

Is a Perfect Storm Looming for Colorado River Storage?

Balaji Rajagopalan, Kenneth Nowak

University of Colorado, Boulder, CO

James Prairie

USBR

Ben Harding

Amec, Boulder

Marty Hoerling, Joseph Barsugli, Bradley

Udall and Andrea Reay

ESRL/NOAA



ESRL Theme on Climate and Water Systems

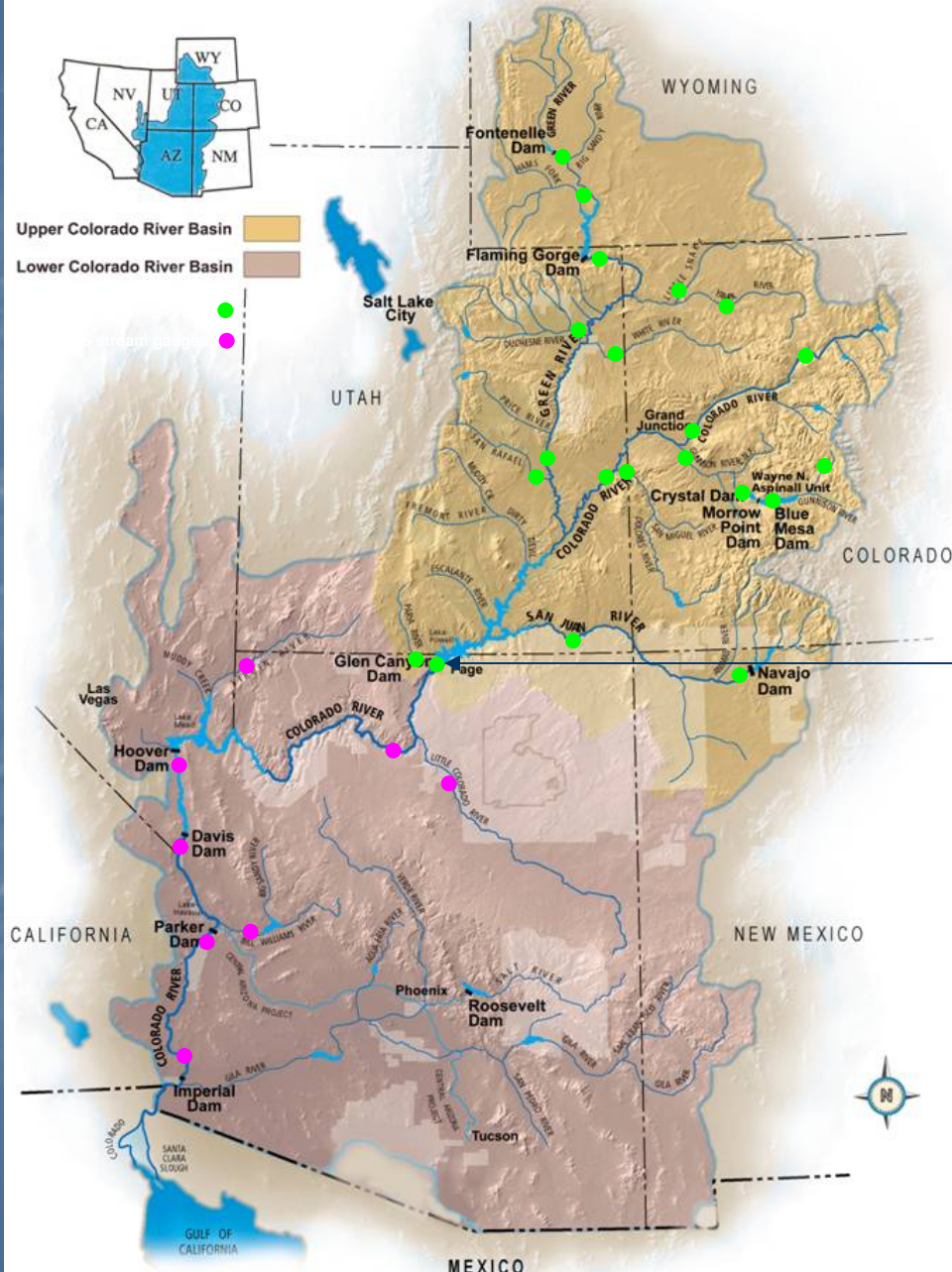
October 1-2 2008

Boulder, CO

Colorado River Basin



Upper Colorado River Basin 
Lower Colorado River Basin 

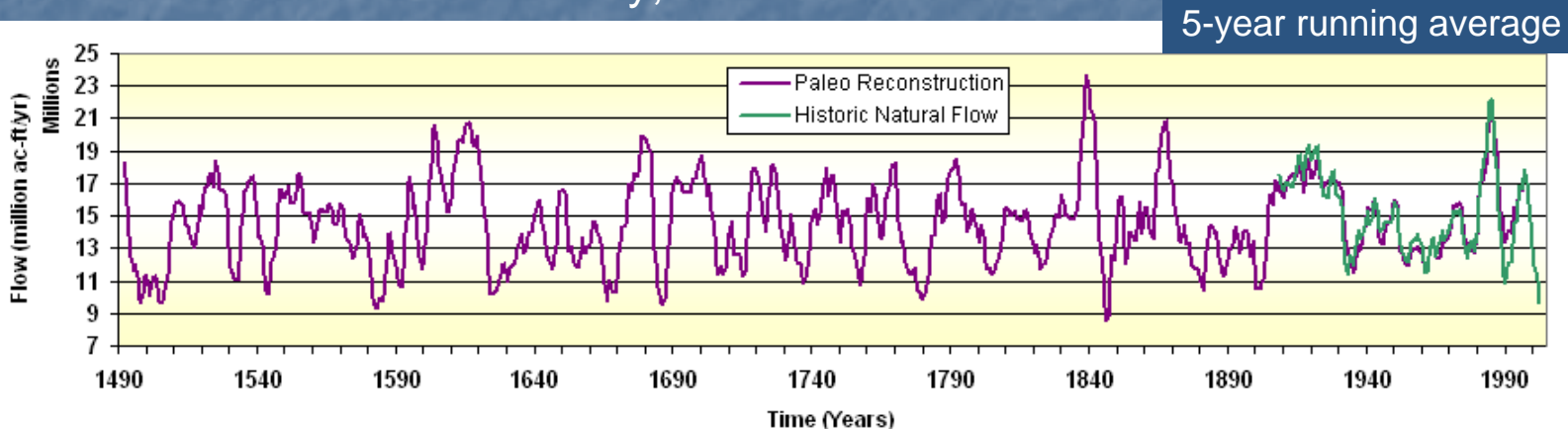


Lees Ferry

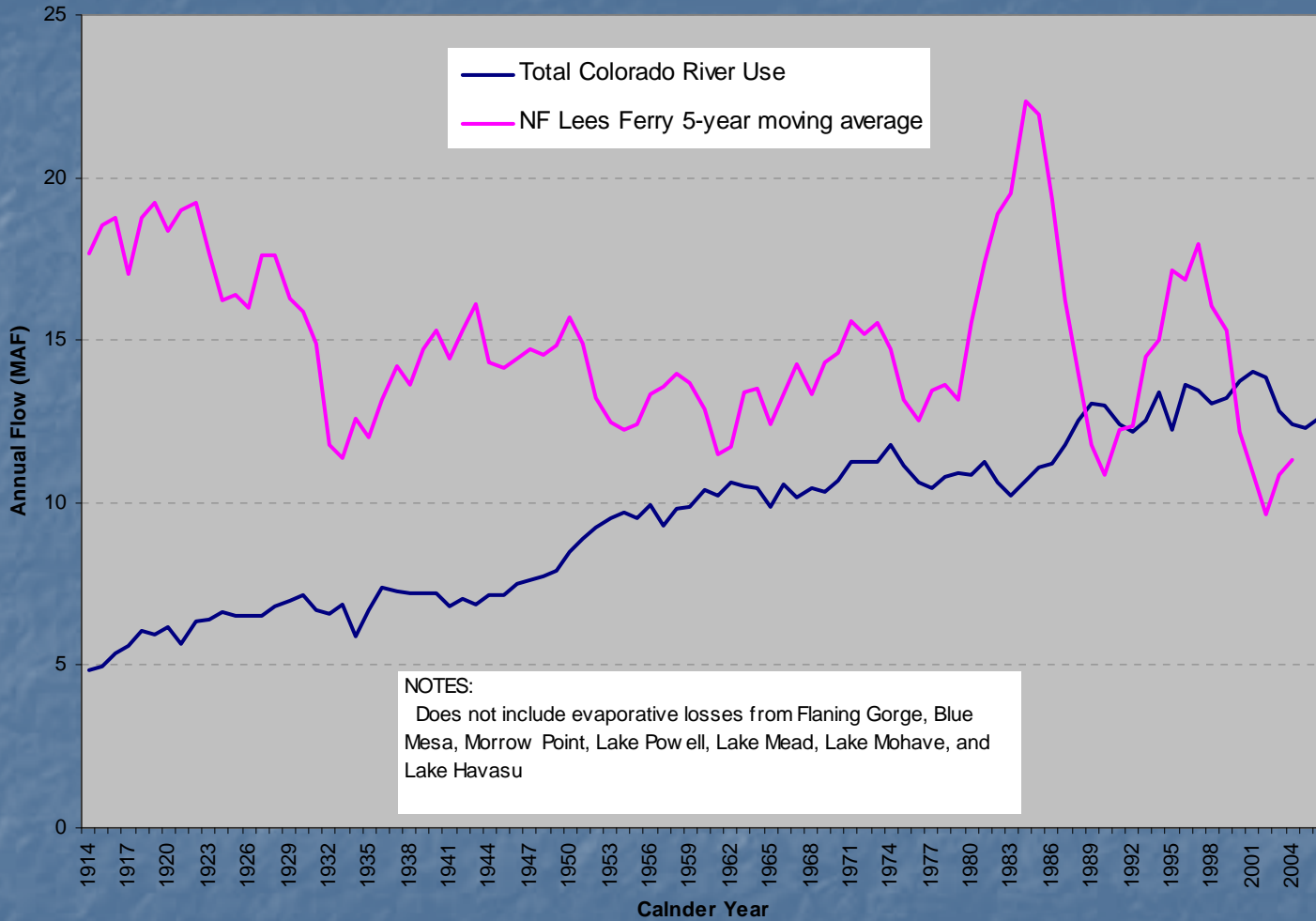
Recent conditions in the Colorado River Basin

- Below normal flows into Lake Powell 2000-2004
 - 62%, 59%, 25%, 51%, 51%, respectively
 - 2002 at 25% lowest inflow recorded since completion of Glen Canyon Dam
- Some relief in 2005
 - 105% of normal inflows
- Not in 2006 !
 - 73% of normal inflows
- 2007 at 68% of Normal inflows
- 2008 at 111% of Normal inflows

Colorado River at Lees Ferry, AZ



