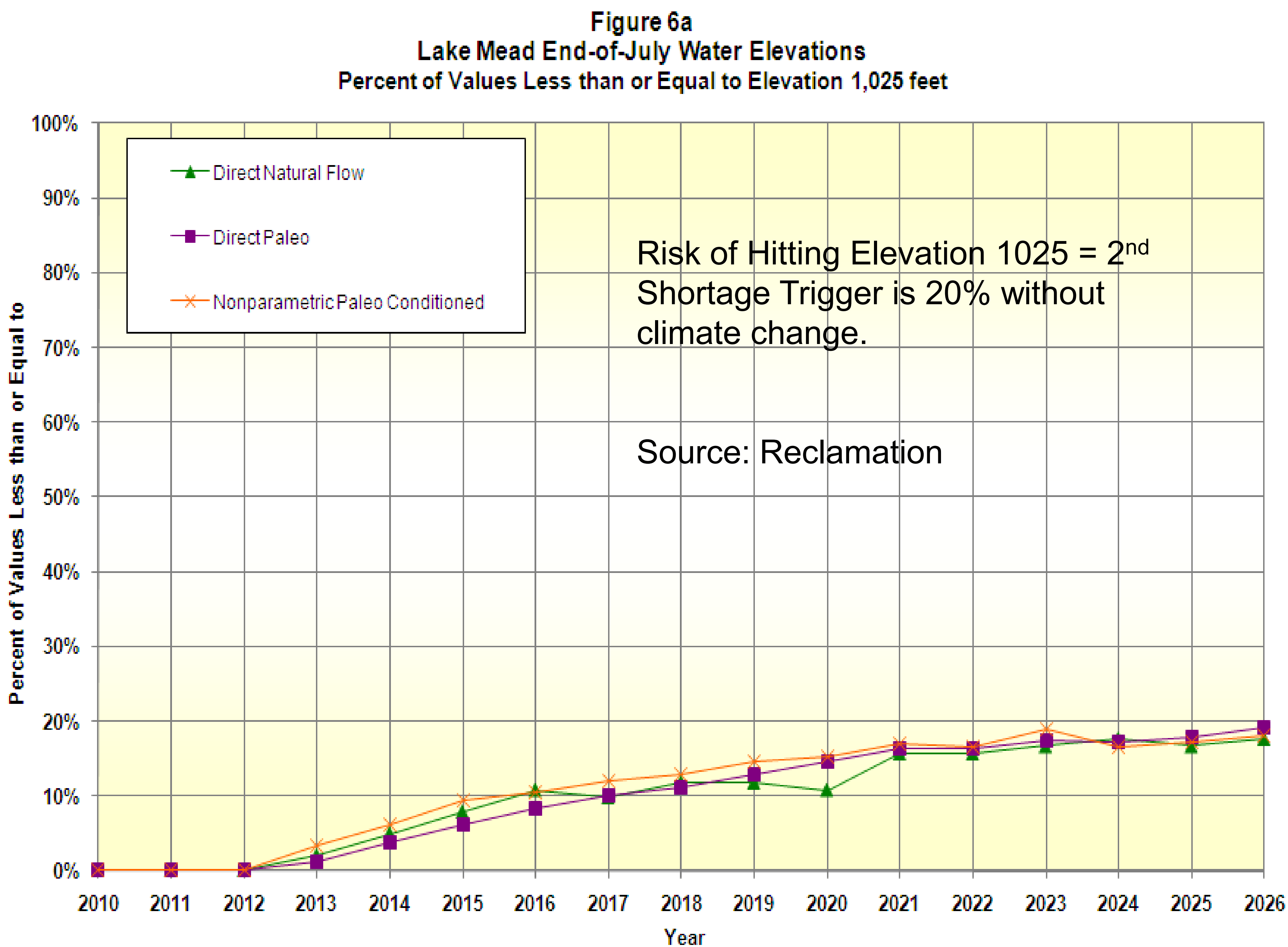


Figure 6a
Lake Mead End-of-July Water Elevations
Percent of Values Less than or Equal to Elevation 1,025 feet
Direct Natural Flow
Direct Paleo
Nonparametric Paleo Conditioned
Risk of Hitting Elevation 1025 = 2nd Shortage Trigger is 20% without climate change.
Source: Reclamation
Percent of Values Less than or Equal to
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
Year

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A Current Problem in the Lower Basin

- Avg Lake Mead Inflows = 9.0 maf
  - 8.23 maf from Powell (Current Operating Rules)
  - 0.77 maf tributaries below Powell
  - 9 maf is all the LB is legally entitled to
- Avg Lake Mead Outflows = 10.4 maf
  - 7.5 maf LB States (4.4 CA, 2.8 AZ, 0.3 NV maf)
  - 1.5 maf Mexico
  - 1.4 maf Evap + Delivery Losses
- Net Balance = -1.4 maf/year
  - (Mead at 11.5 maf now)

A Lurking Problem in the Upper Basin

- How Much Water Left to Develop?
  - Current uses: ~4.5maf per year
  - At 13.5 maf avg , ~0.5 maf left to develop
  - At 15.0 maf avg, ~1.5 maf left to develop
- 'Hydrologic Leftovers' Creates Uncertainty
- Upper Basin Compact penalizes for overuse, but only determined after the fact
- Terror over Compact 'Call' Ramifications

How much water to Develop ?

Source: State of Colorado "CRWAS" Study

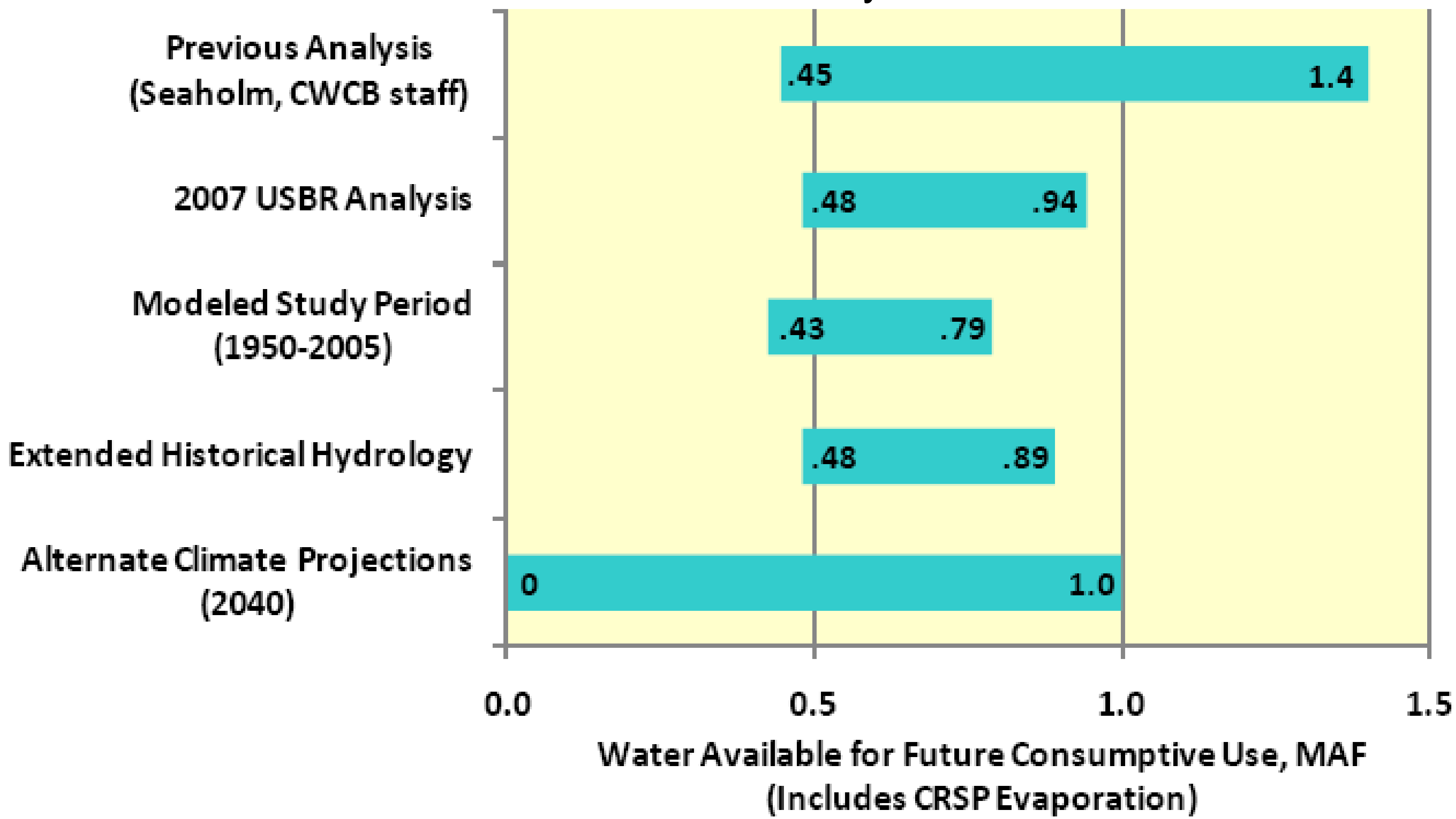

Figure 3-37 –Water Available for Future Consumptive Use by Colorado (MAF)
Revised from preliminary charts presented from January through March 2010 to CWCB, IBCC, Joint Agriculture Committee, and Colorado Water Congress

