Is a Perfect Storm Looming for Colorado River Storage?

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ESRL Theme on Climate and Water Systems
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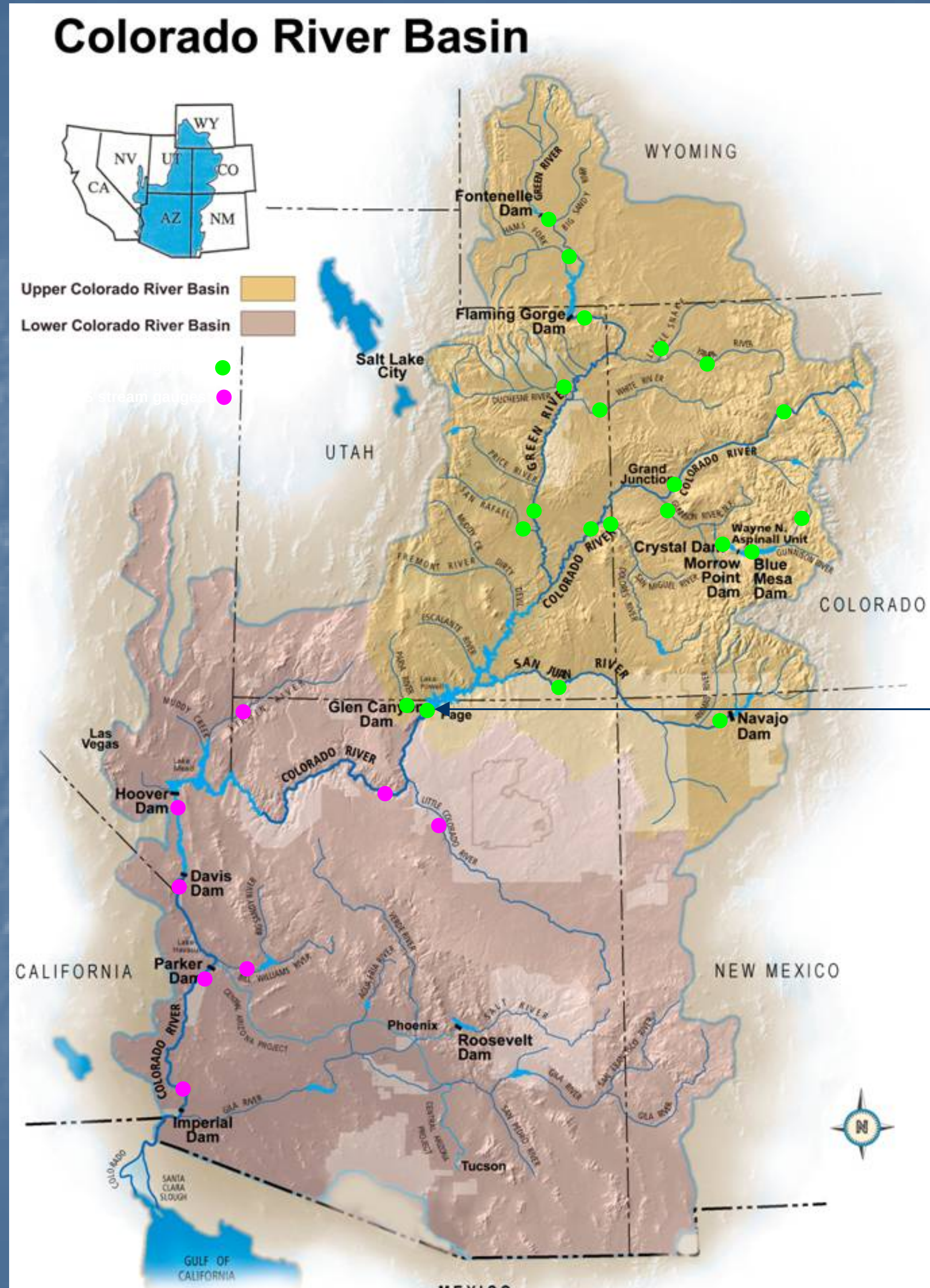

Colorado River Basin
WY
NV
UT
CO
CA
AZ
NM
Upper Colorado River Basin
Lower Colorado River Basin
WYOMING
UTAH
COLORADO
CALIFORNIA
NEW MEXICO
MEXICO
Fontenelle Dam
Flaming Gorge Dam
Salt Lake City
Grand Junction
Wayne N. Aspinall Unit
Crystal Dam
Morrow Point Dam
Blue Mesa Dam
Glen Canyon Dam
Page
Navajo Dam
Las Vegas
Hoover Dam
Davis Dam
Parker Dam
Phoenix
Roosevelt Dam
Tucson
Imperial Dam
GREEN RIVER
COLORADO RIVER
SAN JUAN RIVER
LITTLE COLORADO RIVER
SALT RIVER
GILA RIVER
GULF OF CALIFORNIA