Colorado Water System Demand – Supply *(stressed in recent decades)*



NOTES:
Does not include evaporative losses from Flaming Gorge, Blue Mesa, Morrow Point, Lake Powell, Lake Mead, Lake Mohave, and Lake Havasu

Past Flow Summary

- Paleo reconstructions indicate
 - 20th century one of the most wettest
 - Long dry spells are not uncommon
 - 20-25% changes in the mean flow
 - Significant interannual/interdecadal variability
 - Rich variety of wet/dry spell sequences
- All the reconstructions agree greatly on the 'state' (wet or dry) information
- How will the future differ?
- More important, *What is the water supply risk under changing climate?*

IPCC 2007 AR4 Projections

- Wet get wetter and dry get drier...
- Southwest Likely to get drier

Projected Patterns of Precipitation Changes

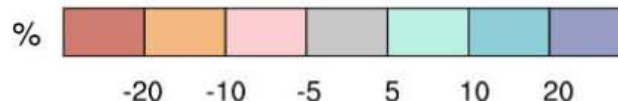
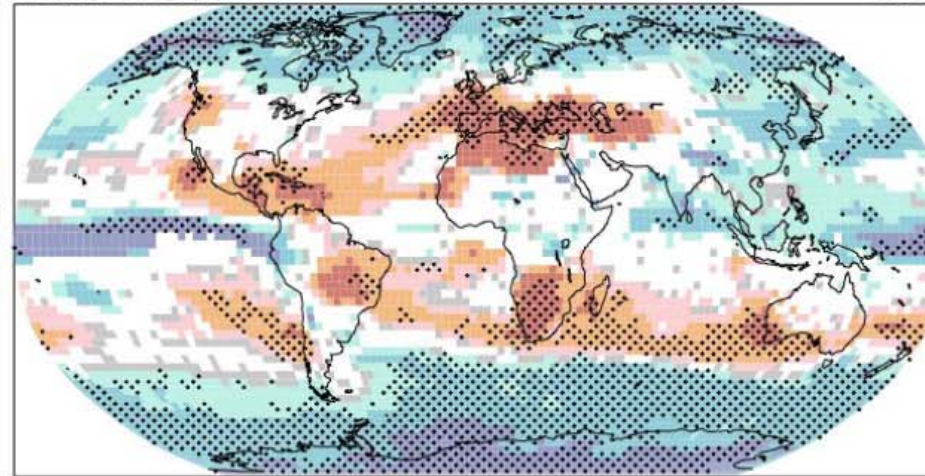
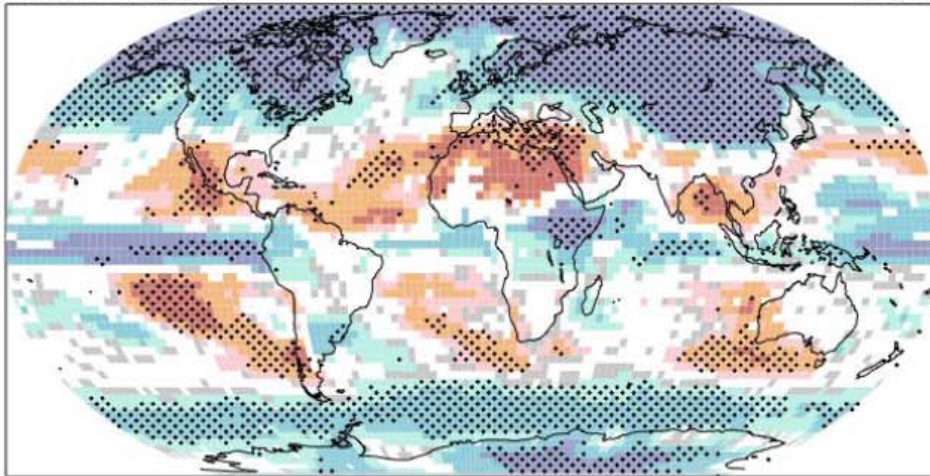
multi-model