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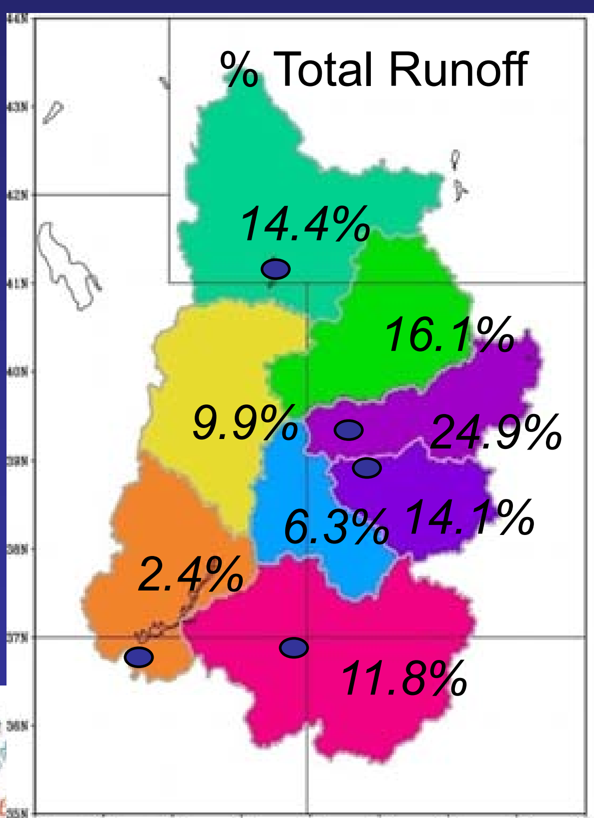
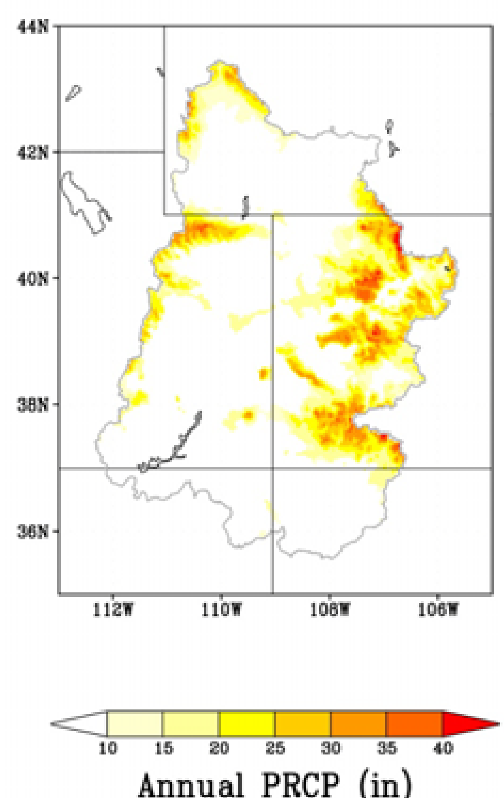
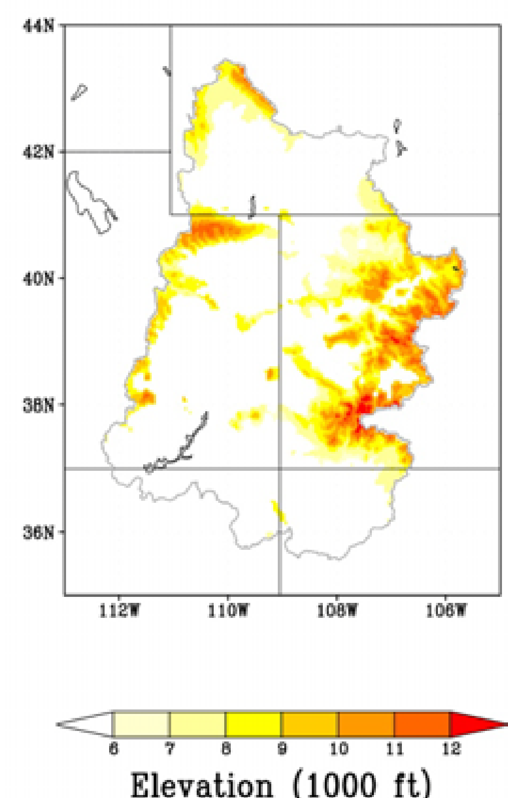
Reconciling Year 1- Scale Matters

- Most runoff comes from small part of the basin > 9000 feet
- Runoff Efficiency Varies Greatly from ~5% (Dirty Devil) to > 40% (Upper Mainstem)
- You can't model the basin at large scales and expect accurate results
  - GCMs (e.g. Milly) and H&E 2006 likely overstate declines







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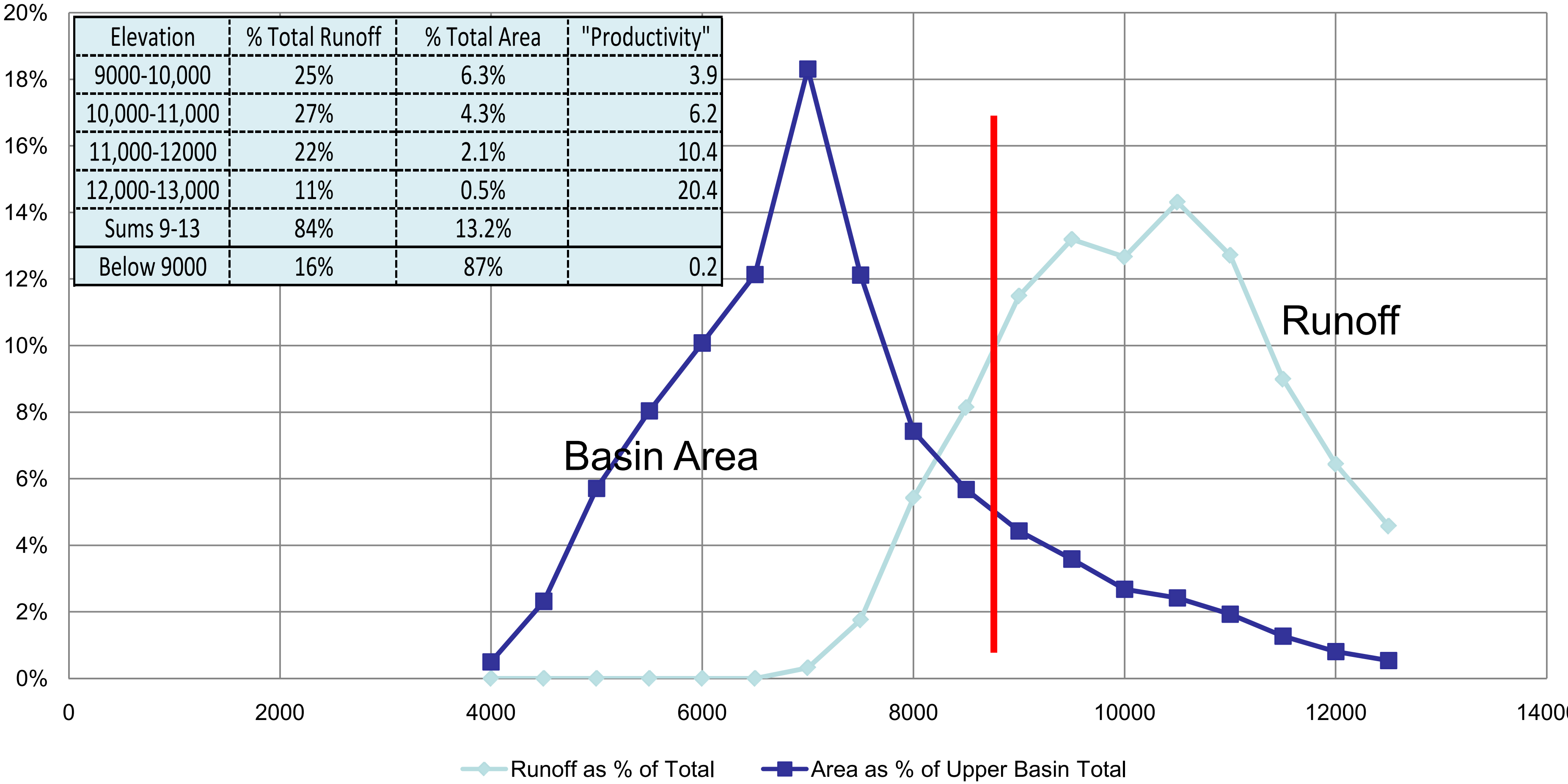
Reconciling Year 1- Scale Matters

- Most runoff comes from small part of the basin > 9000 feet
  - Very Little of the Runoff Comes from Below 9000’ (16% Runoff, 87% of Area)
  - 84% of Total Runoff Comes from 13% of the Basin Area – all above 9000’