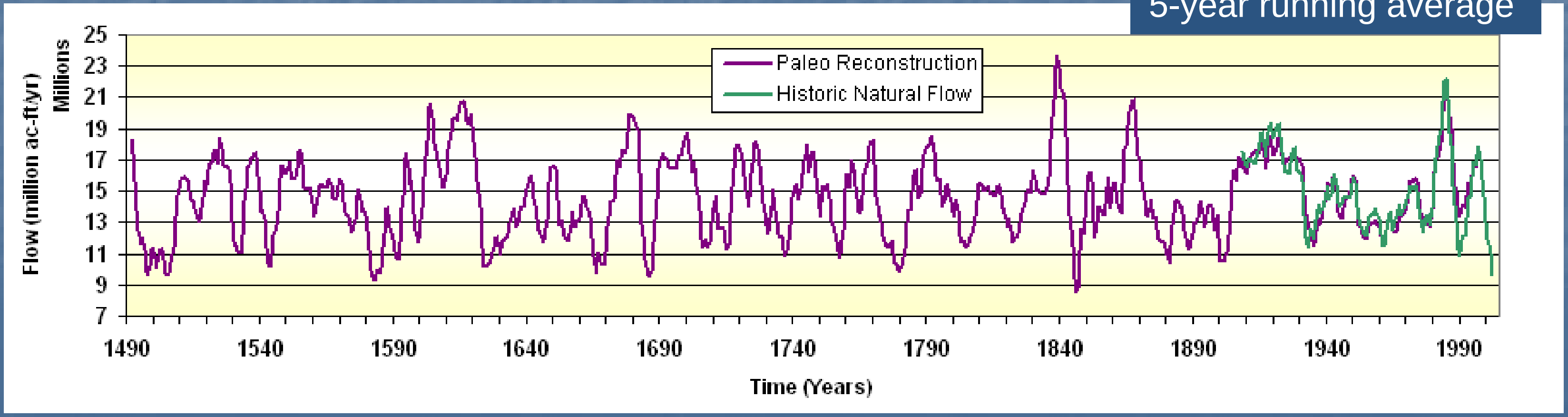
Lees Ferry

Recent conditions in the Colorado River Basin

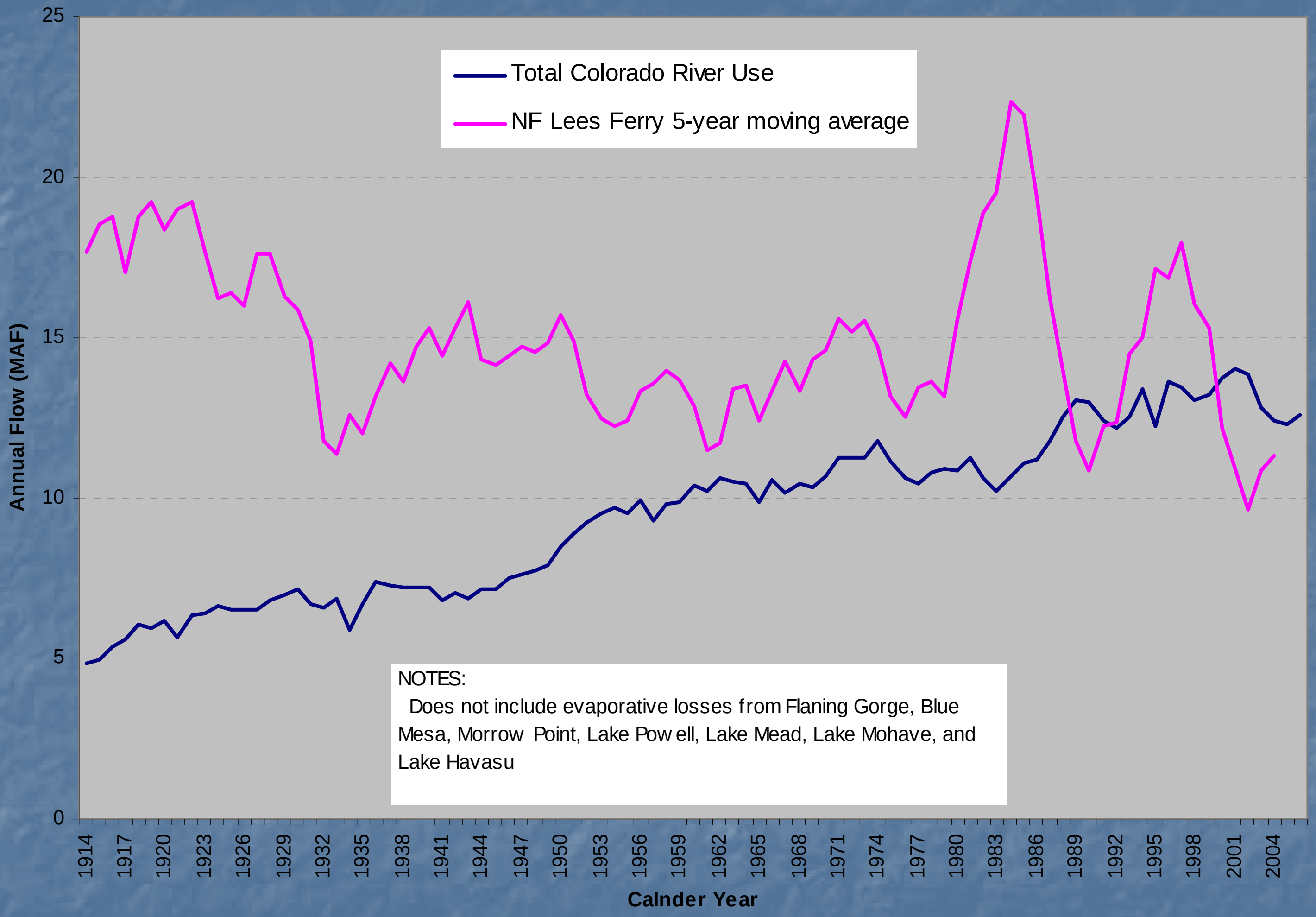
- Below normal flows into Lake Powell 2000-2004
  - 62%, 59%, 25%, 51%, 51%, respectively
    - 2002 at 25% lowest inflow recorded since completion of Glen Canyon Dam
- Some relief in 2005
  - 105% of normal inflows
- Not in 2006 !
  - 73% of normal inflows
- 2007 at 68% of Normal inflows
- 2008 at 111%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

Colorado River at Lees Ferry, AZ

5-year running average



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



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

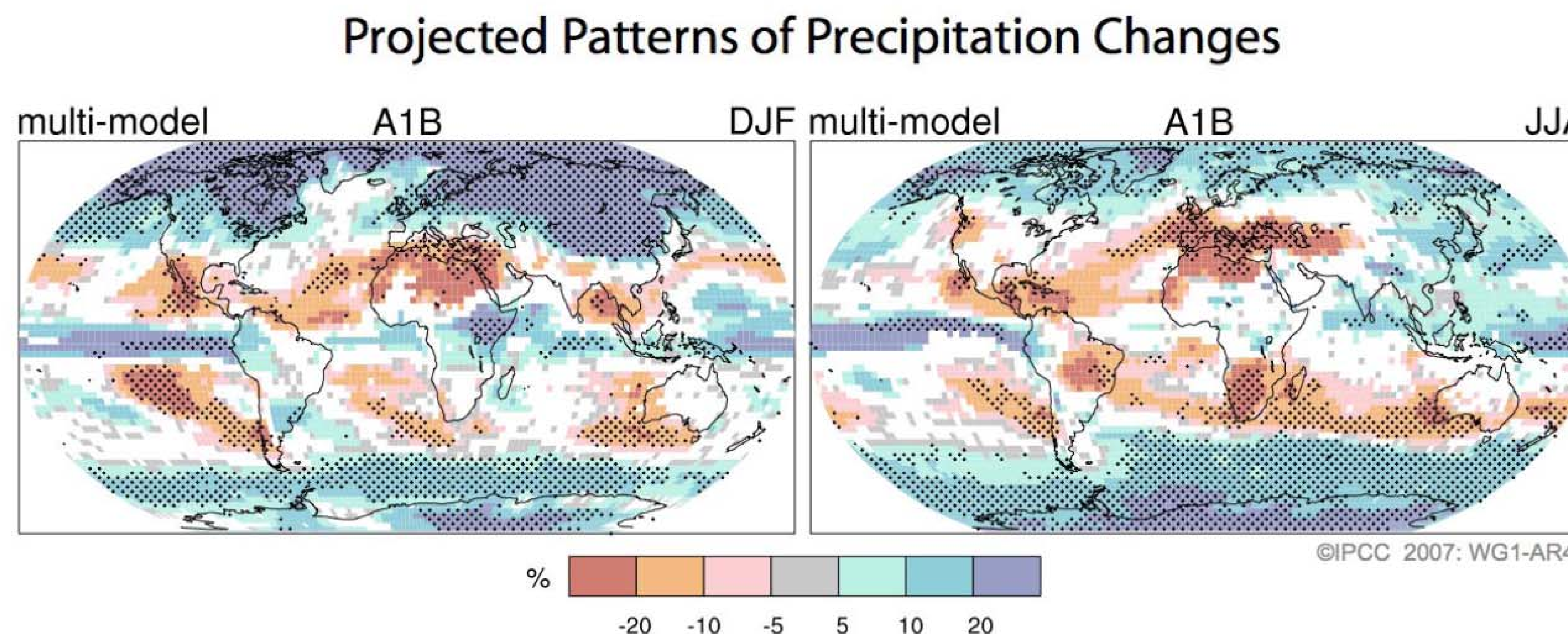
  - All the reconstructions agree greatly on the ‘state’ (wet or dry) information