A1B

DJF multi-model

A1B

JJA



IPCC 2007 Southwest North America Regional Findings

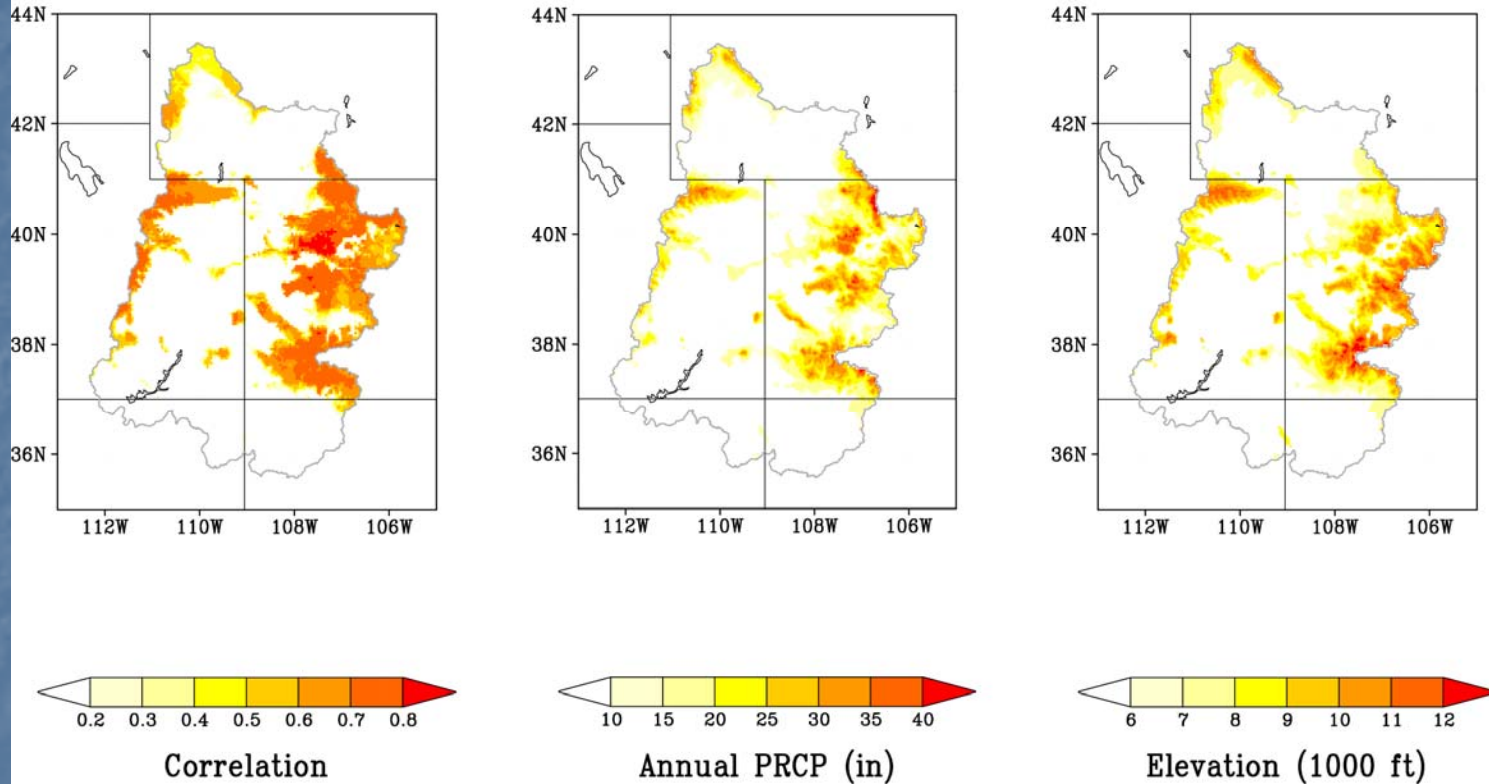
- Annual mean warming likely to exceed global mean
- Western NA warming between 2C and 7C at 2100
- In Southwest greatest warming in summer
- Precipitation likely to decrease in southwest
- Snow season length and depth very likely to decrease
- Less agreement on the upper basin climate – important for water generation in the basin

Models Precip and Temp Biases

- Models show consistent errors (biases)
- Western North America is too cold and too wet
- Weather models show biases, too
- Can be corrected

REGION	SEASON	temperature BIAS					% precipitation BIAS				
		MIN	25	50	75	MAX	MIN	25	50	75	MAX
North America											
ALA	DJF	-9.8	-2.4	-0.8	1.9	8.2	3	33	51	89	179
	MAM	-7.4	-1.4	0.2	1.0	3.8	25	58	86	108	197
	JJA	-4.9	-1.6	-0.4	0.4	3.1	8	18	40	54	113
	SON	-5.7	-1.6	-0.6	1.4	4.8	14	33	52	65	113
	ANN	-5.2	-1.8	-0.4	0.6	3.7	14	41	53	59	106
CGI	DJF	-12.5	-4.5	-2.4	0.5	4.8	-14	5	14	29	98
	MAM	-6.3	-2.6	-1.1	1.0	5.5	-4	18	29	45	97
	JJA	-4.4	-2.7	-0.9	0.9	4.7	4	13	16	30	47
	SON	-7.5	-3.8	-1.9	-0.4	6.6	0	10	15	21	72
	ANN	-7.	-3.2	-2.0	0.3	5.3	0	12	21	29	69
WNA	DJF	-4.7	-2.7	-0.9	-0.5	0.9	32	66	93	103	192
	MAM	-4.6	-2.9	-2.0	-1.0	0.1	37	62	71	93	158
	JJA	-2.5	-1.3	-0.4	0.9	2.2	-9	22	28	45	98
	SON	-4.4	-1.8	-1.2	-0.3	1.1	10	45	61	75	110
	ANN	-3.8	-1.8	-1.3	0.5	0.7	29	53	65	74	130
CNA	DJF	-4.0	-2.4	-0.8	0.8	3.0	-37	-6	7	20	84
	MAM	-4.1	-1.3	-1.1	0.6	2.8	-17	-3	8	25	41
	JJA	-1.8	-0.3	0.4	1.6	3.5	-34	21	-12	15	39
	SON	-3.8	-1.3	-0.6	0.4	2.3	-37	-24	-16	0	24
	ANN	-3.2	-1.0	-0.5	0.6	2.6	-18	-8	2	5	21
ENA	DJF	-4.6	-2.8	-1.6	-0.6	3.4	-18	-2	17	25	55
	MAM	-4.5	-2.1	-1.3	-0.7	2.4	-5	13	21	27	38
	JJA	-3.7	-1.4	-0.9	-0.5	2.3	-10	-2	13	18	45
	SON	-4.2	-2.0	-1.2	-0.6	2.0	-30	-17	-4	6	25
	ANN	-4.2	-2.1	-1.2	-0.6	2.2	-7	1	9	17	27

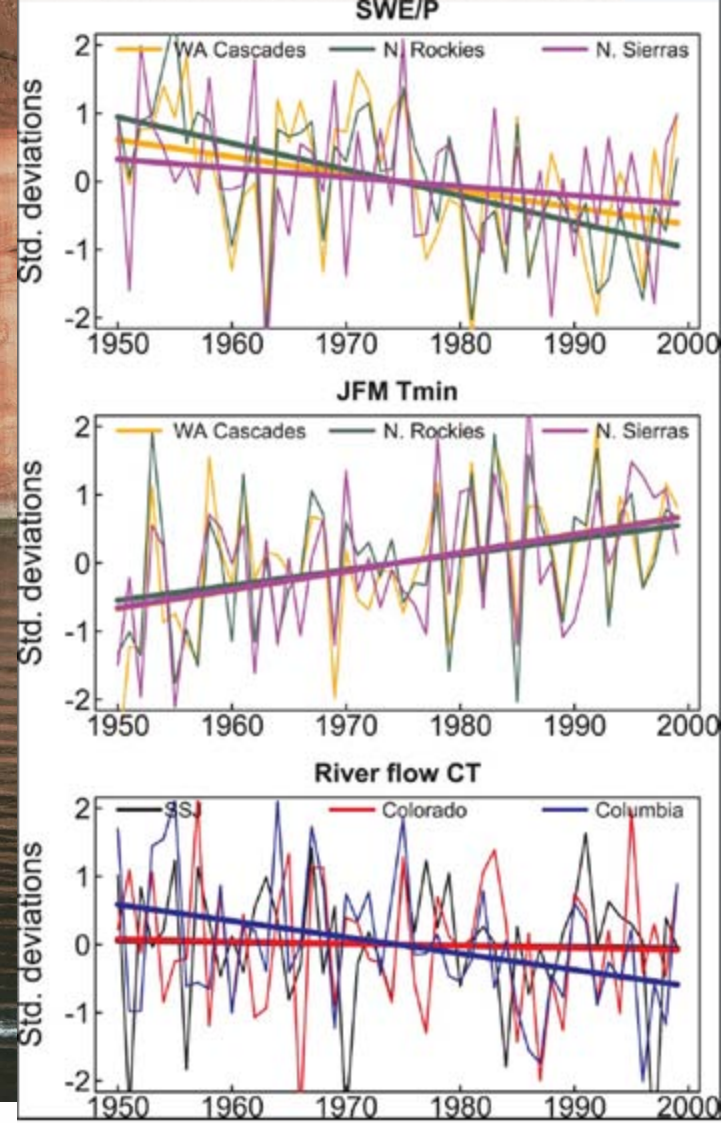
Origins for Colorado River Water Supply



- Almost all the water is generated from a small region of the basin at very high altitude
- GCM projections for the high altitude regions are uncertain



