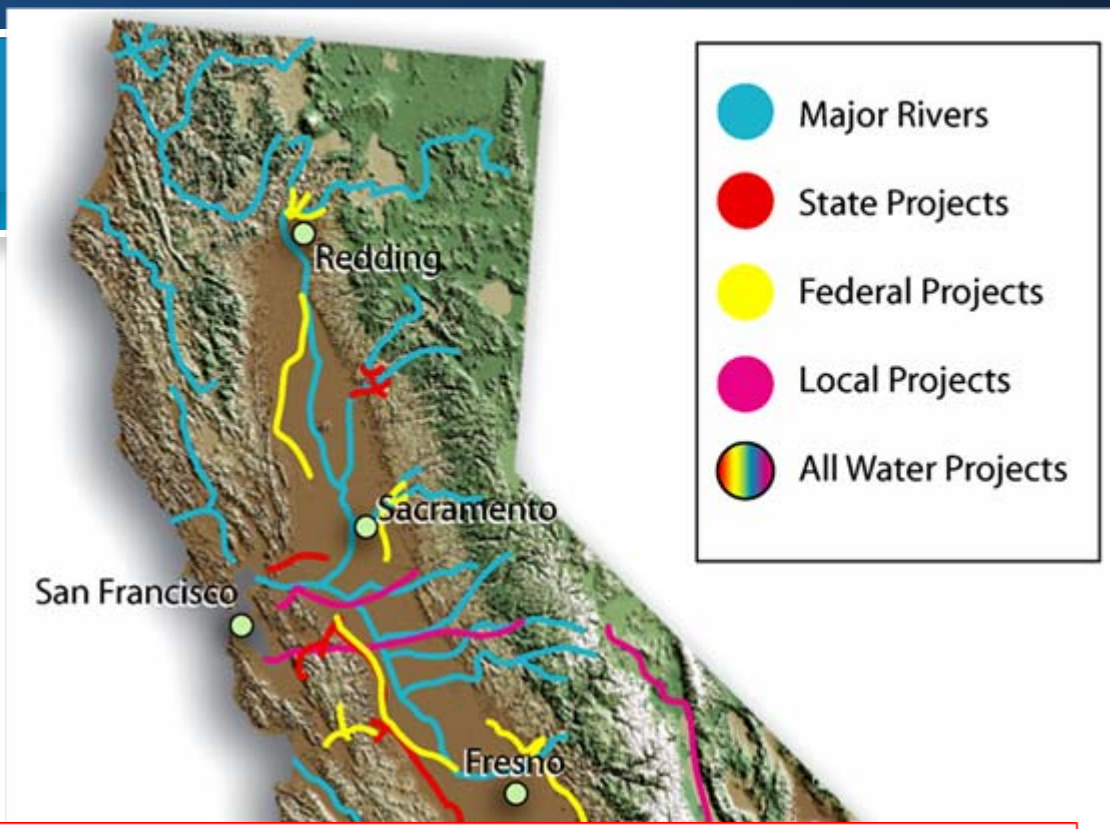
Climate Change, Ecohydrology, and Potential Outcomes in the Sierra Nevada

Joshua H. Viers

Center for Watershed Sciences
University of California, Davis

The Entire State is Plumbed

The linchpins of California's water delivery systems are the massive federal Central Valley Project



cherieziegler wrote on 02/02/2009 06:45:48 AM:

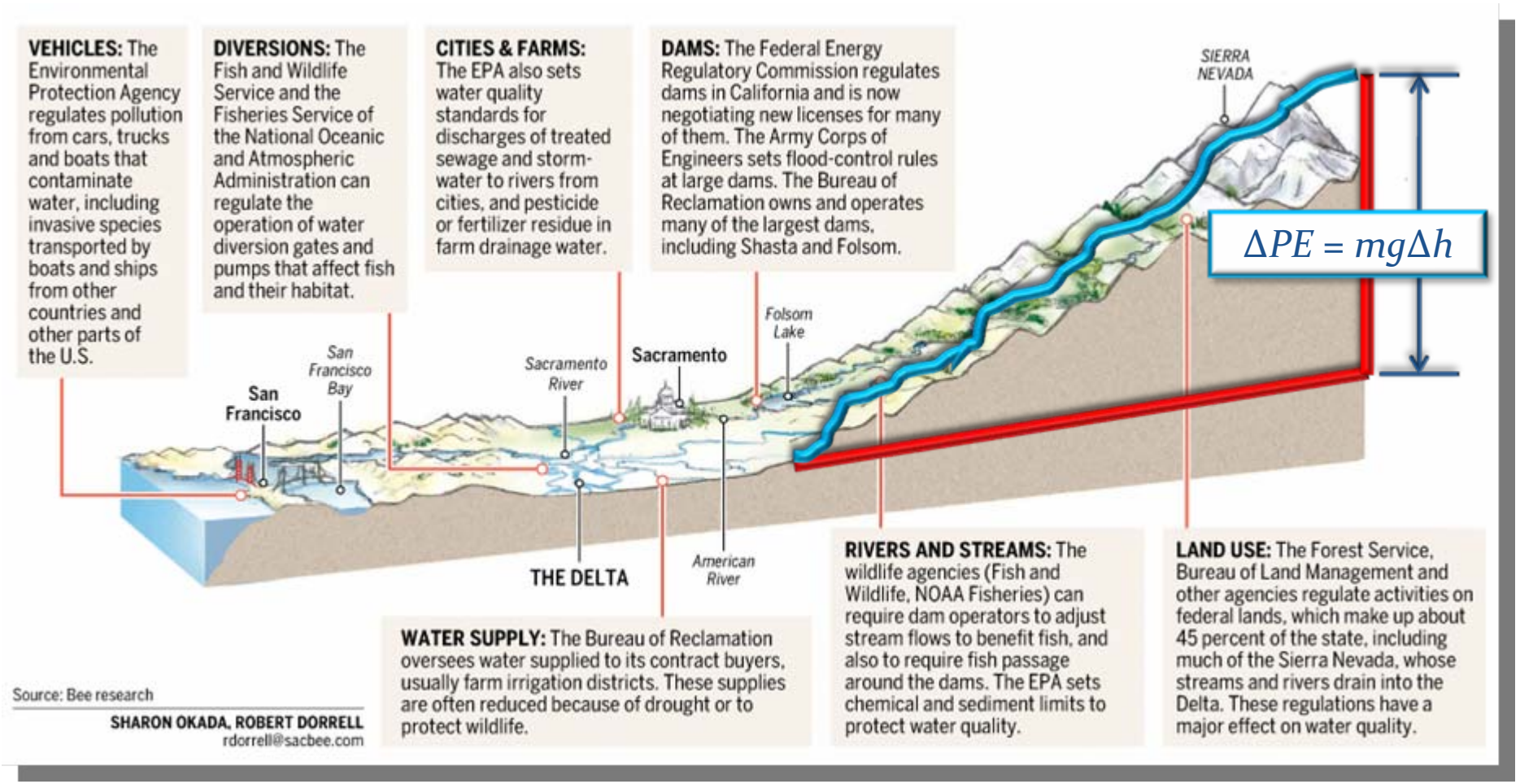
I wonder if there is an engineer anywhere in the country who could design a way to create a canal system, much like and possibly paralleling the country's freeway systems, that would take water from flooded areas and divert it to dry areas. We would solve at least two problems right there---reduce flooding and drought, not to mention the jobs it would create.