- 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



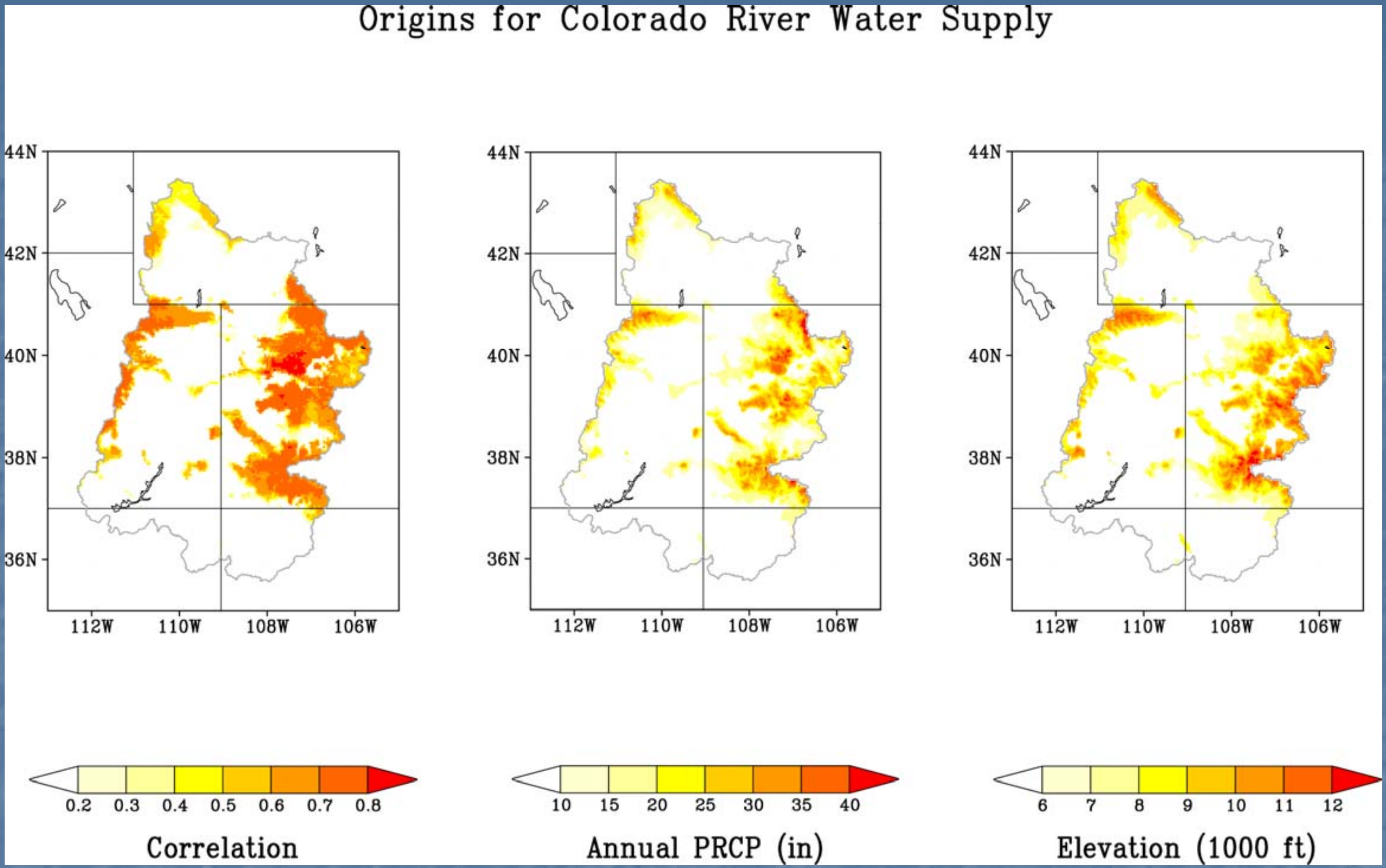
IPCC 2007 Southwest North America Regional Findings

- 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

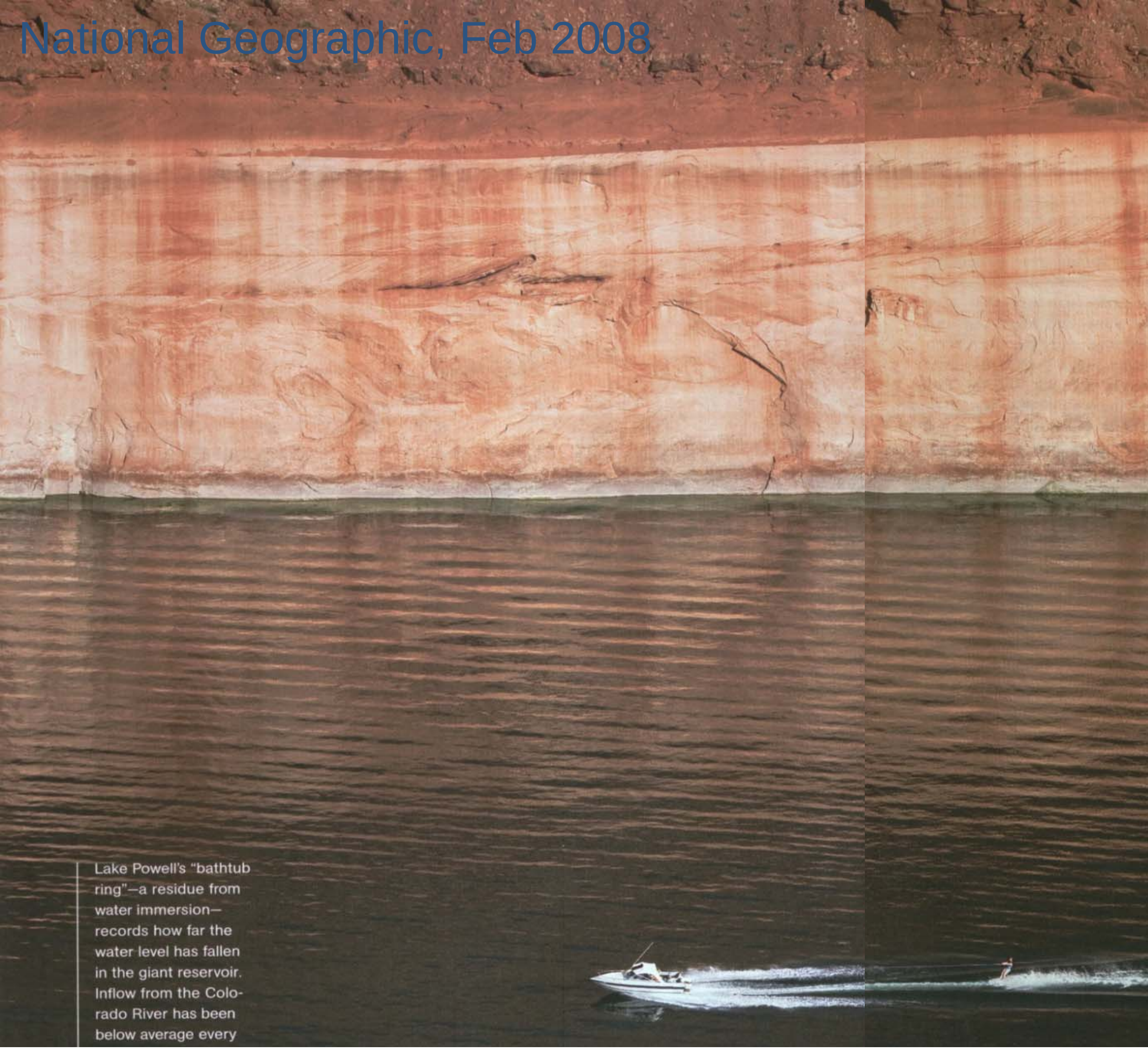
- Models show consistent errors (biases)
- Western North America is too cold and too wet
- Weather models show biases, too
- Can be corrected