Lake Powell's "bathtub ring"—a residue from water immersion—records how far the water level has fallen in the giant reservoir. Inflow from the Colorado River has been below average every



Scienceexpress

Science, February 1, 2008

Human-Induced Changes in the Hydrology of the Western United States

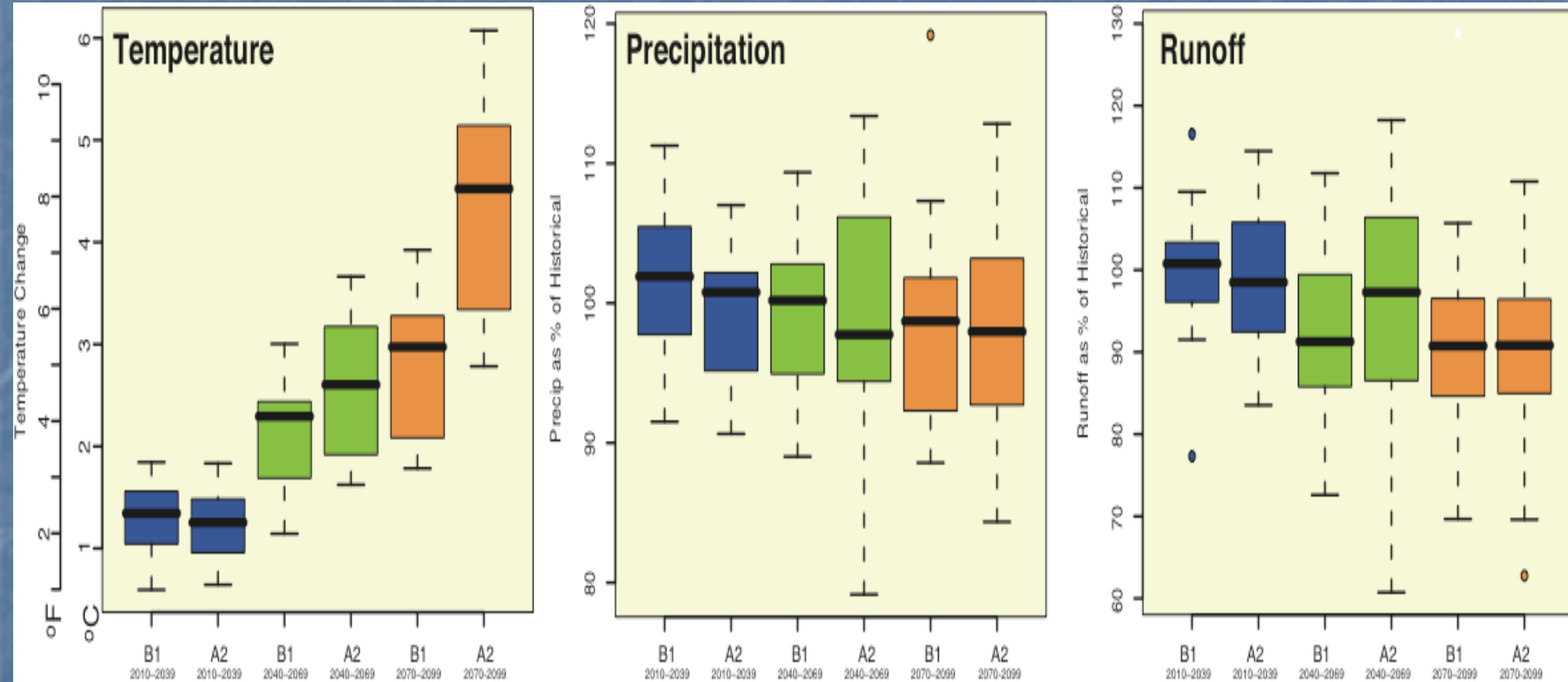
Tim P. Barnett,^{1*} David W. Pierce,¹ Hugo G. Hidalgo,¹ Celine Bonfils,² Benjamin D. Santer,² Tapash Das,¹ Govindasamy Bala,² Andrew W. Wood,³ Toru Nozawa,⁴ Arthur A. Mirin,² Daniel R. Cayan,¹ Michael D. Dettinger¹

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
 - 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)
 - Barnett and Pierce, 2008, "When will Lake Mead Go Dry?"
- National Research Council Colorado River Report, 2007

Study	Climate Change Technique (Scenario/GCM)	Flow Generation Technique (Regression equation/Hydrologic model)	Runoff Results	Operations Model Used [results?]	Notes
Stockton and Boggess, 1979	Scenario	Regression: Langbein's 1949 US Historical Runoff- Temperature- Precipitation Relationships	+2C and -10% Precip = ~ -33% reduction in Lees Ferry Flow		Results are for the warmer/drier and warmer/wetter scenarios.
Revelle and Waggoner, 1983	Scenario	Regression on Upper Basin Historical Temperature and Precipitation	+2C and -10% Precip = -40% reduction in Lee Ferry Flow		+2C only = -29% runoff,
					-10% Precip only = -11% runoff.
Nash and Gleick, 1991 and 1993	Scenario and GCM	NWSRFS Hydrology model runoff derived from 5 temperature & precipitation Scenarios and 3 GCMs using doubled CO2 equilibrium runs.	+2C and -10% Precip = ~ -20% reduction in Lee Ferry Flow	Used USBR CRSS Model for operations impacts.	Many runoff results from different scenarios and sub-basins ranging from decreases of 33% to increases of 19%.
Christensen et al., 2004	GCM	UW VIC Hydrology model runoff derived from temperature & precipitation from NCAR GCM using Business as Usual Emissions.	+2C and -3% Precip at 2100 = -17% reduction in total basin runoff	Created and used operations model, CRMM.	Used single GCM known not to be very temperature sensitive to CO2 increases.
Hoerling and Eischeid, 2006	GCM	Regression on PDSI developed from 18 AR4 GCMs and 42 runs using Business as Usual Emissions.	+2.8C and ~0% Precip at 2035-2060 = -45% reduction in Lee Fee Flow		
Christensen and Lettenmaier, 2006	GCM	UW VIC Hydrology Model runoff using temperature & precipitation from 11 AR4 GCMs with 2 emissions scenarios.	+4.4C and -2% Precip at 2070-2099 = -11% reduction in total basin runoff	Also used CRMM operations model.	Other results available, increased winter precipitation buffers reduction in runoff.

Climate Projections from 11 GCMS for Upper Colorado Christensen and Lettenmaier (2007)

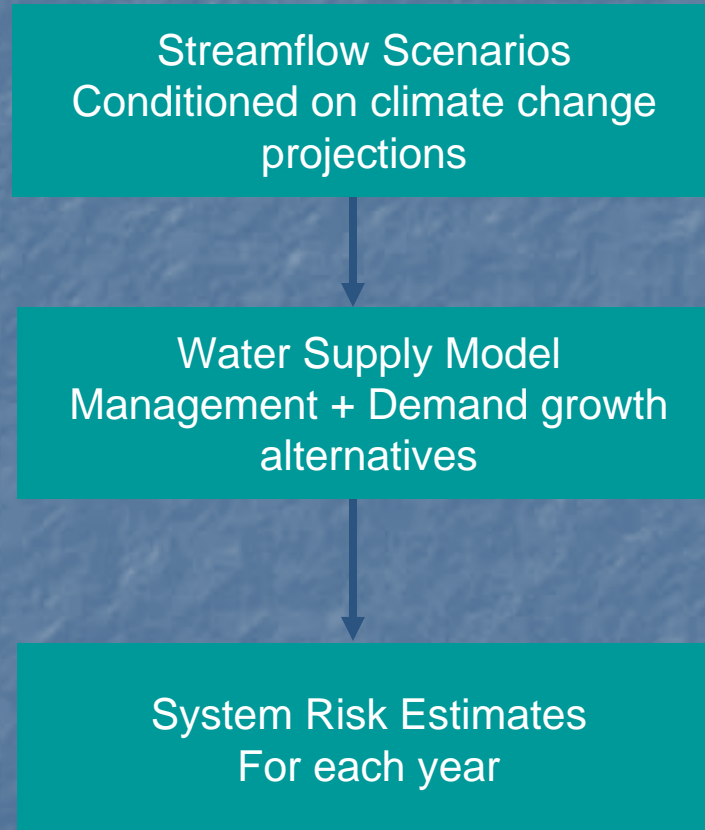


Recent Studies (Seager et al., 2007; Milly et al., 2007 etc. suggest a reduction of 10 ~ 25% in the average annual flow)