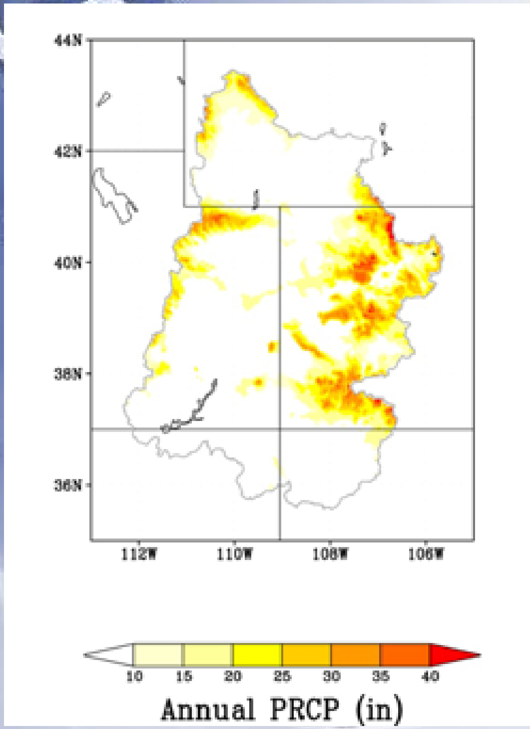
Basin Area and Runoff By Elevation

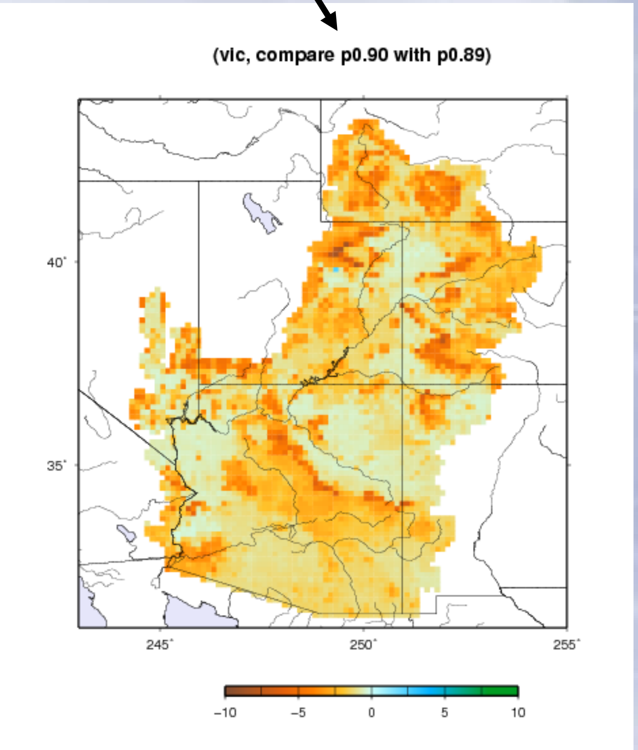
Elevation	% Total Runoff	% Total Area	"Productivity"
9000-10,000	25%	6.3%	3.9
10,000-11,000	27%	4.3%	6.2
11,000-12000	22%	2.1%	10.4
12,000-13,000	11%	0.5%	20.4
Sums 9-13	84%	13.2%	
Below 9000	16%	87%	0.2



Precipitation Elasticity for Colorado River Flows at Lees Ferry

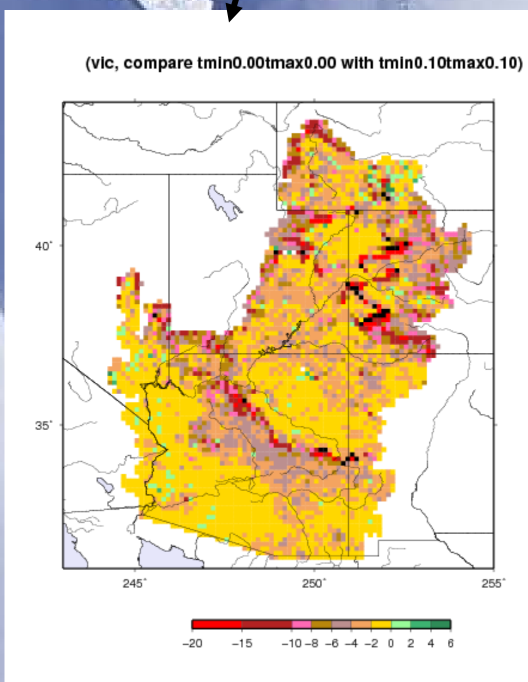
VIC	**2.4%**
2-Layer Model	**2.0%**





Temperatures sensitivities for Colorado River Flow at Lees Ferry

VIC T_{max} and T_{min}	-5.9%
VIC T_{max}	-10.8%
2-Layer Model	-9.0%



Sensitivity between models is dependant on how PET is calculated:

Penman-Monteith versus Thornthwaite

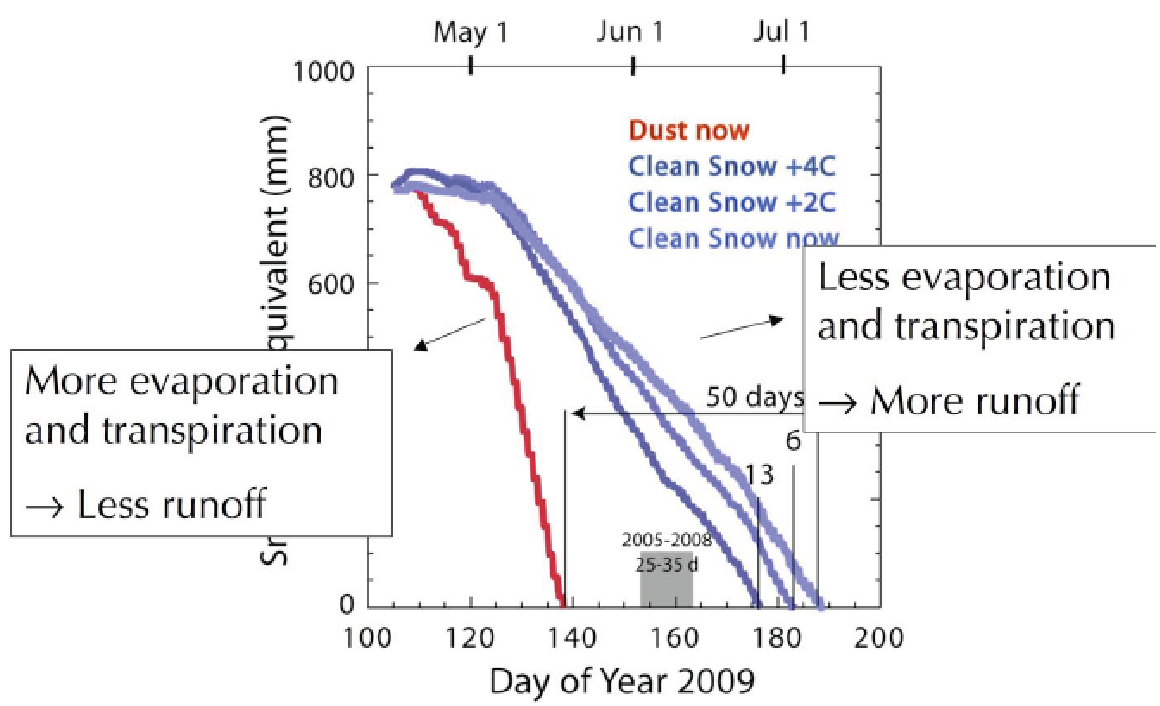
How temperature applied (T_{max} vs $T_{max\&min}$) changes radiation budget

New Dust on Snow Research

Senator Beck Basin Study Area

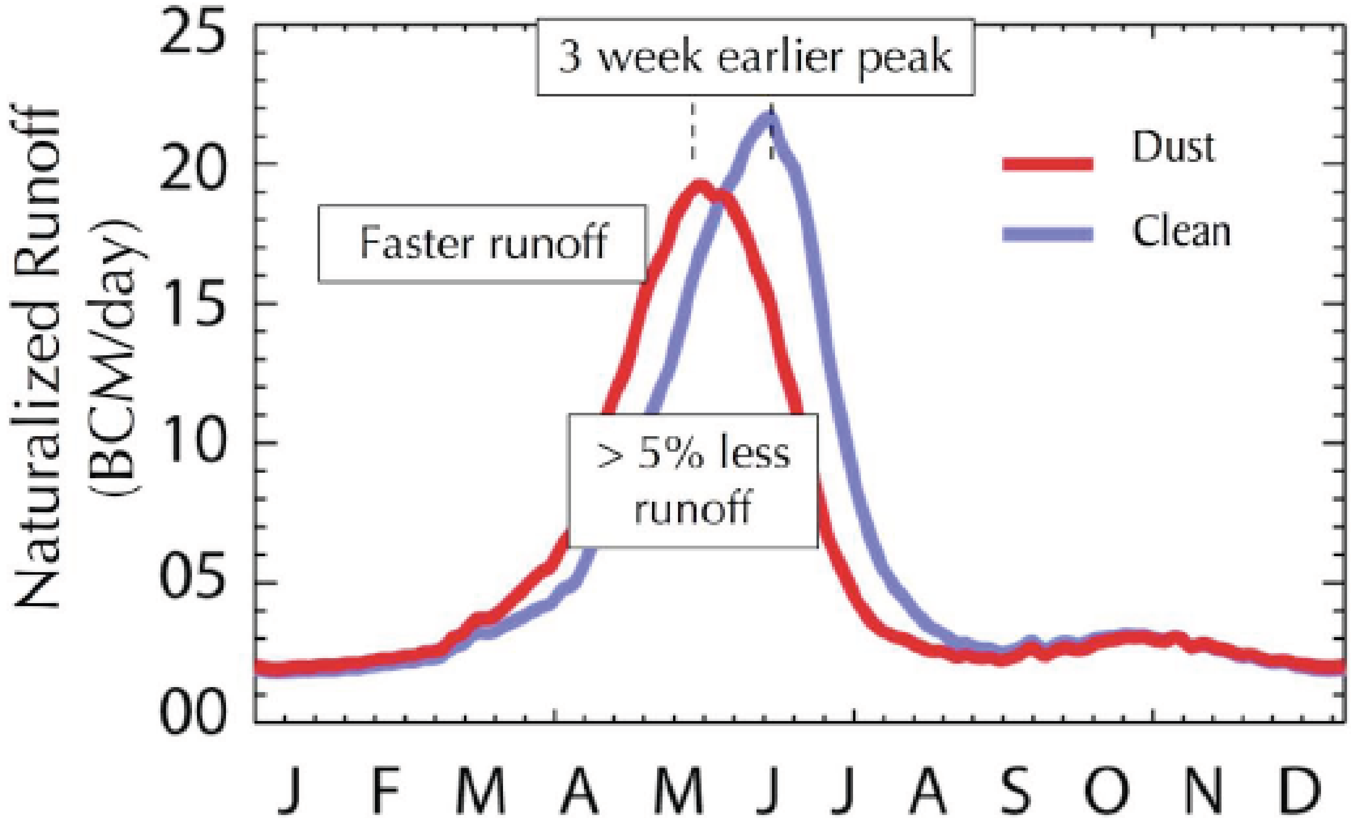
Dust on Snow absorbs lots of solar energy