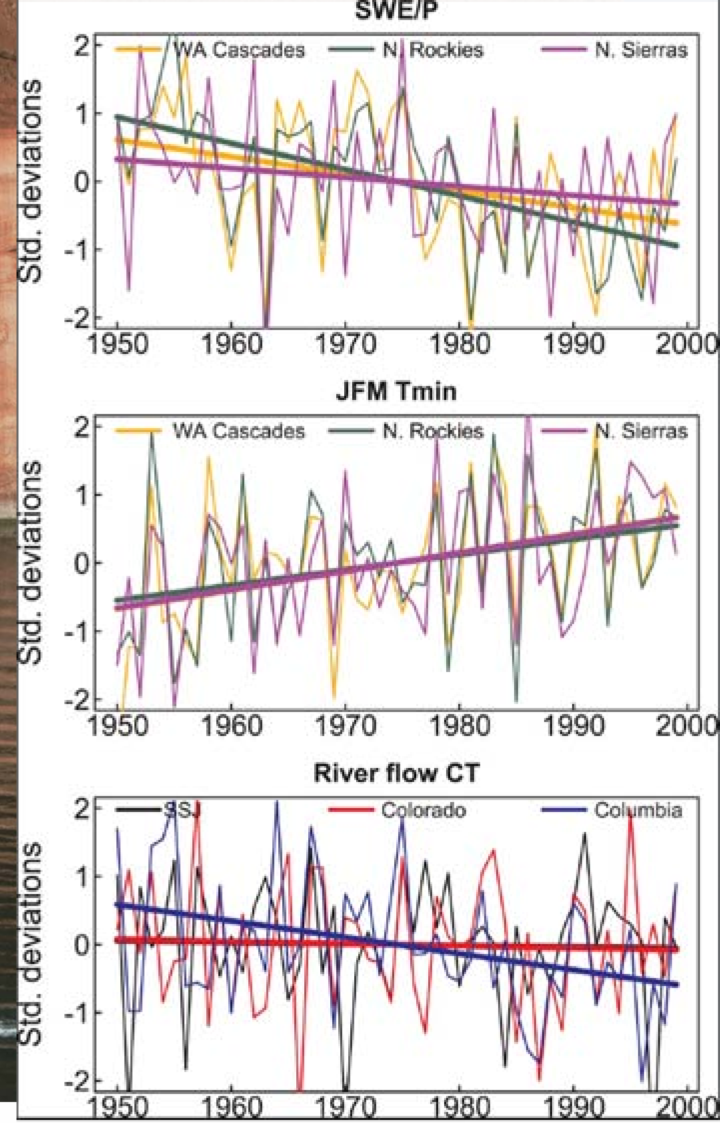
		temperature BIAS					% precipitation BIAS				
REGION	SEASON	MIN	25	50	75	MAX	MIN	25	50	75	MAX
North America											
ALA	DJF	-9.8	-2.4	-0.8	1.9	8.2	3	33	51	89	179
	MAM	-7.4	-1.4	0.2	1.0	3.8	25	58	86	108	197
	JJA	-4.9	-1.6	-0.4	0.4	3.1	8	18	40	54	113
	SON	-5.7	-1.6	-0.6	1.4	4.8	14	33	52	65	113
	ANN	-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	10	29	45	97
	JJA	-4.4	-2.7	-0.9	0.9	4.7	4	13	16	20	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



•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





Sciencexpress

Science, February 1, 2008

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

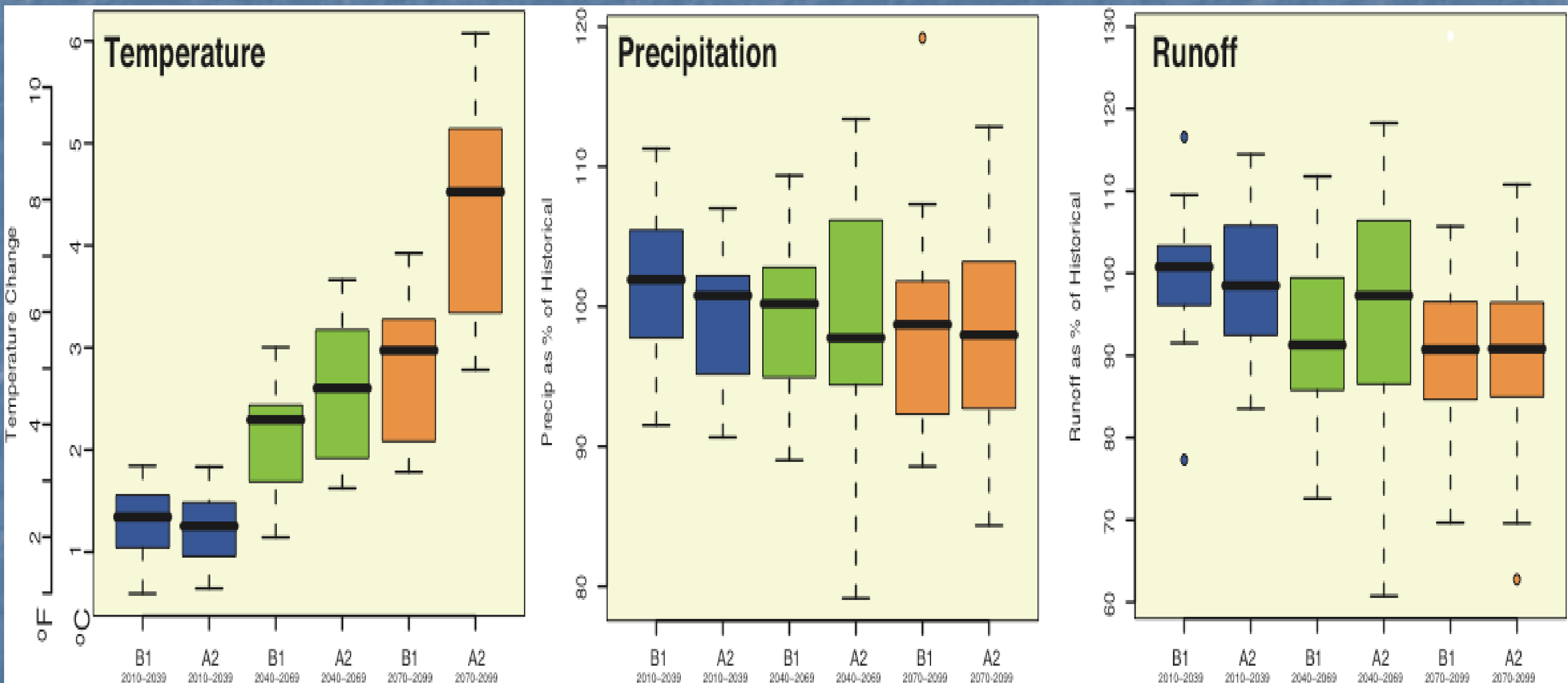
Tim P. Barnett,[1]* David W. Pierce,[1] Hugo G. Hidalgo,[1] Celine Bonfils,[2] Benjamin D. Santer,[2] Tapash Das,[1] Govindasamy Bala,[2] Andrew W. Wood,[3] Toru Nozawa,[4] Arthur A. Mirin,[2] Daniel R. Cayan,[1] Michael D. Dettinger[1]

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

Streamflow Scenarios
Conditioned on climate change projections

↓

Water Supply Model
Management + Demand growth alternatives

↓

System Risk Estimates
For each year

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.