Future Flow Summary

- Future projections of Climate/Hydrology in the basin based on current knowledge suggest
 - Increase in temperature with less uncertainty
 - Decrease in streamflow with large uncertainty
 - Uncertain about the summer rainfall (which forms a reasonable amount of flow)
 - Unreliable on the sequence of wet/dry (which is key for system risk/reliability)
- The best information that can be used is the projected mean flow

Water Supply System Risk Estimation



Need for Combination

(Paleo, Observational and Climate Change projection)

- Recent *Dry Spell* not unusual, based on Paleo reconstructions
- Colorado River System has enormous storage of approx 60MAF ~ 4 times the average annual flow - consequently,
 - wet and dry sequences are *crucial* for system risk/reliability assessment
- Streamflow generation tool that can generate flow scenarios in the basin that are *realistic* in
 - wet and dry spell sequences
 - Magnitude
- Paleo reconstructions are
 - Good at providing 'state' (wet or dry) information
 - Poor with the magnitude information
- Observations are reliable with the state and magnitude
 - Climate change projections have
 - Uncertain sequence and magnitude information
 - Reasonable projections of the mean flow
- *Need for combining all the available information*

Observed Annual average flow (15MAF) is used to define wet/dry state.

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Streamflow Generation Modification to Prairie et al. (2008, WRR)

Nonhomogeneous Markov Chain
Model on the observed & Paleo
data

Generate system state
(S_t)

Generate flow conditionally
(K-NN resampling of historical flow)

$$f(x_t | S_t, S_{t-1}, x_{t-1})$$

Intervening flow of the
Resampled year is
Added to this Lees Ferry
Flow

10000 Simulations
Each 50-year long
2008-2057

Superimpose Climate Change
trend (10% and 20%)

Water Balance Model

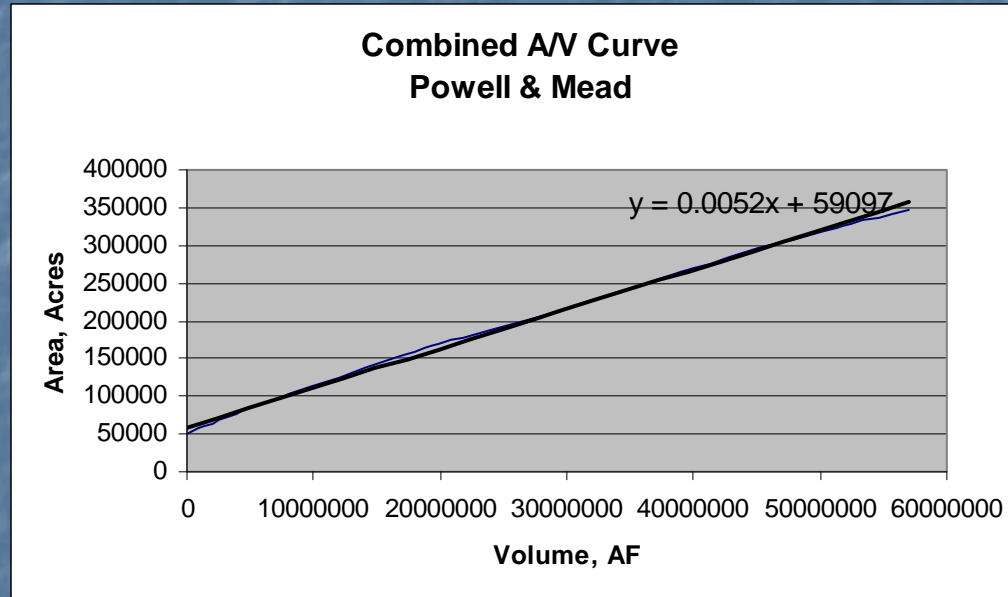
(Modification of Barnett and Pierce, 2008)

Storage in any year is computed as:

$$\text{Storage} = \text{Previous Storage} + \text{Inflow} - \text{ET} - \text{Demand}$$

- Upper and Lower Colorado Basin demand = 13.5 MAF/yr
- Lakes Powell and Mead are modeled as one 50 MAF reservoir (active storage)
- Initial storage of 25 MAF (i.e., current reservoir content)
- Inflow values are natural flows at Lee's Ferry, AZ + Intervening flows between Powell and Mead and below Mead
- ET computed using Lake Area – Lake volume relationship and an average ET coefficient of 0.436

Combined Area-volume Relationship ET Calculation



ET coefficients/month
(Max and Min)

0.5 and 0.16 at Powell

0.85 and 0.33 at Mead

Average ET coefficient : 0.436

$ET = Area * Average\ coefficient * 12$

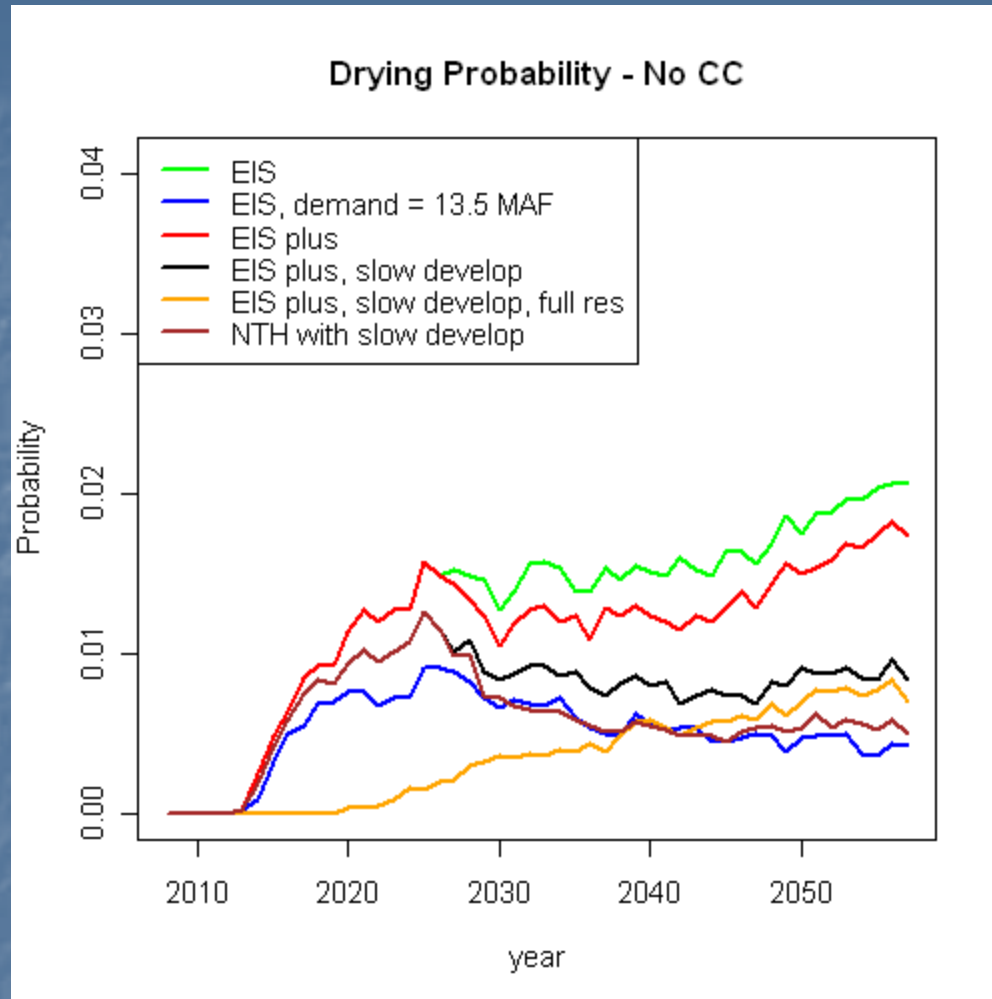
Management and Demand Growth Combinations

1. The interim EIS operational policies employed with demand growing based on the upper basin depletion schedule.
2. 1. with the demand fixed at the 2008 level.
3. 1. with larger delivery shortages post 2026 (EIS Plus).
4. 3. with a 50% reduced upper basin depletion schedule.
5. 4. with full initial storage.
6. 4. with post 2026 policy that establishes new shortage action thresholds and volumes.
7. 6. with demand fixed at the 2008 level.