- Melts Faster
- Reduces Runoff



It doesn't just melt faster…

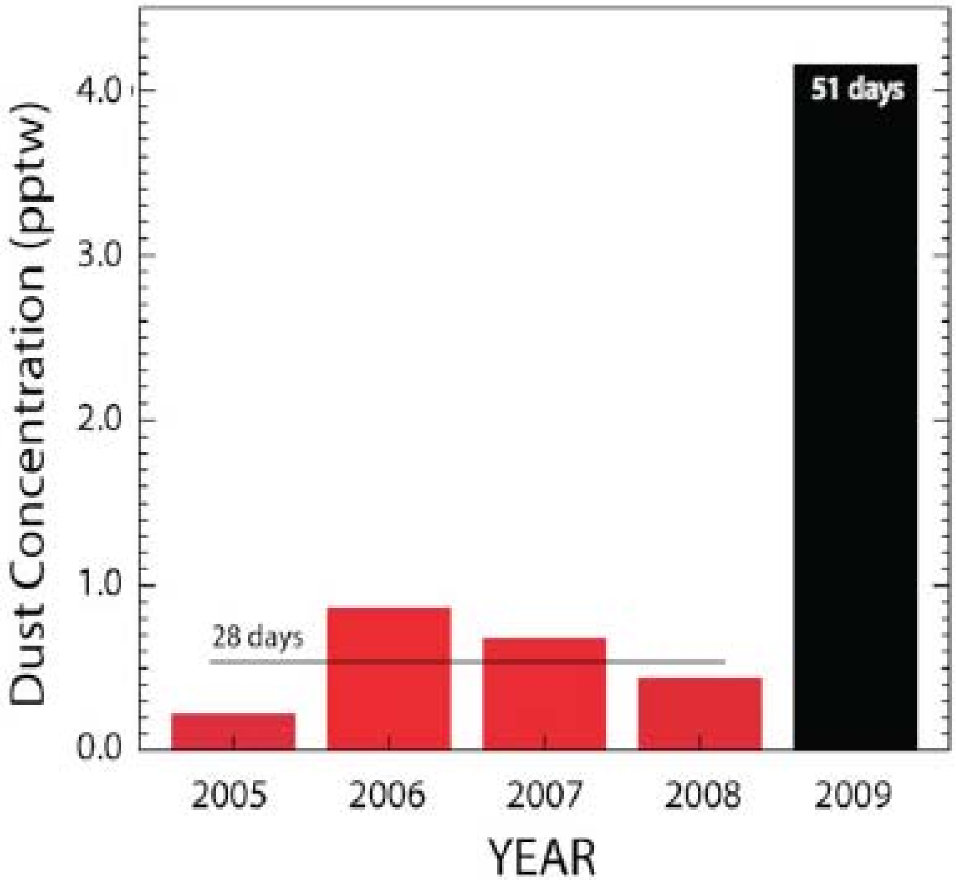
Runoff at Lee's Ferry, AZ



Daily averages across 1915-2003

from *Painter et al (2009)*

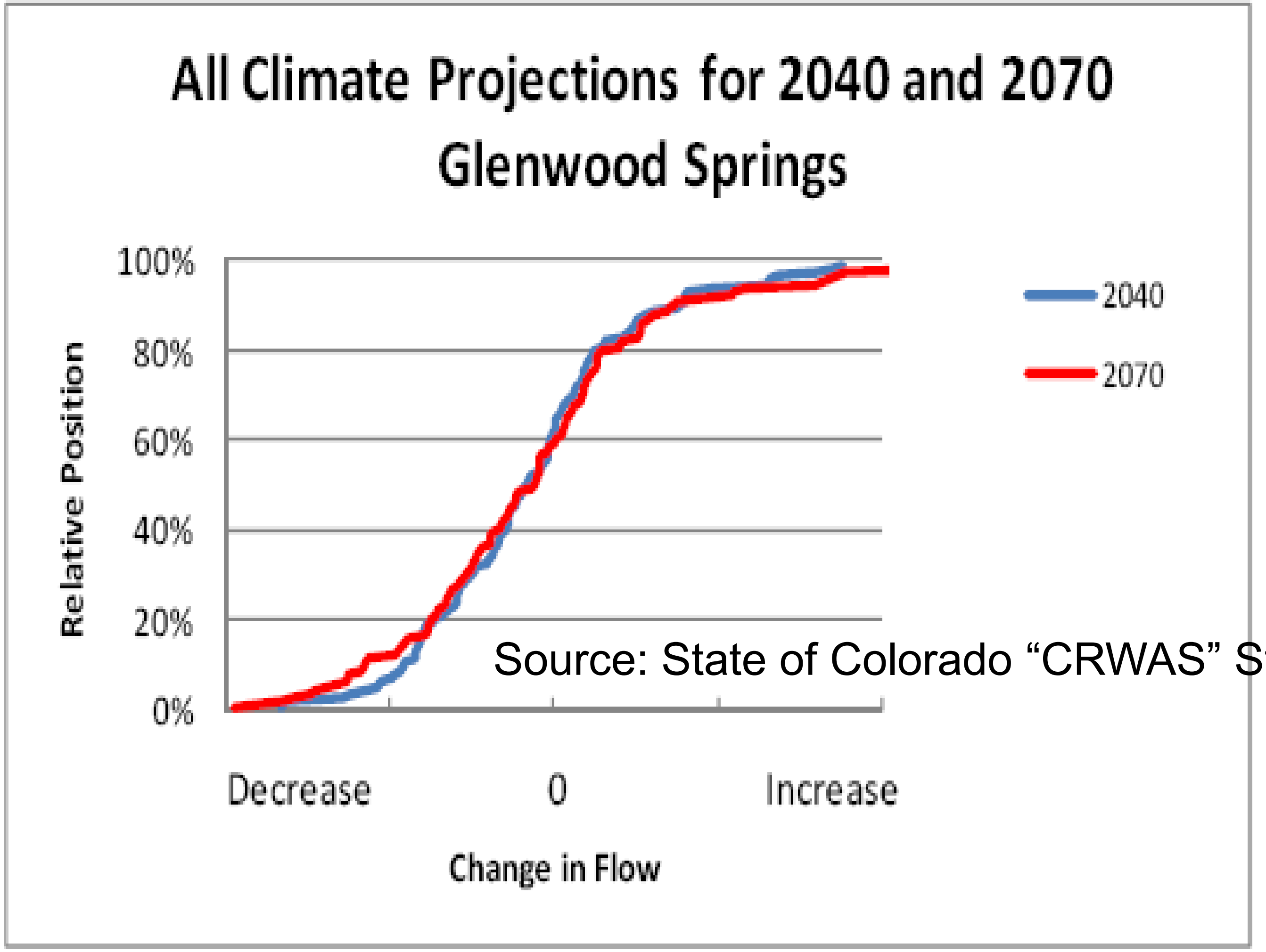
2009 a vision into the future ?



Dust Accelerates Snow Melt in San Juan Mountains

Hydrology Model Issues

- Why is 2070 no different from 2040?



Source: State of Colorado "CRWAS" Study

Figure 2-10 – Comparison of Relative Impact on Flow at Glenwood Springs All 2040 and 2070 Projections

Demand Issues

- Total Demand Increases by 1.5 to 5 maf at 2040. Average Increase ~ 20%. 18 Days Longer Growing Season
- At 2070 Average Increase ~30%, 30 Days.

Table 3-5 – 2040 Average Annual Study Basin CIR Compared to Historical Conditions (AF)

Source: State of Colorado "CRWAS" Study

Study Basin	Historical Period	Minimum Projection	Maximum Projection	Average of Projections	% Increase From Historical
Yampa River	214,271	225,440	263,438	245,964	15%
White River	45,937	50,123	62,182	56,713	23%
Upper Colorado River	577,043	618,704	736,863	686,314	19%
Gunnison River	618,070	660,364	768,486	724,335	17%
San Juan/Dolores Rivers	554,821	591,795	685,620	647,506	17%
Total	**2,010,142**	**2,146,426**	**2,516,589**	**2,360,832**	**17%**