Need for Combination
(Paleo, Observational and Climate Change projection)

- 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

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

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

Superimpose Climate Change trend (10% and 20%)

10000 Simulations
Each 50-year long
2008-2057

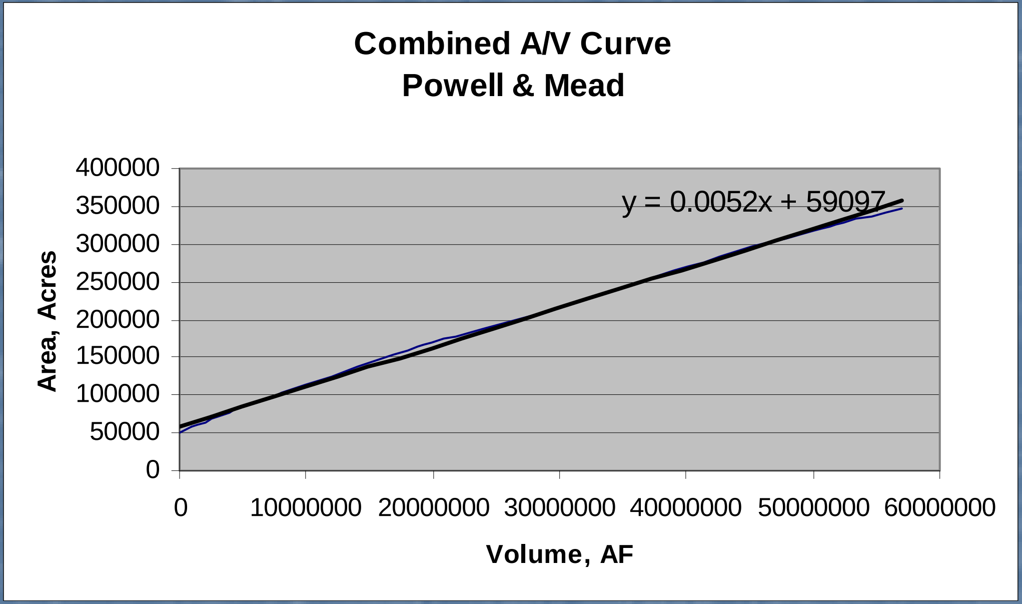
Water Balance Model
(Modification of Barnett and Pierce, 2008)

Storage in any year is computed as:

Storage = Previous Storage + Inflow - ET- 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

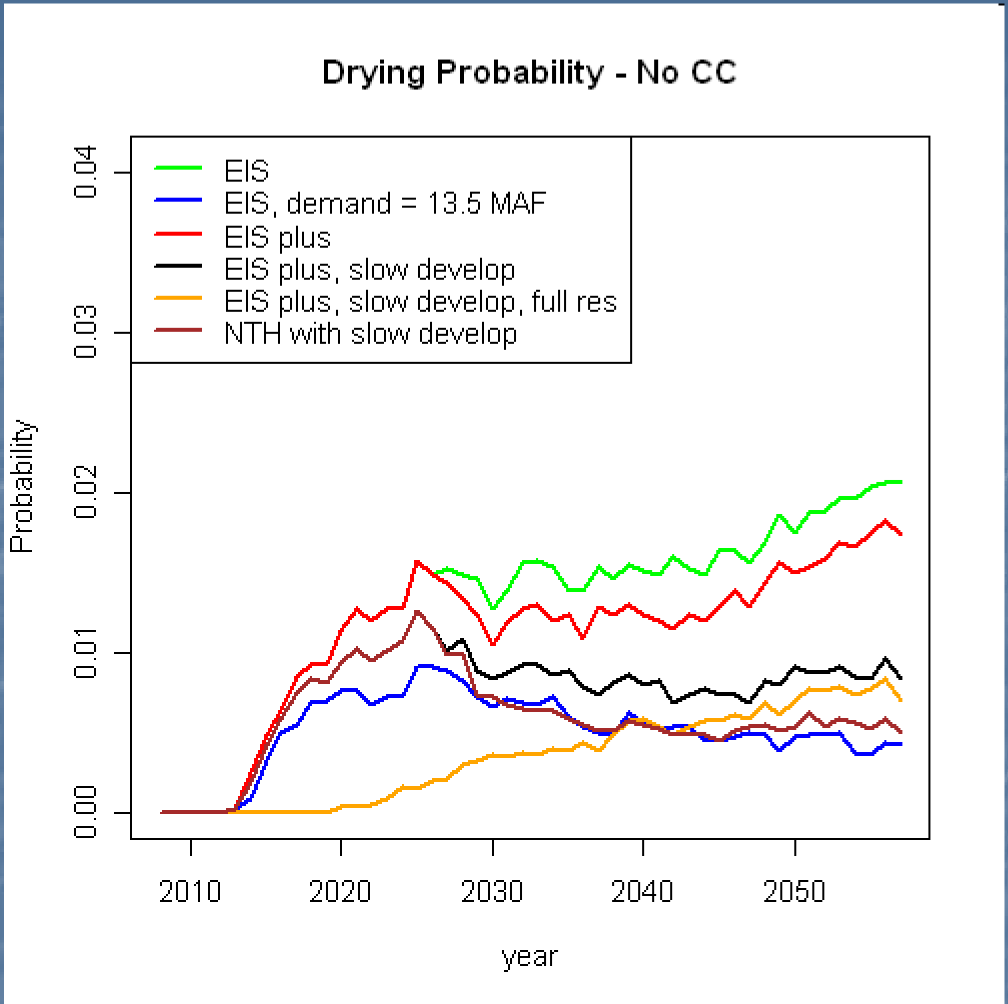
Management and Demand Growth Combinations

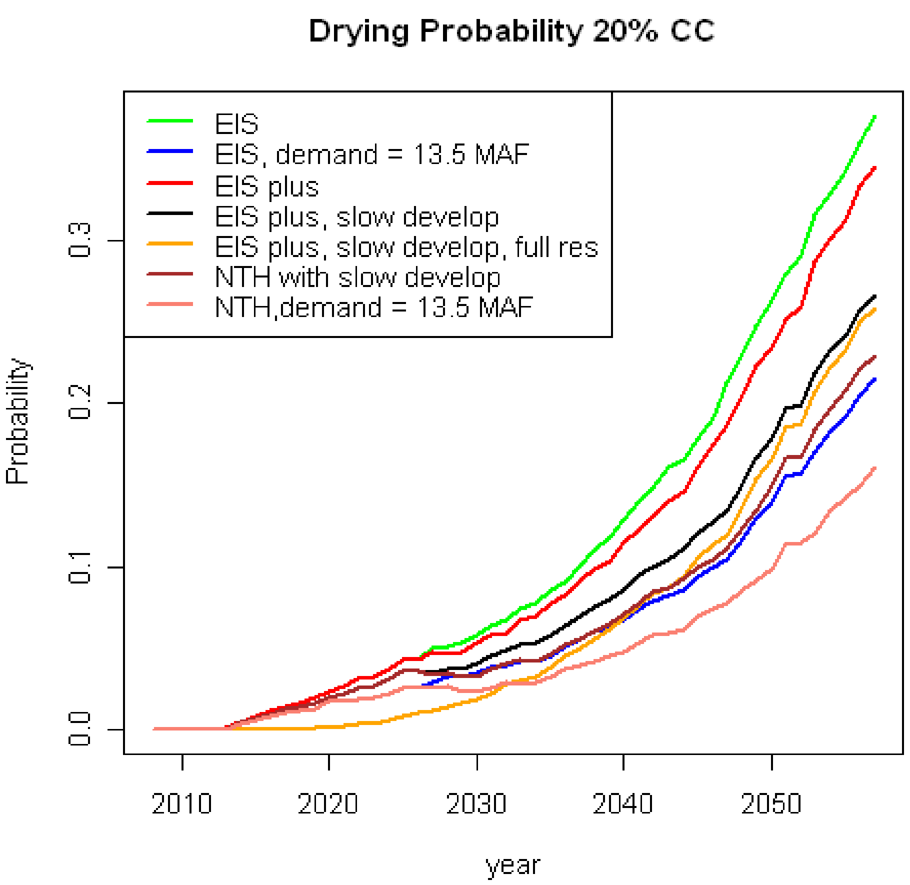
1. The interim EIS operational policies employed with demand growing based on the upper basin depletion schedule.
2. 1. with the demand fixed at the 2008 level.
3. 1. with larger delivery shortages post 2026 (EIS Plus).
4. 3. with a 50% reduced upper basin depletion schedule.
5. 4. with full initial 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