All the reservoir operation policies take effect from 2026

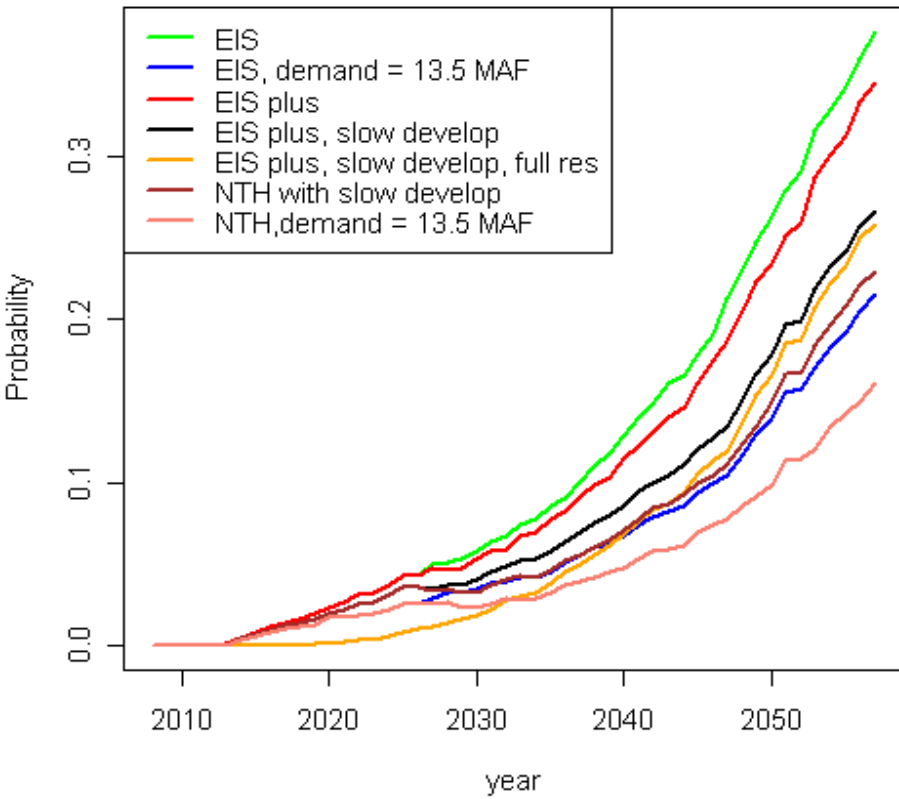
INTERIM EIS		INTERIM PLUS		NEW THRESHOLD	
Res. Storage (%)	Shortage (kaf)	Res. Storage (%)	Shortage (% of current demand)	Res. Storage (%)	Shortage (% of current demand)
36	333	36	5	50	5
30	417	30	6	40	6
23	500	23	7	30	7
				20	8