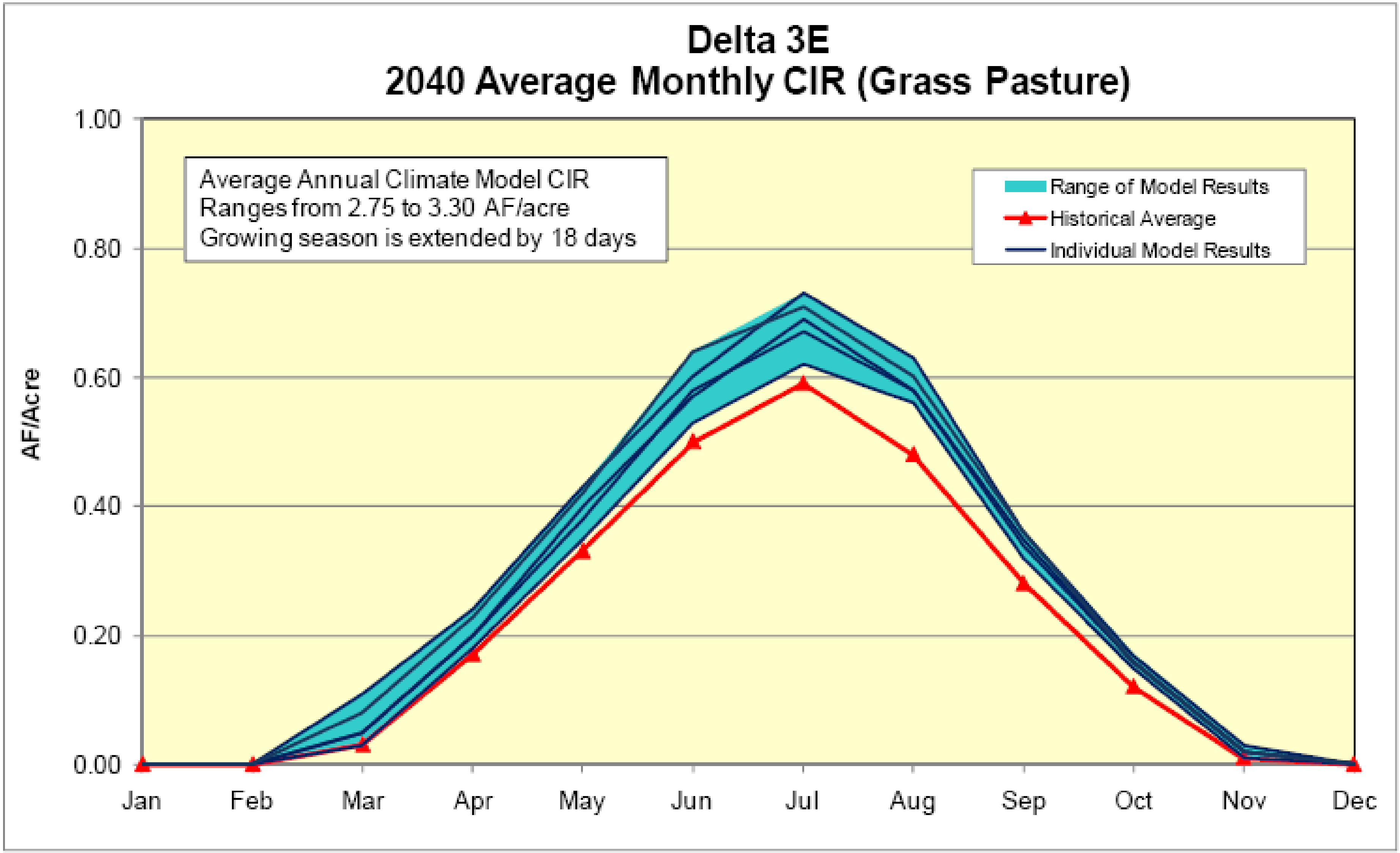


Figure 3-6 – Delta 2040 Average Monthly CIR Comparison

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Acceptable Reservoir Risks

- Reservoirs are designed to fluctuate
- Traditional Reservoir sizing techniques simulate history of inflows and desired demand and have the reservoir hitting bottom once
- If 100 years of simulation, 1 failure is 1% risk of drying, BUT all demands still met (barely)
- This is our ‘Probability of Drying’ metric, BP2008 uses a different metric
- 1% to maybe 5% is manageable. Beyond this, life is challenging for reservoir managers
- 50% drying is not acceptable level of risk

When Will Lake Mead Go Dry?

Water Resources Research, 2008, Barnett and Pearce

- Water Budget Analysis
  - One 50 maf reservoir, increasing UB demands (13.5 in 2008 ->14.1 maf/yr in 2030, 15 maf /yr inflows, current starting contents
  - Linear Climate Change Reduction in Flows w/ some natural variability
- Results With Linear 20% Reduction in mean flows Over 50 years
  - 10% Chance Live Storage Gone by 2013
  - 50% Chance Live Storage Gone by 2021
  - 50% Chance Loss of Power by 2017
- Problems
  - 1.7 maf/year fixed evaporation plus bank storage
  - Missing 850 kaf/yr inflows below Lees Ferry
  - Reservoirs can and do recover, even with declining flows
- Critical Issues Regardless of these Results
  - System is close to Demand = Supply which has big implications
  - Normal climate variability can push us over the edge without climate change

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Four Responses to BP2008

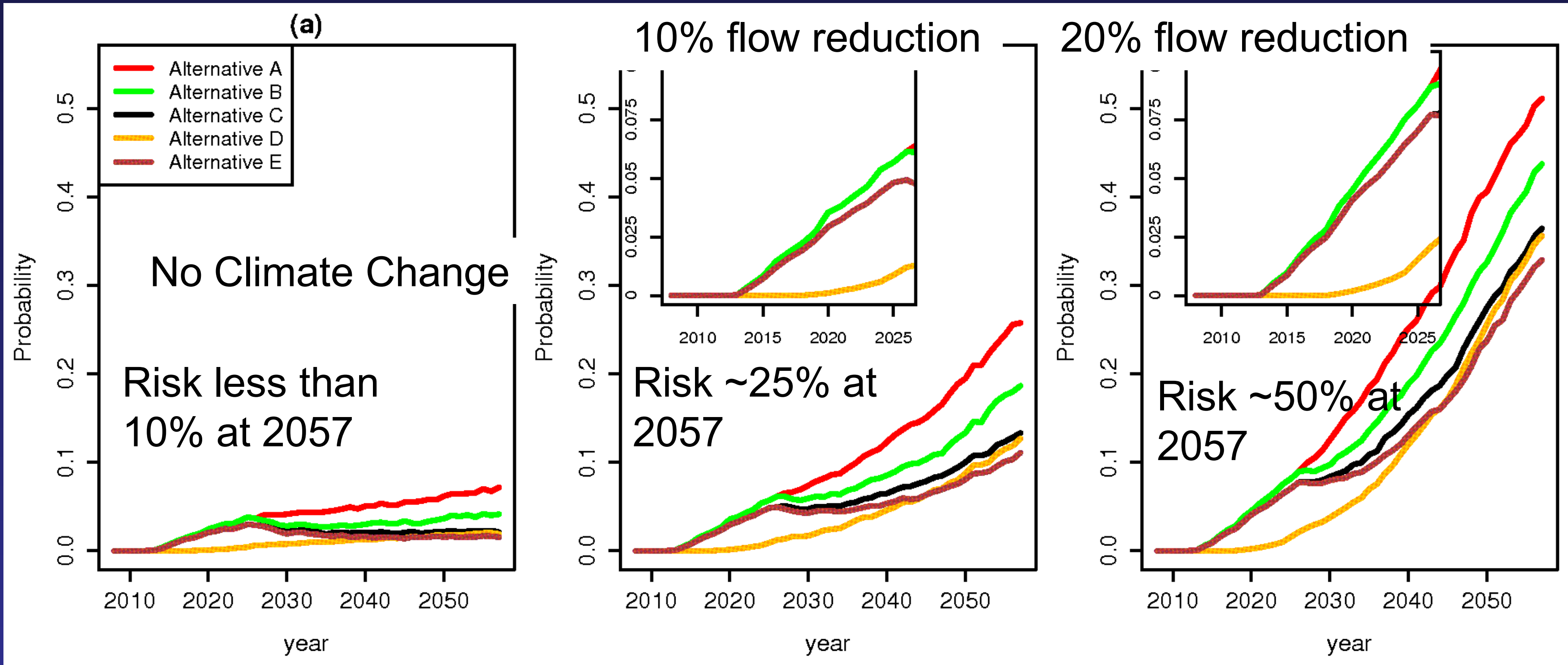
- 1. "Comment on Paper"
  - Joe Barsugli, Ken Nowak, Balaji Rajagopalan
- 2. Reply to Comment by BP
- 3. Barnett and Pierce 2009, PNAS
- 4. "Water Supply Risk on the Colorado River: Can Management Mitigate?"
  - Balaji Rajagopalan, Ken Nowak, Jim Prairie, Ben Harding, Joe Barsugli, Andrea Ray, Brad Udall

A New Lake Mead Dry Paper

Why the difference between -10% and -20% Runoff Matters

- Balaji Rajagopalan, Ken Nowak, Jim Prairie, Ben Harding, Joe Barsugli, Andrea Ray, Brad Udall
- Study Combines Historic Flows, Tree-rings and Climate Change
  - 10,000 year flow sequences created using combined dry/wet spells from tree-rings and resampling historic record
  - 3 Sequences: no change, -10%, -20% runoff
- Simple Operations Model: 60 maf Reservoirs, EIS Shortage Rules, CRB Deliveries at 13.5 maf, Active Evaporation calculations, No infiltration, U. Basin Demand Growth over Time
- 6 Policy Options to investigate changing risk – Alts A-F
  - A Mix of Current EIS, Increased Shortage Amounts, More Aggressive Reservoir Thresholds for Shortages, and Various UB Demands starting points and growth rates
- At first glance different from Barnett and Pierce…but upon more investigation, results are similar, if assumptions are the same…

Risk of Reservoir Drying 2009 to 2057 – Can Management Mitigate?