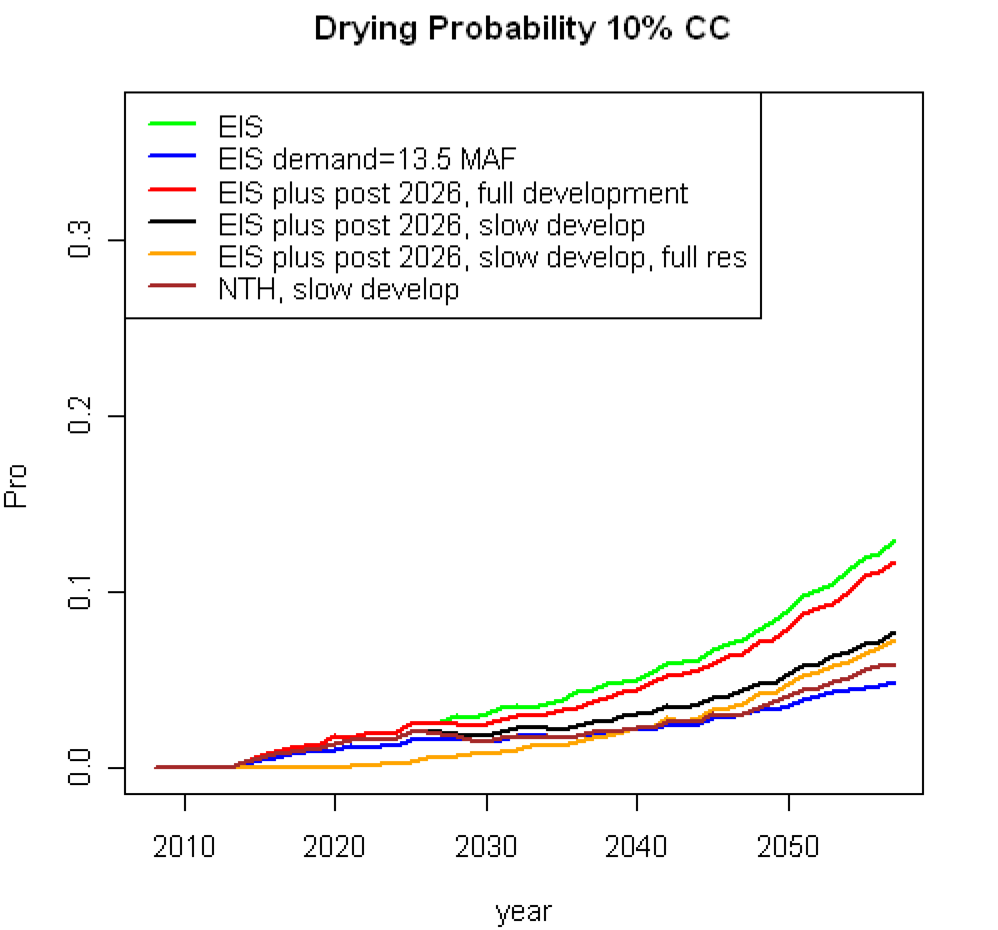
INTERIM EIS		INTERIM PLUS		NEW THRESHOLD	
Res. Storage (%)	Shortage (kaf)	Res. Storage (%)	Shortage (% of current demand)	Res. Storage (%)	Shortage (% of current demand)
36	333	36	5	50	5
30	417	30	6	40	6
23	500	23	7	30	7
				20	8