Natural Climate Variability

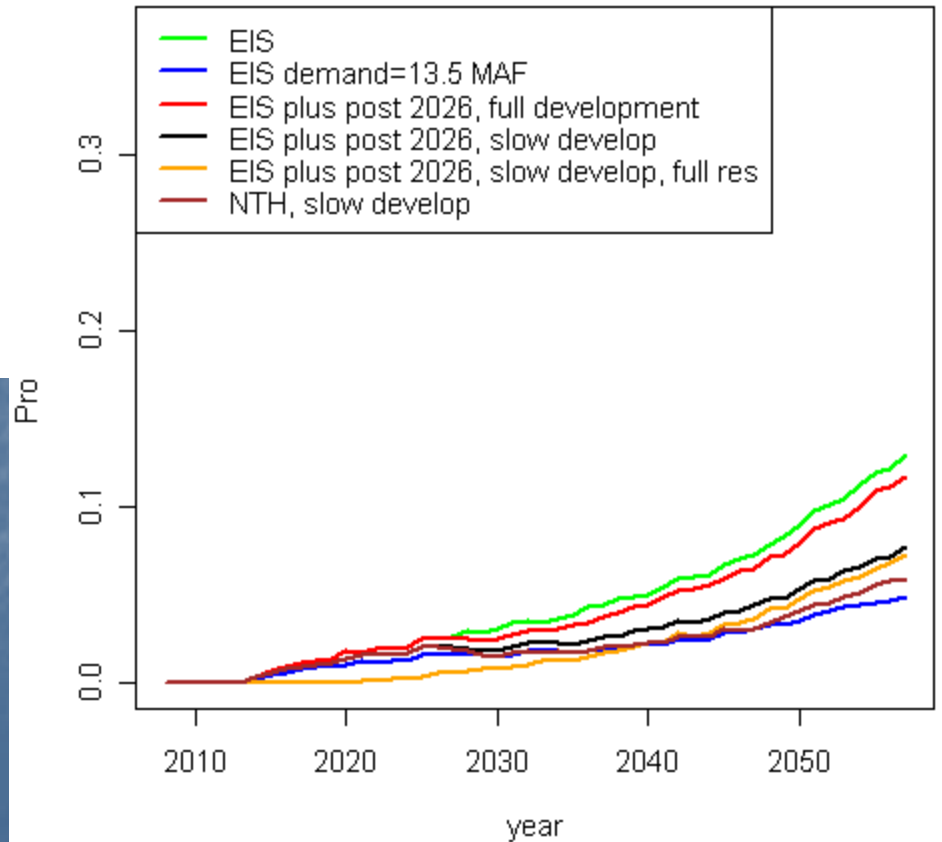


Climate Change – 20% reduction

Drying Probability 20% CC

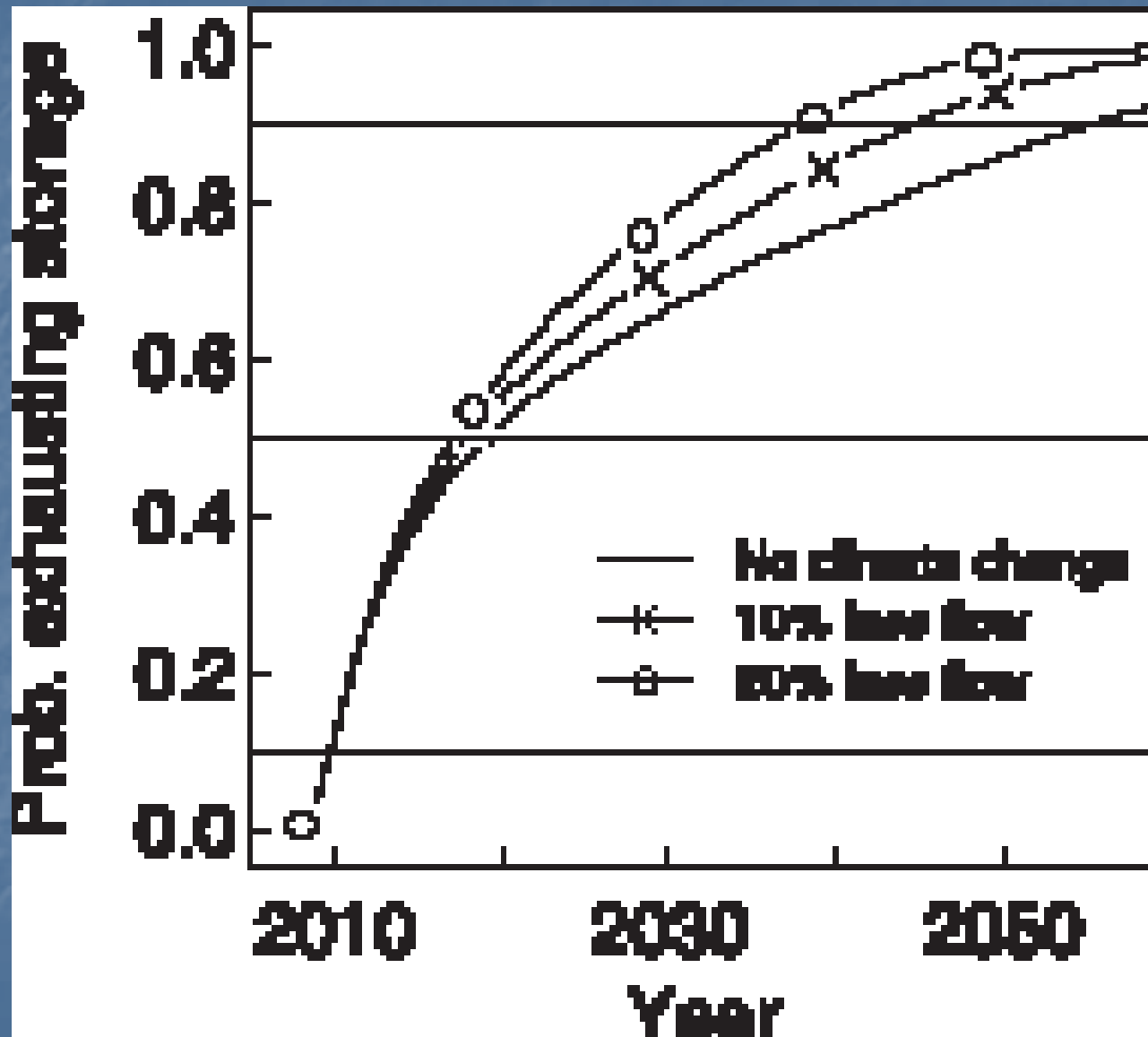


Drying Probability 10% CC

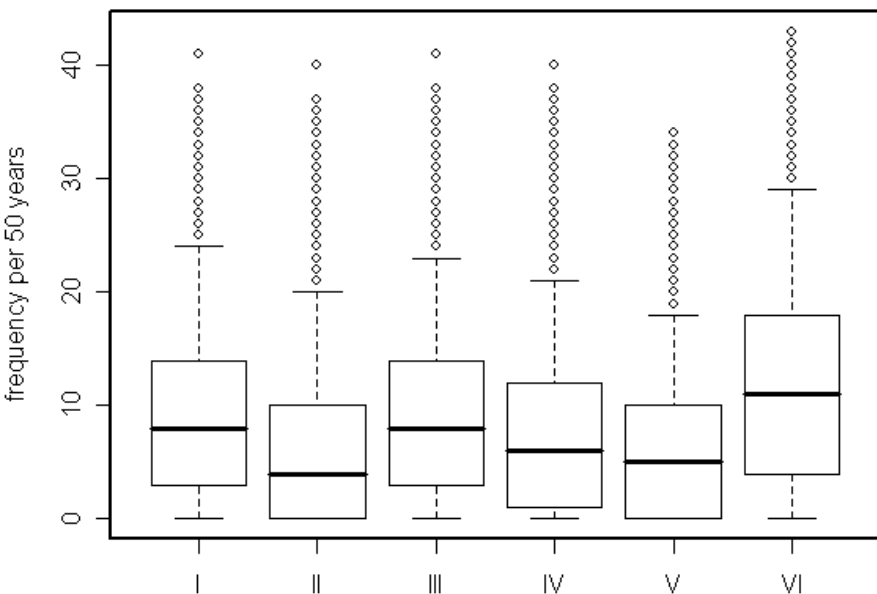


Climate Change – 10% reduction

Probability of at least one drying – Barnett and Pierce (2008)

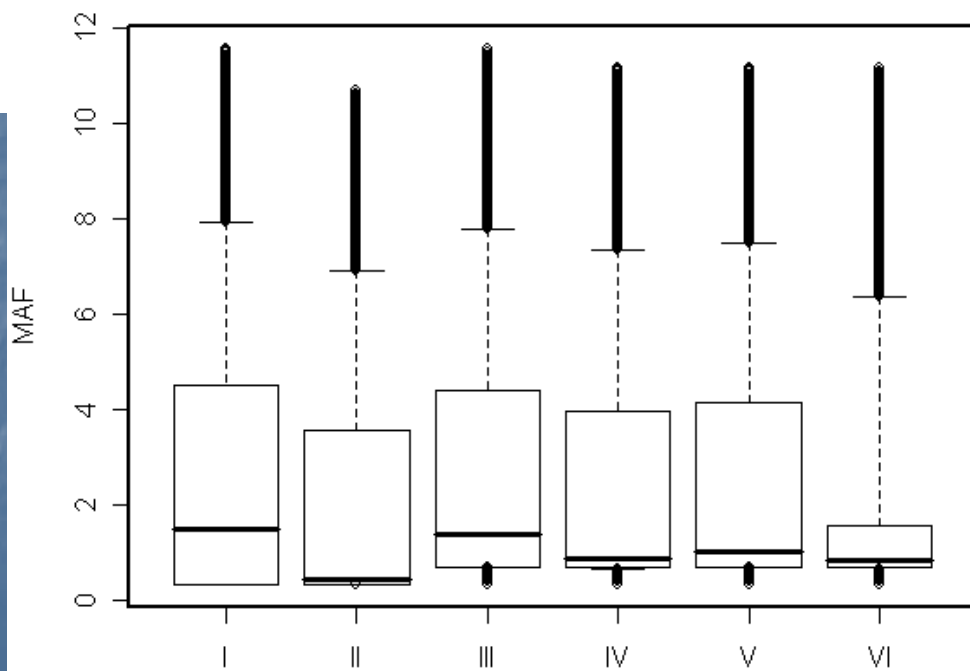


20% Climate Change Deficit Frequency



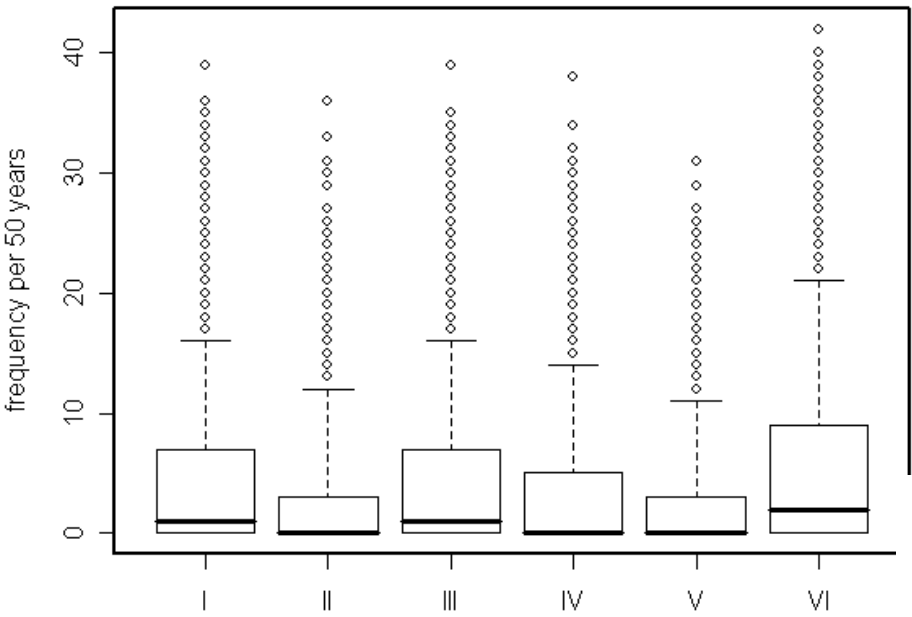
I = Current EIS, II = EIS with demand = 13.5,
 III = EIS Plus with full develop, IV = EIS Plus with demand slow develop,
 V = EIS Plus with slow develop and full res, VI = NTH with slow develop