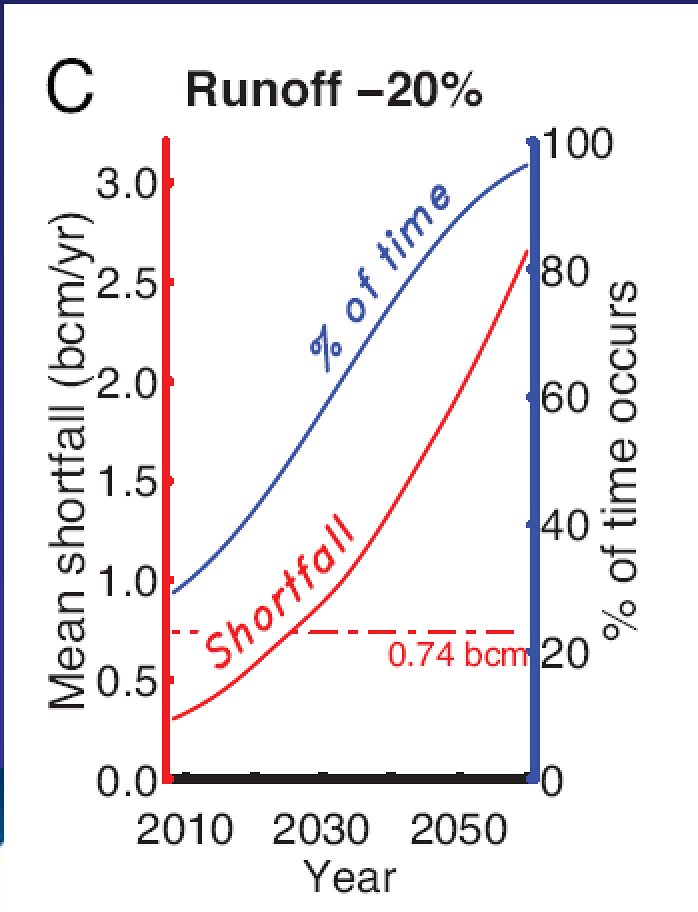


- 5 Future Management Alternatives (colored lines above)
- Near-term risks relatively low
- Management can offer some risk mitigation
- 2057 results for -10% and -20% are unacceptable

(Rajagopalan et al, 2009)

Sustainable Water Deliveries in a Changing Climate – BP 2009

- New Metric for Risk – shortage amounts
- - 10% flow means shortages 58% of time by 2050, -20% 88% of time shortages
- Mean annual shortages are ~10% of total deliveries or 1.5 maf at -10% flow (All of AZ's CAP allocation) by 2050
- With different assumptions mean shortages could by 3.0 maf/year
- Long term sustainable deliveries are 0 to -20% of current amounts



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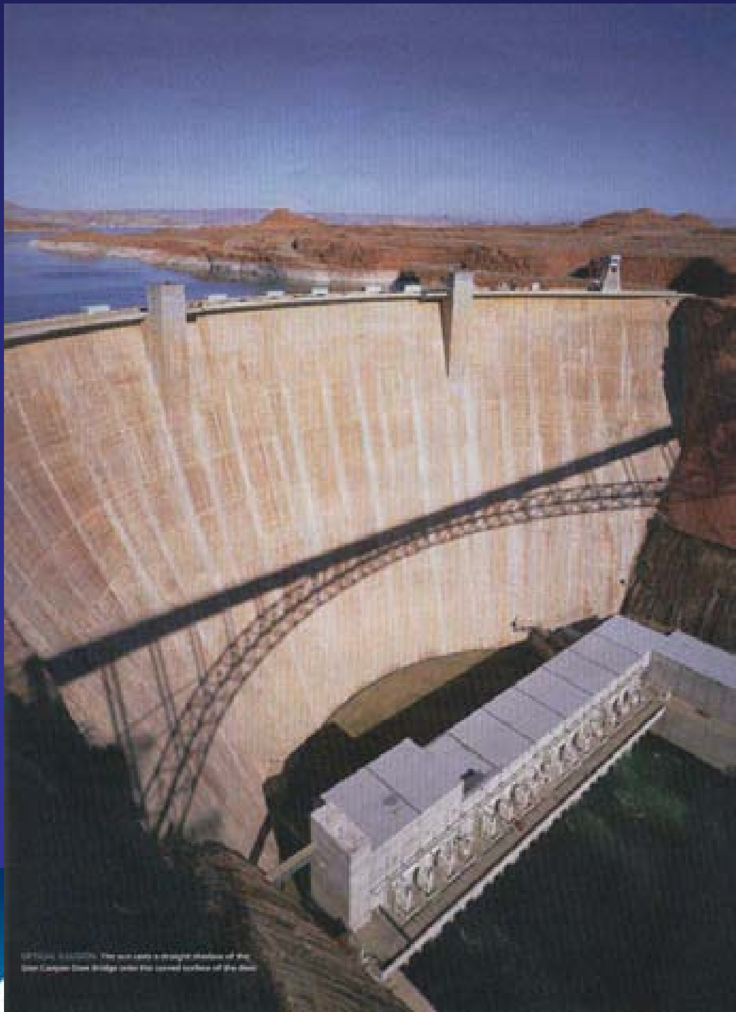
Common to Studies

- On a collision course between supply and demand
- When collision occurs is the real question
- It all depends on starting conditions…
  - If Assume Deficit now, then problems very soon
  - If no deficit now then more time
- There is a broad envelope of risk to consider
  - This is the key lesson for the 21st Century –
  - How do we build resilient systems???



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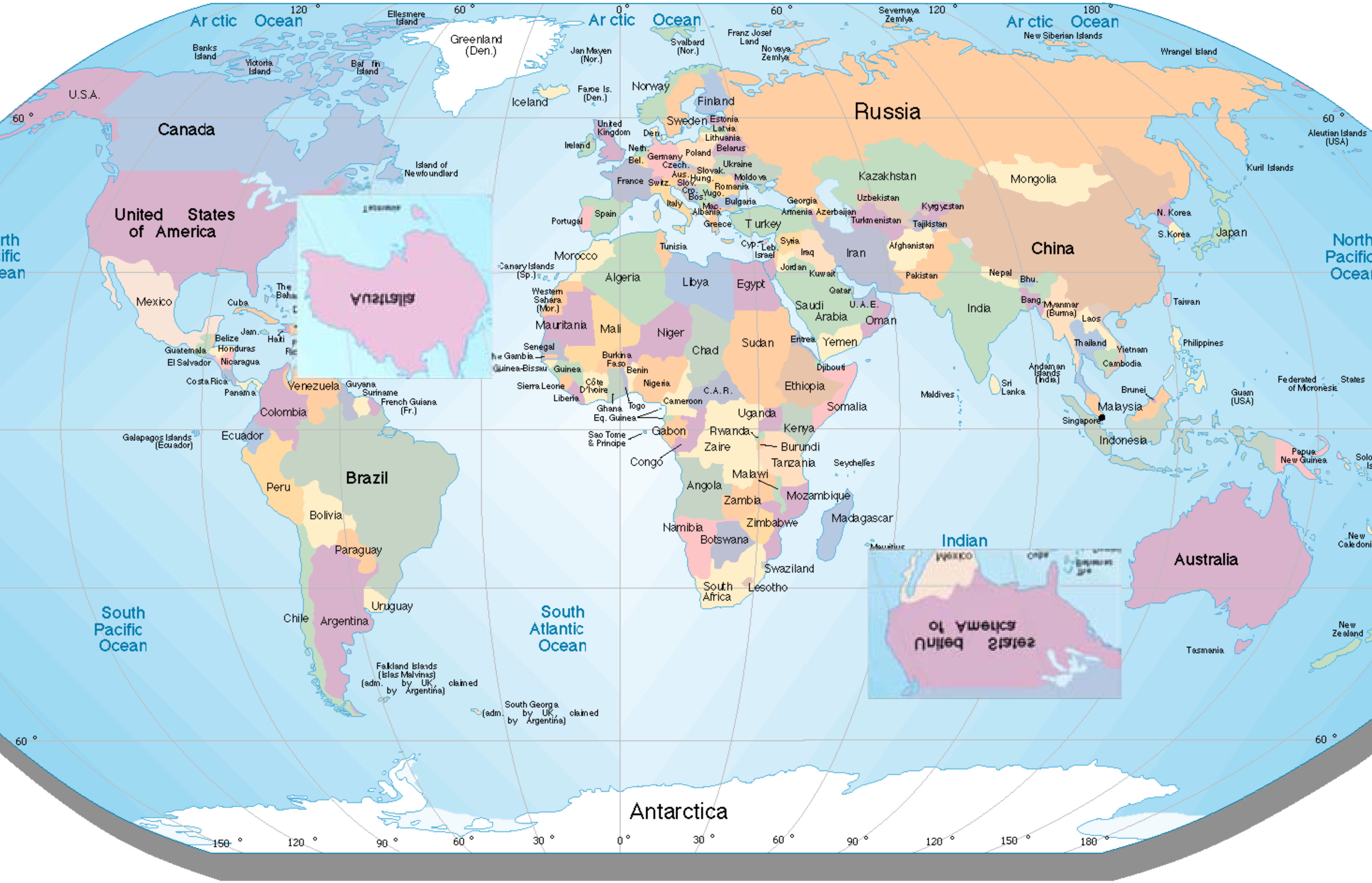
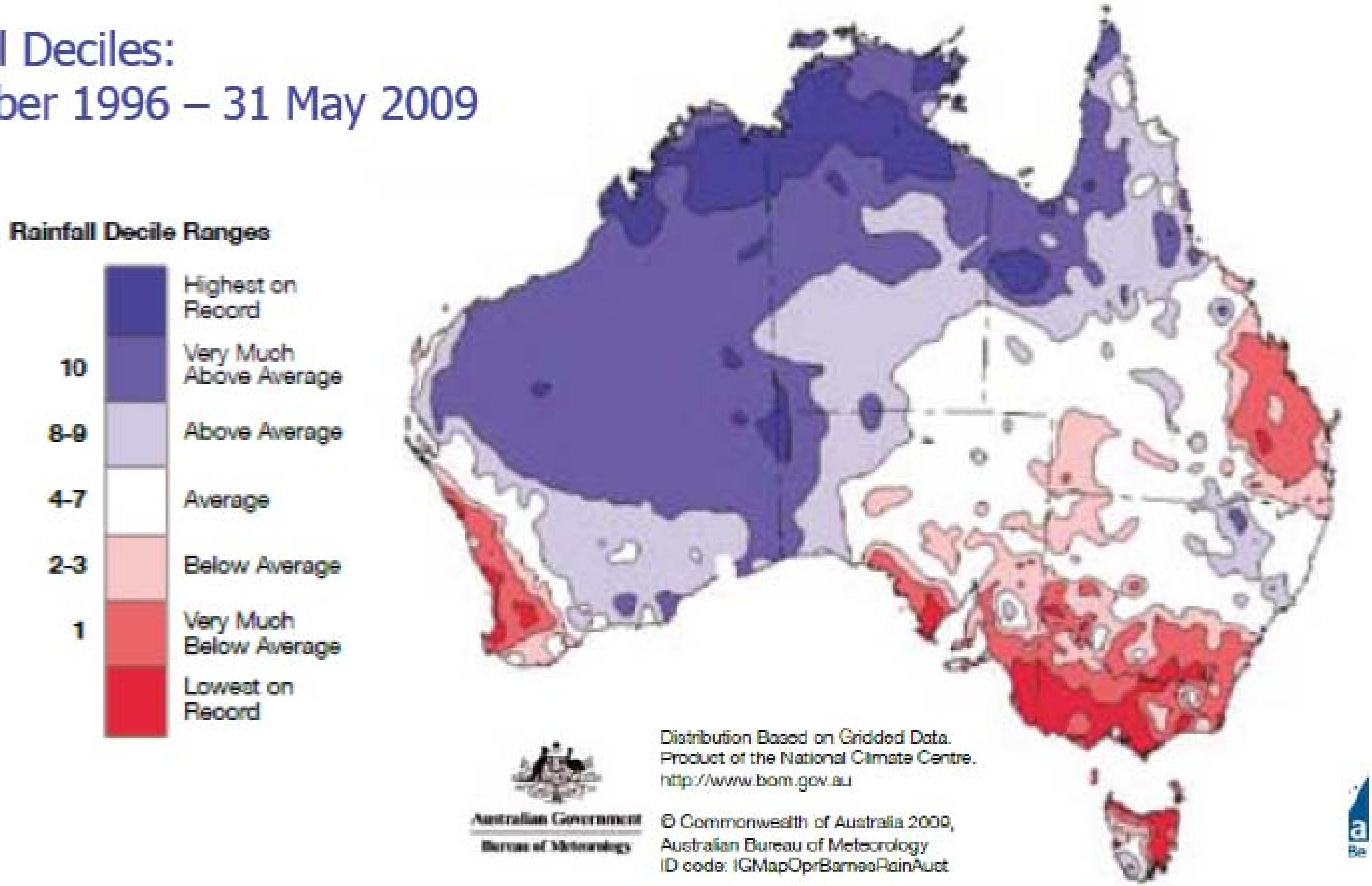