Comment found on **SacBee.com**

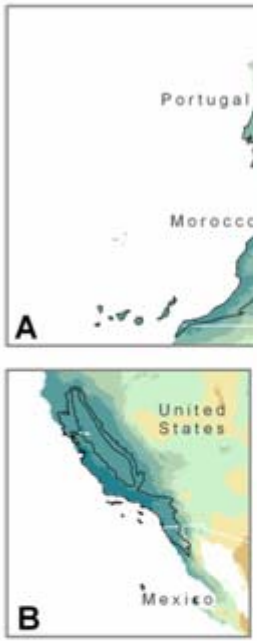
Recommend (1) Report abuse

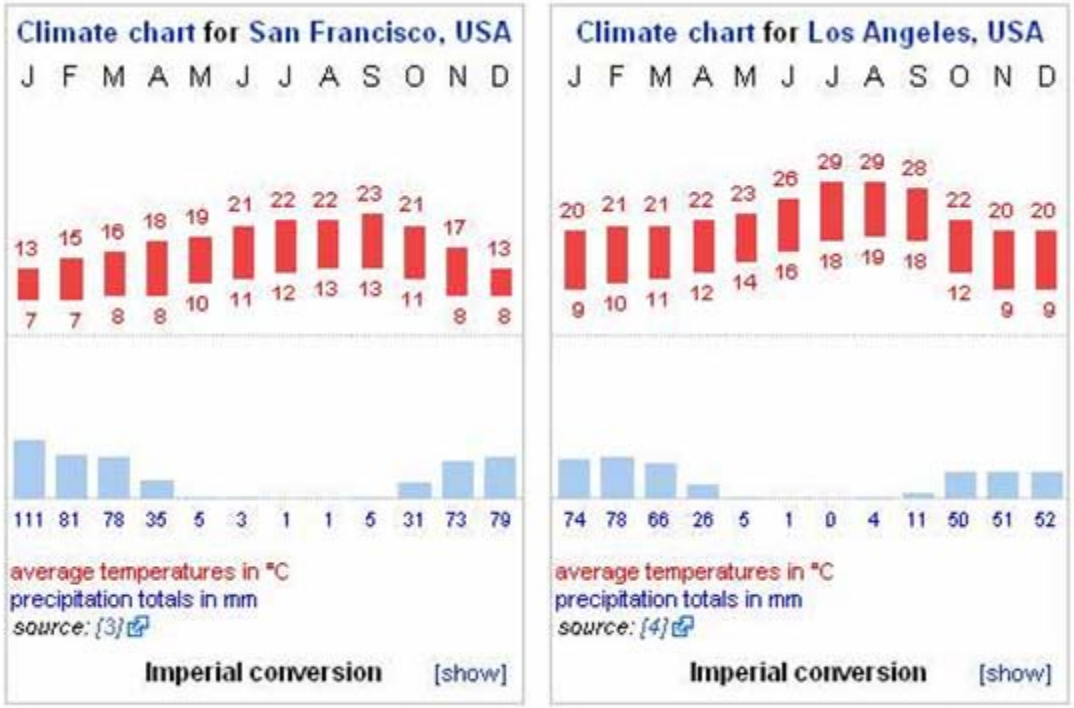
Vast Potential Energy

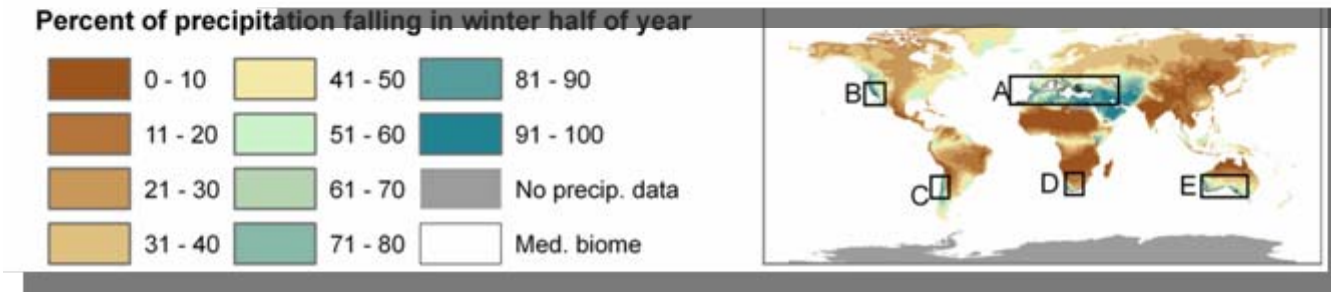
Hydropower ~20% of California's Energy Supply (CEC 2007)