20% Climate Change non-zero Deficit

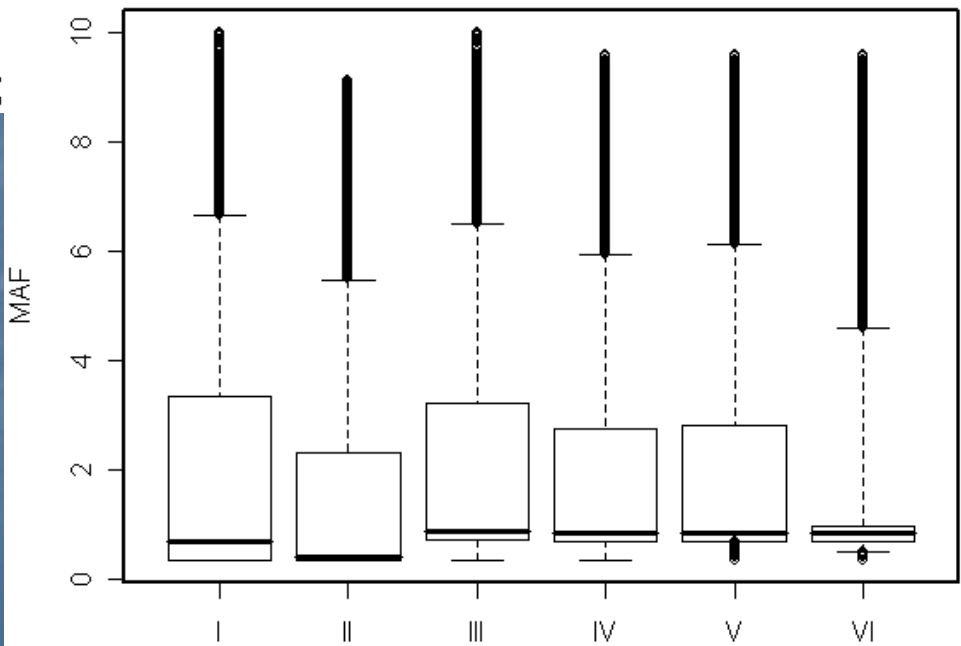


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10% Climate Change Deficit Frequency

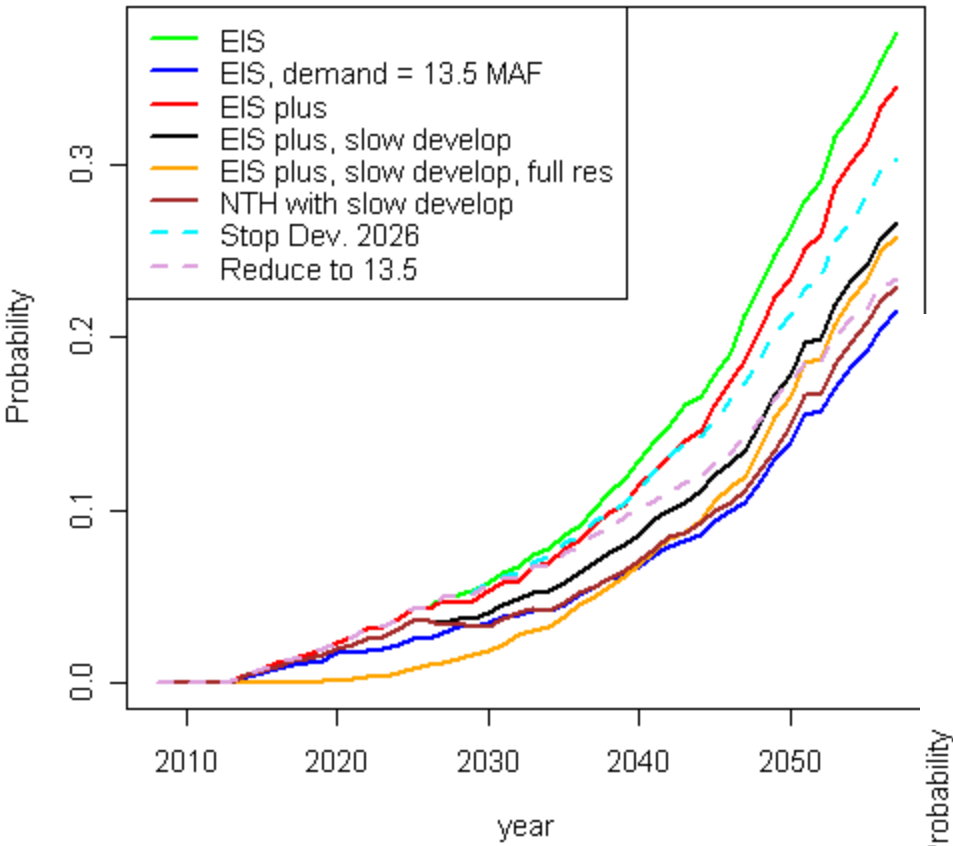


10% Climate Change non-zero Deficit



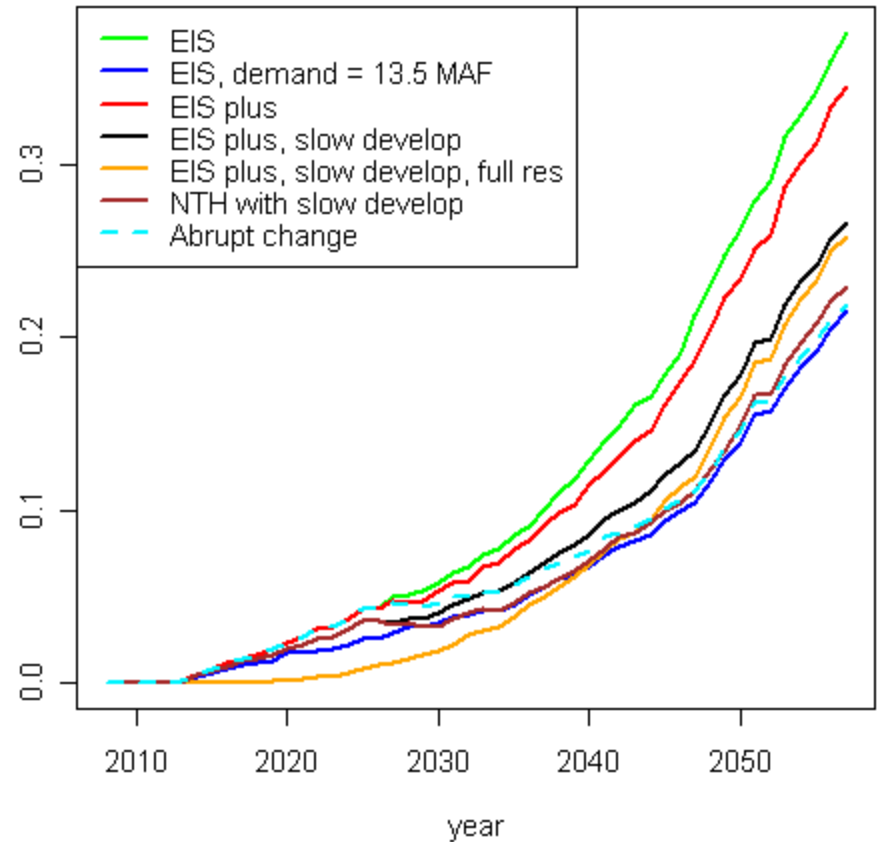
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Drying Probability 20% CC



Cost of Inaction

Drying Probability 20% CC



Summary

- Water supply risk (i.e., risk of drying) is small ($< 5\%$) in the near term ~ 2026 , for any climate variability (*good news*)
- Risk increases dramatically by about 7 times in the three decades thereafter (*bad news*)
- Risk increase is highly nonlinear
- There is flexibility in the system that can be exploited to mitigate risk.
 - Considered alternatives provide ideas
- Smart operating policies and demand growth strategies need to be instilled
 - Demand profiles are not rigid
- Delayed action can be too little too late
- Risk of various subsystems need to be assessed via the basin wide decision model (CRSS)

Perfect Storm looms but its impact can be mitigated