Arctic Ocean
Arctic Ocean
Arctic Ocean
North Pacific Ocean
South Pacific Ocean
South Atlantic Ocean
Indian
Ellesmere Island
Banks Island
Victoria Island
Baffin Island
Greenland (Den.)
Jan Mayen (Nor.)
Svalbard (Nor.)
Franz Josef Land
Novaya Zemlya
Severnaya Zemlya
New Siberian Islands
Wrangel Island
Aleutian Islands (USA)
Kuril Islands
U.S.A.
Canada
Iceland
Faroe Is. (Den.)
Norway
Finland
Sweden
Estonia
Latvia
Lithuania
Belarus
Russia
United Kingdom
Ireland
Den.
Neth.
Bel.
Germany
Poland
Czech.
Slovak.
Ukraine
Aus.
Hung.
Moldova
France
Switz.
Slov.
Romania
Cro.
Yugo.
Bos.
Italy
Mac.
Bulgaria
Albania
Greece
Spain
Portugal
Island of Newfoundland
United States of America
Mexico
Cuba
The Bahamas
Jam.
Haiti
Belize
Guatemala
Honduras
El Salvador
Nicaragua
Costa Rica
Panama
Venezuela
Guyana
Suriname
French Guiana (Fr.)
Colombia
Ecuador
Galapagos Islands (Ecuador)
Peru
Brazil
Bolivia
Paraguay
Uruguay
Chile
Argentina
Falkland Islands (Islas Malvinas) (adm. by UK, claimed by Argentina)
South Georgia (adm. by UK, claimed by Argentina)
Georgia
Armenia
Azerbaijan
Turkey
Kazakhstan
Uzbekistan
Turkmenistan
Kyrgyzstan
Tajikistan
Mongolia
China
N. Korea
S. Korea
Japan
Taiwan
Cyp.
Leb.
Israel
Syria
Iraq
Iran
Afghanistan
Pakistan
Jordan
Kuwait
Qatar
Saudi Arabia
U.A.E.
Oman
Yemen
Nepal
Bhu.
Bang.
India
Myanmar (Burma)
Laos
Thailand
Vietnam
Cambodia
Philippines
Andaman Islands (India)
Sri Lanka
Maldives
Brunei
Malaysia
Singapore
Indonesia
Guam (USA)
Federated States of Micronesia
Papua New Guinea
Morocco
Tunisia
Canary Islands (Sp.)
Algeria
Libya
Egypt
Western Sahara (Mor.)
Mauritania
Mali
Niger
Chad
Sudan
Eritrea
Senegal
The Gambia
Guinea-Bissau
Guinea
Burkina Faso
Benin
Sierra Leone
Côte D'Ivoire
Liberia
Nigeria
Ghana
Togo
Cameroon
Eq. Guinea
C.A.R.
Ethiopia
Djibouti
Somalia
Sao Tome & Principe
Gabon
Congo
Uganda
Kenya
Rwanda
Burundi
Zaire
Tanzania
Seychelles
Angola
Malawi
Zambia
Mozambique
Madagascar
Namibia
Zimbabwe
Botswana
Swaziland
South Africa
Lesotho
Mauritius
Australia
New Caledonia
New Zealand
Tasmania
Antarctica

Rainfall During Last 12 Years

Rainfall Deciles:
1 October 1996 – 31 May 2009



Australian Temps 2001-2005

A protracted dry and exceptionally hot period affecting NSW and most of eastern Australia, 2001-2006.

Clinton Rakich and Perry Wiles
NSW Climate Services Centre, Bureau of Meteorology

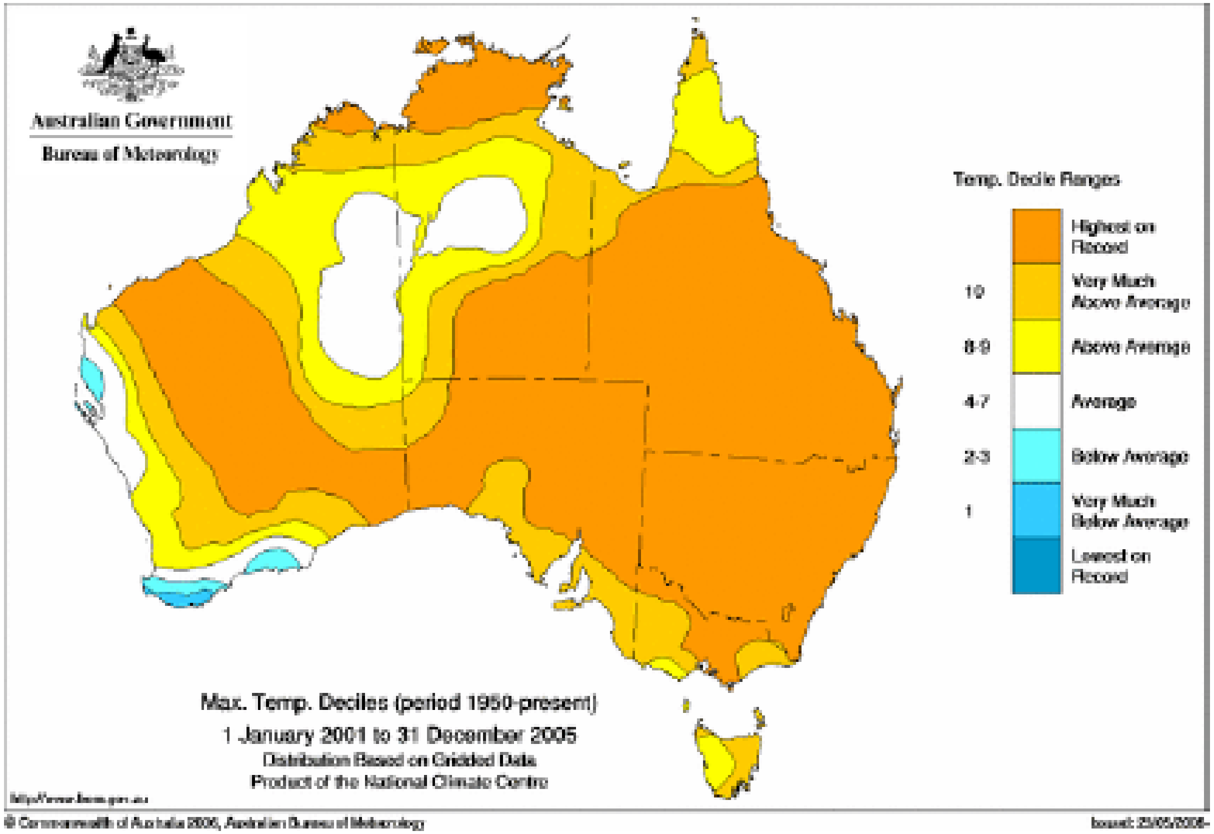
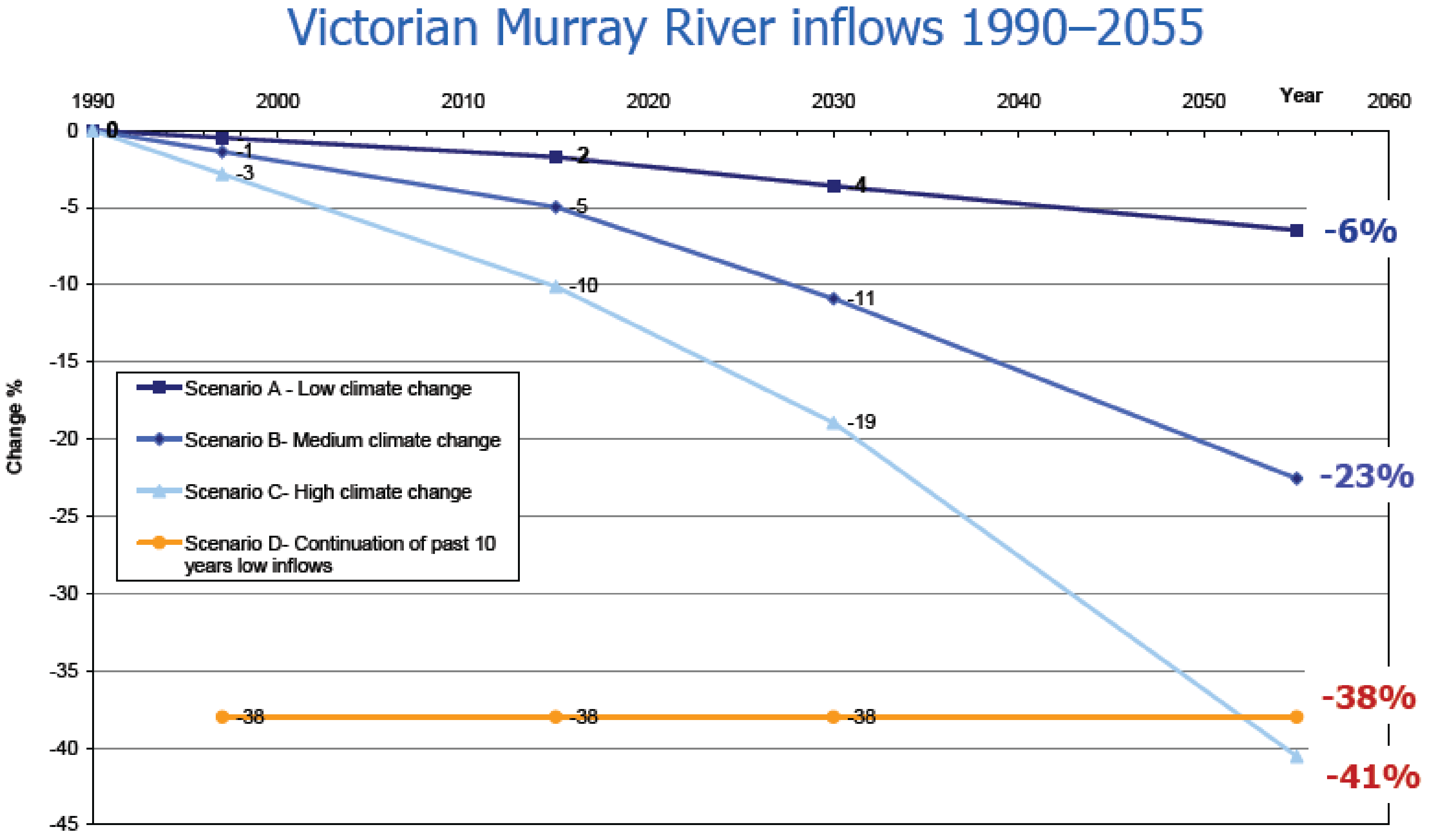