Mediterranean – Montane Climate







Citation: Klausmeyer KR, Shaw MR (2009) Climate Change, Habitat Loss, Protected Areas and the Climate Adaptation Potential of Species in Mediterranean Ecosystems Worldwide. PLoS ONE 4(7): e6392. doi:10.1371/journal.pone.0006392

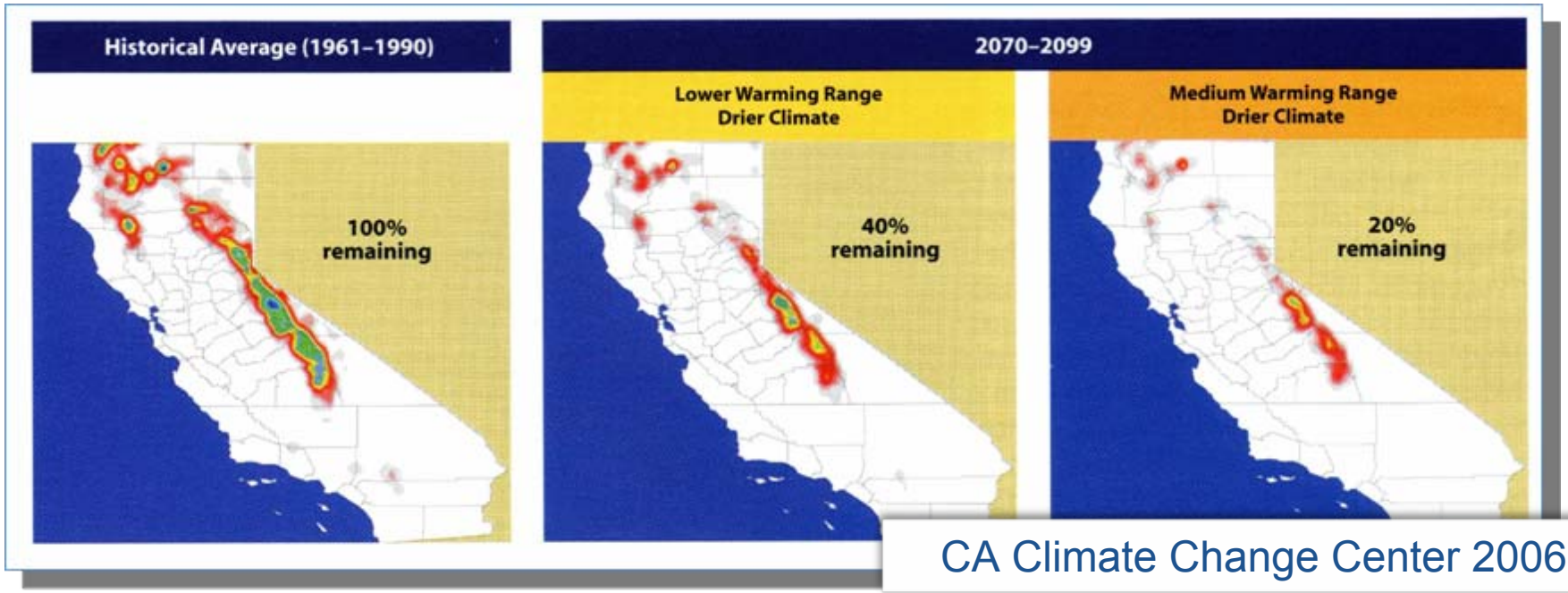
A regionally-consistent prediction of a future with less snow & more rain

Projected Climatic Changes for California's Sierra Nevada

- Increase in Air Temperature › 2-8°C
- Slight drying trend in Precipitation,
- ↑ volatility (inter and intra-annual variability)