Natural Climate Variability



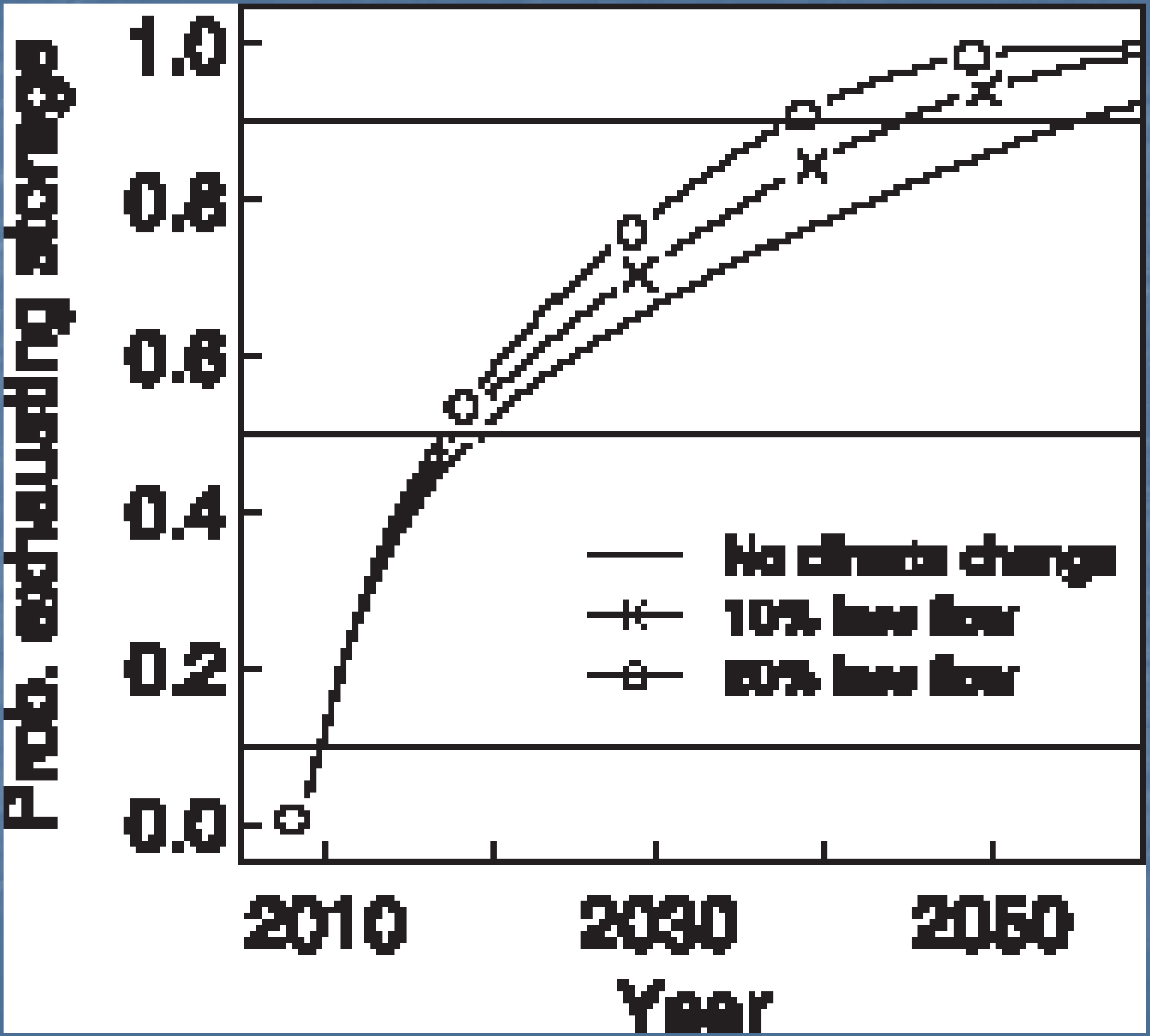


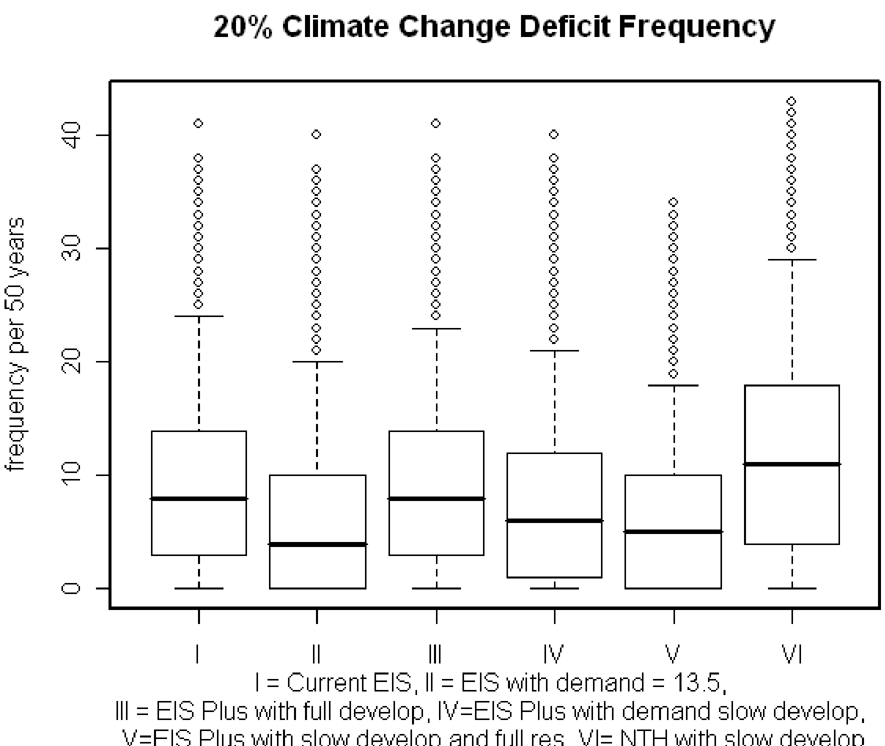
Climate Change – 20% reduction

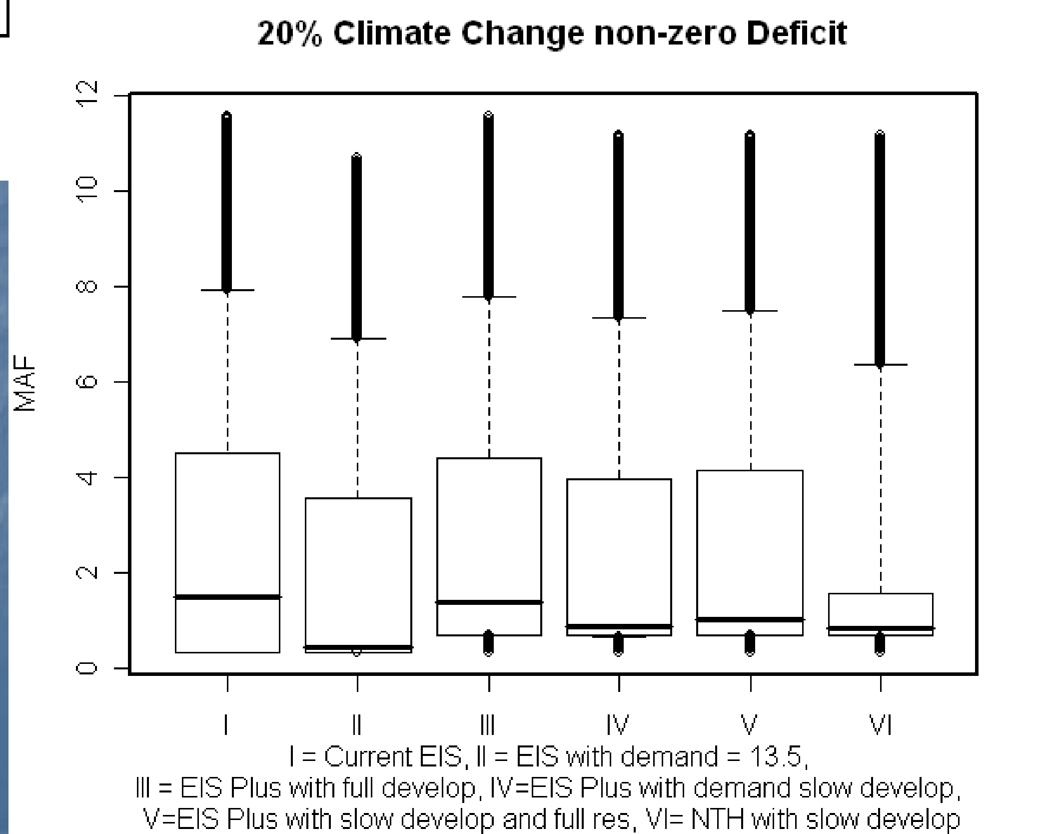


Climate Change – 10% reduction

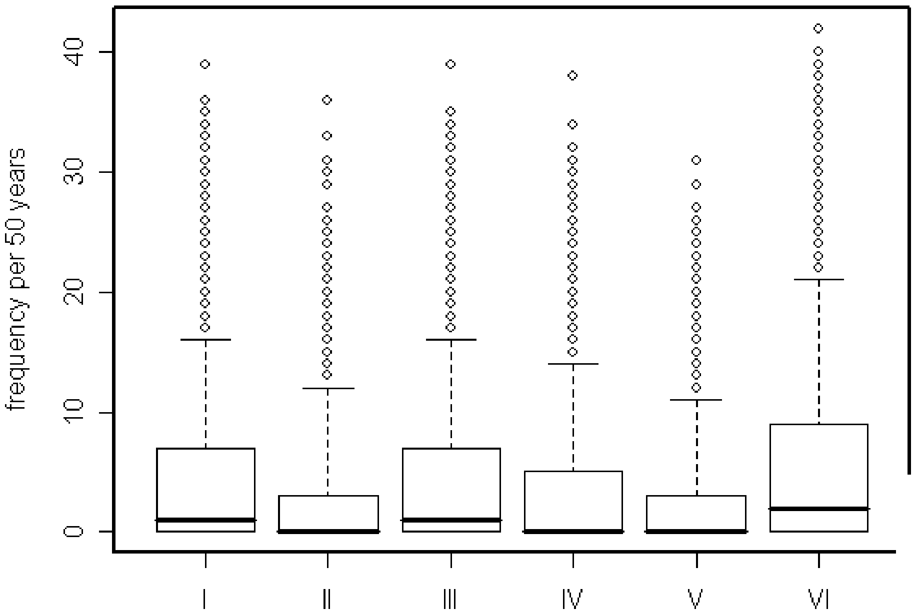
Probability of atleast one drying – Barnett and Pierce (2008)




20% Climate Change Deficit Frequency
frequency per 50 years
0
10
20
30
40
I
II
III
IV
V
VI
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
MAF
0
2
4
6
8
10
12
I
II
III
IV
V
VI
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