Figure 3. Australian maximum temperature deciles for the period 1 January 2001 to 31 December 2005.

Models May Not Set Lower Bound on Future Runoff



Outline

- Climate Change Studies
- Recent Climate
- Systemic Allocation Problems
- Science Issues
- Systemic Reservoir Risk
- Lessons from Australia
- Closing Thoughts

Who Gets Shorted?

- Very Different Upper Basin and Lower Basin Implications
  - Upper Basin on the hook at first glance due to 75 maf/10 year compact delivery requirement
  - But Upper Basin is not using full supply – using from 3.7 to 4.5 maf/year now vs. maybe 6 maf/year supply
  - Lower Basin is using that excess water now to meet demands, including system losses, in excess of its 7.5 compact maf allocation
  - Lower Basin (via Reclamation Contracts) has contracts for well in excess of 7.5 maf, and no provision for payment of losses within allocation. (e.g. assumption ‘extra’ UB water would pay for losses)
  - So, Both UB and LB are threatened
    - LB in the long run due to either climate change or UB growth will have to live within its compact allocation by reducing demand ~1.4 maf
    - This primarily means Arizona
    - UB may, or may not be able to grow its use depending on the intersection of the delivery requirement with available water in the future
  - No study has addressed UB/LB issues yet...

Lower Basin Ramifications

- Due to 1968 Act, Arizona's 1.6 maf CAP deliveries first to receive shortages
  - Price for CA support of the funding
- Current Rules short AZ and MX up to 600 kaf (500 AZ, 100 MX)
  - AZ agreed to rules in part because little current pain
  - But at 1.6maf total shortage, AZ would struggle

Upper Basin Musings

- UB is using from 3.7 to 4.5 maf/year
- Compact Delivery Requirement (IIId) was really an afterthought to compact negotiations
  - The original goal of the CRC was equal UB/LB use
- While UB might tolerate no additional growth in use, they would not tolerate climate change related cutbacks below current use which would occur somewhere around 12 maf
- Colorado is contemplating rules for new projects
  - Avoid short term private sector gain for long-term public pain
- CRWAS Study is causing some serious re-thinking about water management

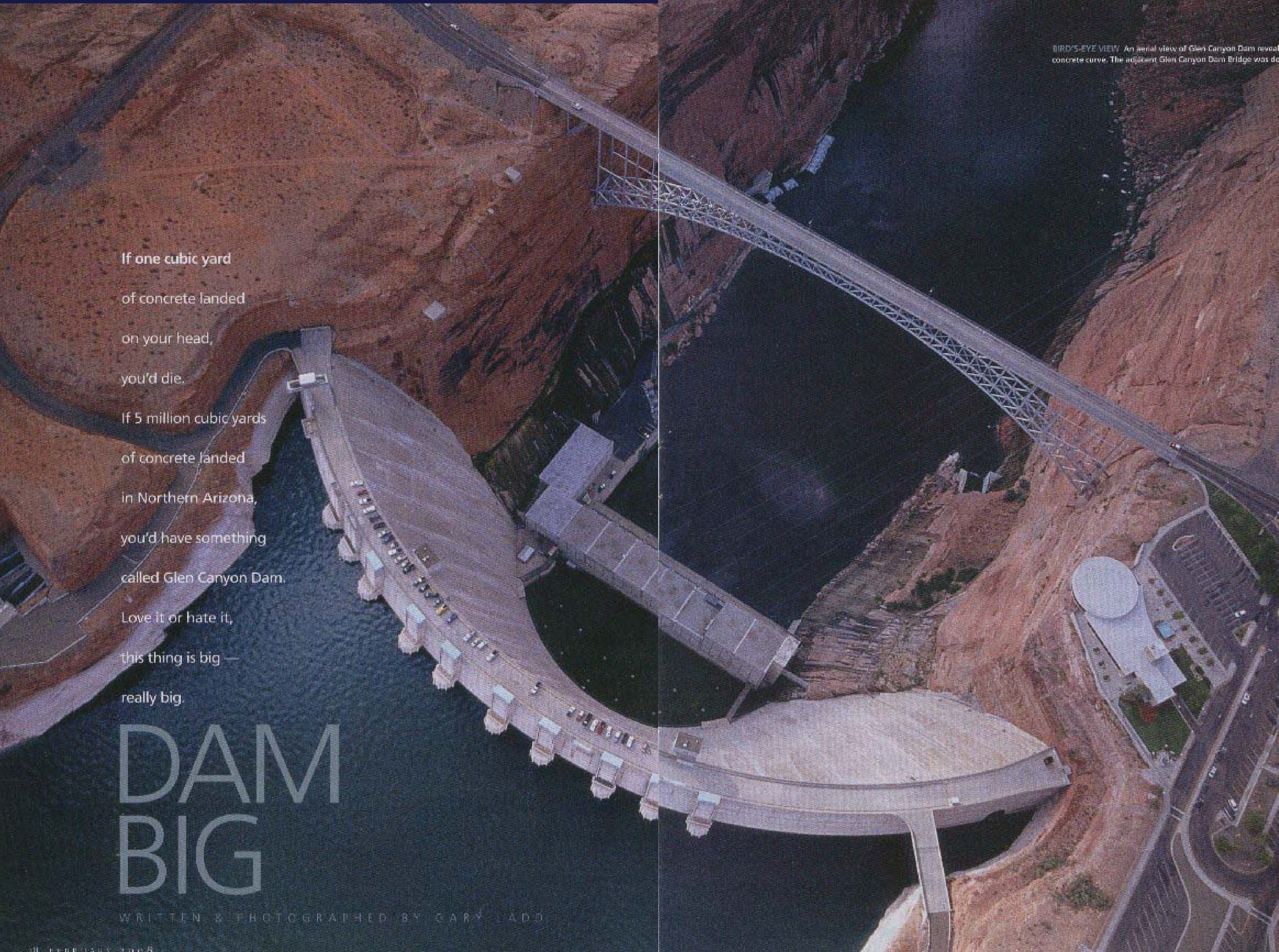
Take Home Points

- Short-term Risk to the System is very dependent on current low reservoirs
  - Low Reservoir Levels heighten risk substantially regardless of future flows
  - ‘Initial net Inflow’ is one key metric to overall risk
- There is an envelope of future risk that is highly dependent on
  - Changes in Inflows
  - Demand Growth
- Range of Reservoir Drying at 2026 is 5% to 10%, at 2058 could be as high as 50%
- Either Demand Growth or Inflow Reductions will cause Lower Basin reductions over time – a certainty
- Inflow Reductions will reduce available water for Upper Basin Growth
- Now is the time to begin discussions about how we should operate these systems during extended droughts, not when Mead hits 1025.

DAM BIG

WRITTEN & PHOTOGRAPHED BY GARY LADD

If one cubic yard
of concrete landed
on your head,
you'd die.
If 5 million cubic yards
of concrete landed
in Northern Arizona,
you'd have something
called Glen Canyon Dam.
Love it or hate it,
this thing is big —
really big.



BIRD'S-EYE VIEW An aerial view of Glen Canyon Dam reveal
concrete curve. The adjacent Glen Canyon Dam Bridge was do