***In Progress* Climatic Changes for California's Sierra Nevada**

- Progressive negative shift in onset of spring snowmelt pulse
- Negative shift in center of mass (i.e., centroid timing is earlier)



CA Climate Change Center 2006

ALTERATION ANALYSIS OF GLOBAL CLIMATE MODEL DRIVEN MACRO-HYDROLOGY

In Prep

AK Fremier, EH Girvetz, and JH Viers

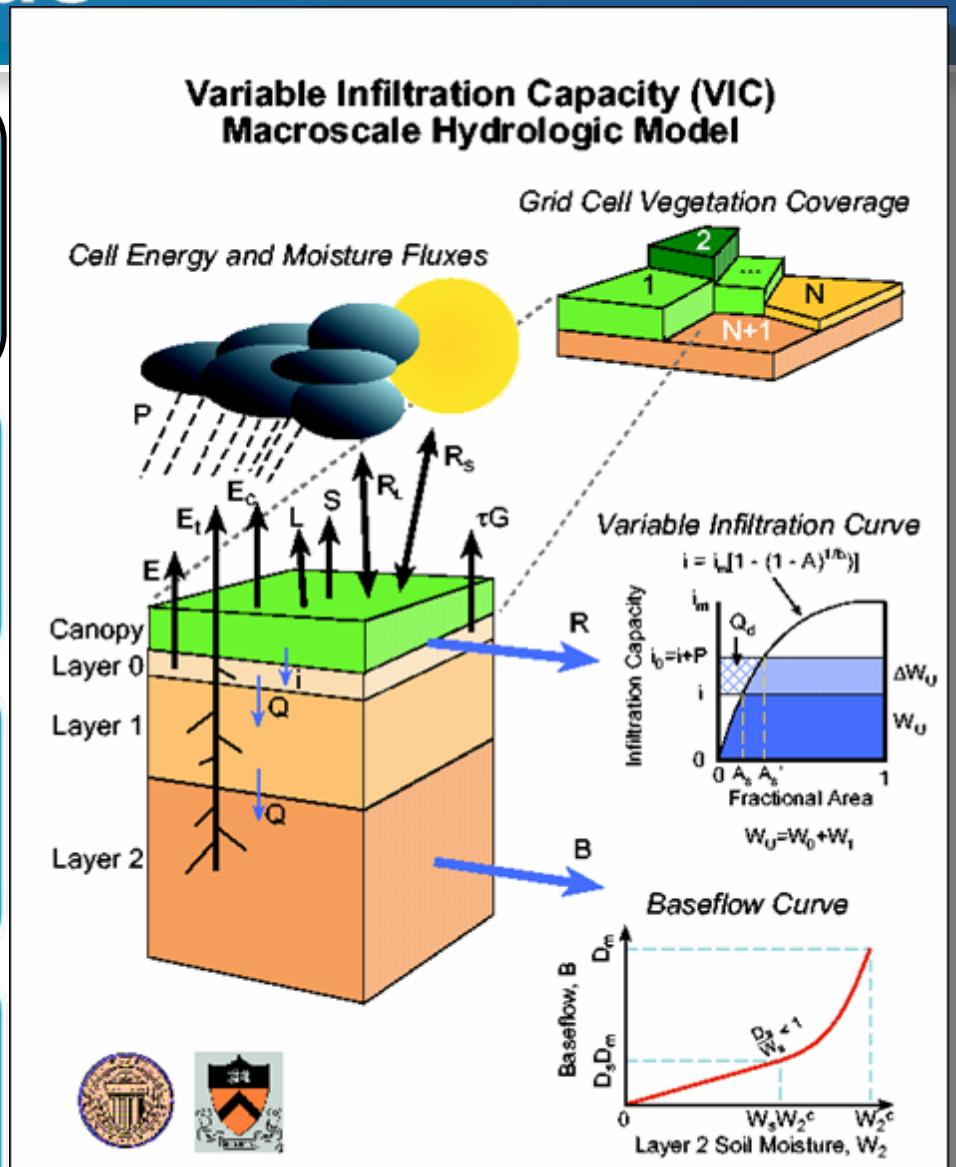
VIC/IHA Methods

Data were created from **six climate scenarios** and run through the **Variable Infiltration Capacity** (VIC) macroscale hydrologic model to produce stream discharges in the past and future (California Climate Change Center 2008).