10% Climate Change Deficit Frequency



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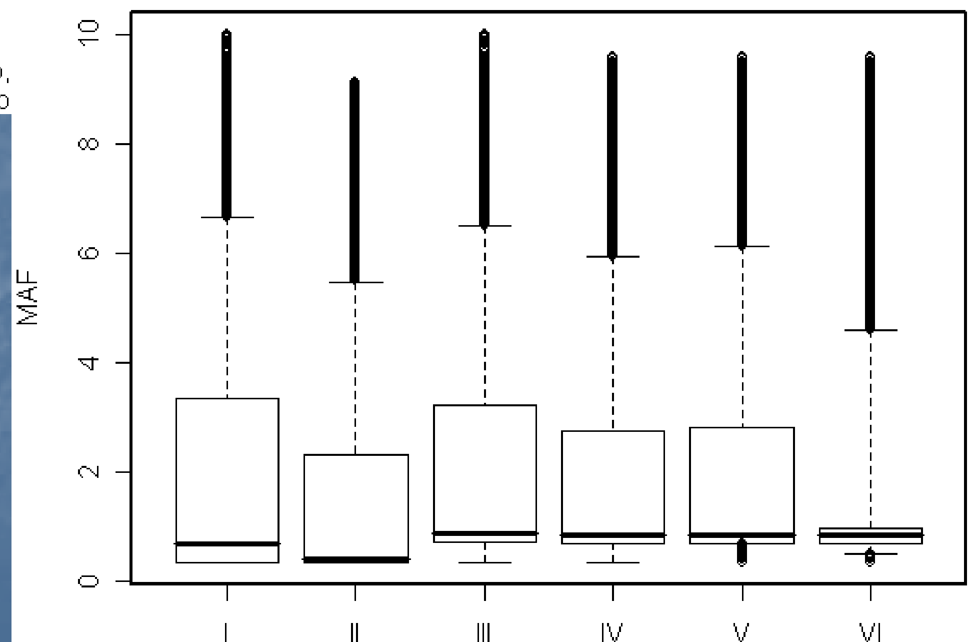
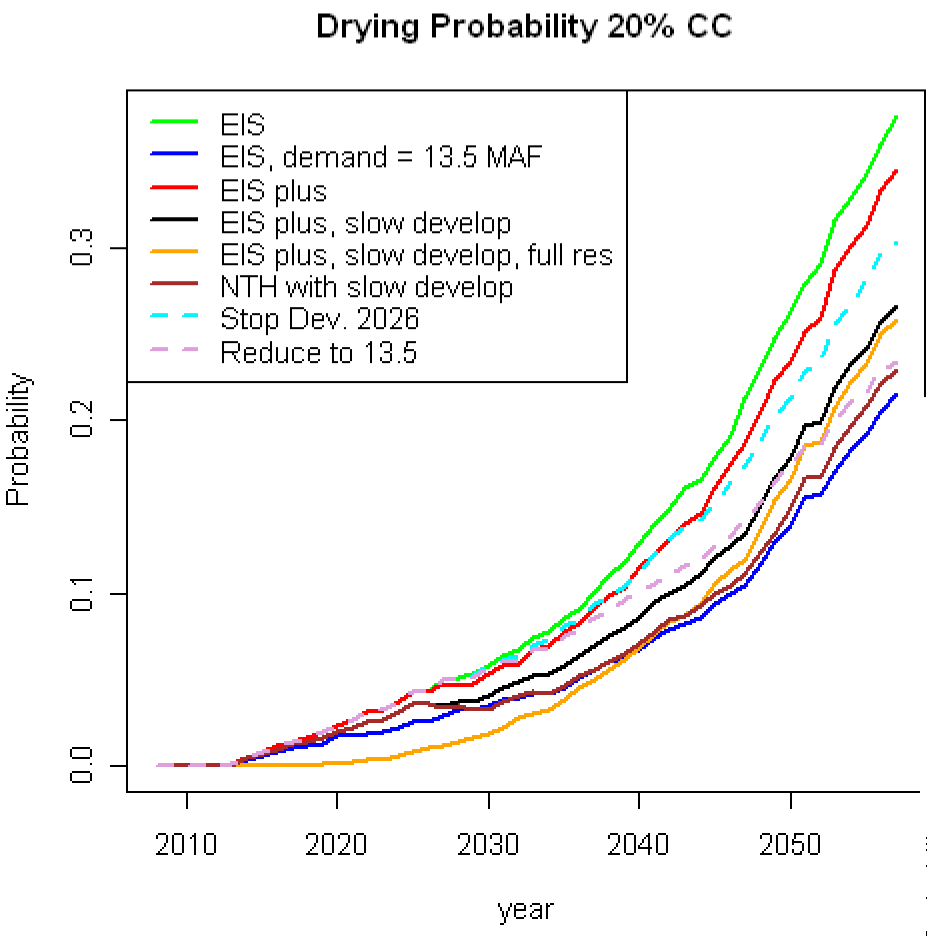
V=EIS Plus with slow develop and full res, VI= NTH with slow develop

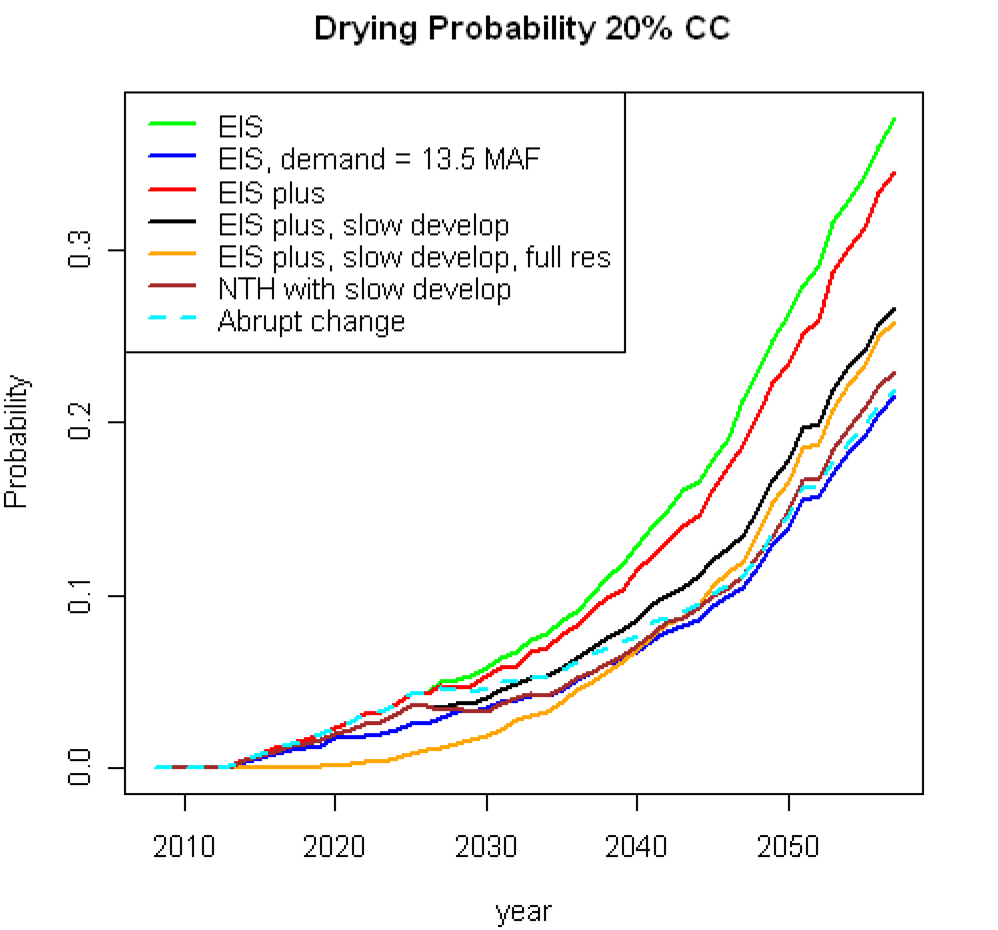
10% Climate Change non-zero Deficit



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

Cost of Inaction





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