The **bcsd downscaling method** was used to generate inputs to the VIC. The VIC simulation generated estimates of daily streamflow over a **100-year period**.

Three hydrology datasets were examined – 'observed' stream flow, modeled historical stream flow (both 1958-2008) and modeled future stream flow (2008-2058) for eight rivers in the Sierra Nevada.

With these datasets we used the **Indicators of Hydrologic Alteration** (IHA) analysis tool to measure **67 hydrology parameters**. . (see "A method for assessing hydrologic alteration within ecosystems " BD Richter, et al.- *Conservation Biology*, 1996)



http://www.hydro.washington.edu/Lettenmaier/Models/VIC/

VIC/IHA Methods

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bias correction and spatial downscaling (BCSD)

See Maurer, E.P. and H.G. Hidalgo (2008) for specifics.
Utility of daily vs. monthly large-scale climate data: an intercomparison of two statistical downscaling methods
(Hydrology and Earth System Sciences Vol. 12, 551-563)

GCMs (n =6):

- CNRM-CM3 — Centre National de Rech. Météorologiques
- GFDL-CM2.1 — Geophysical Fluid Dynamics Laboratory
- MIROC3.2(medres) — Center for Climate System Research
- ECHAM5/MPI-OM — Max Planck Institute for Meteorology
- CCSM3 — National Center for Atmospheric Research
- PCM — National Center for Atmospheric Research

These models used atmospheric carbon levels as predicted by the SRES A2 climate scenario. This climate change simulation predicts maximum C02 levels of 850ppm based on assumptions of self-reliance, population increases, and slow economic growth.

VIC/IHA Methods

Data were created from **six climate scenarios** and run through the **Variable Infiltration Capacity** (VIC) macroscale hydrologic model to produce stream discharges in the past and future (California Climate Change Center 2008).

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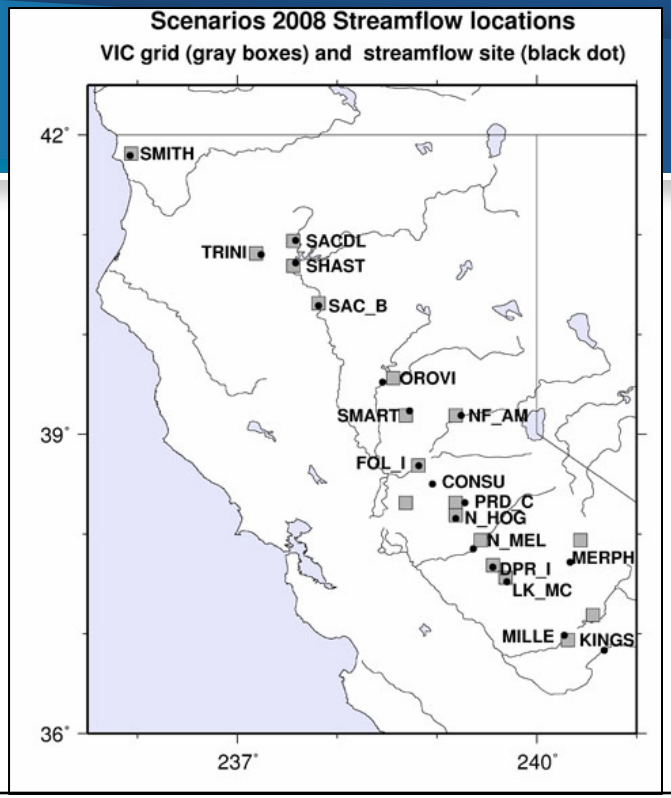


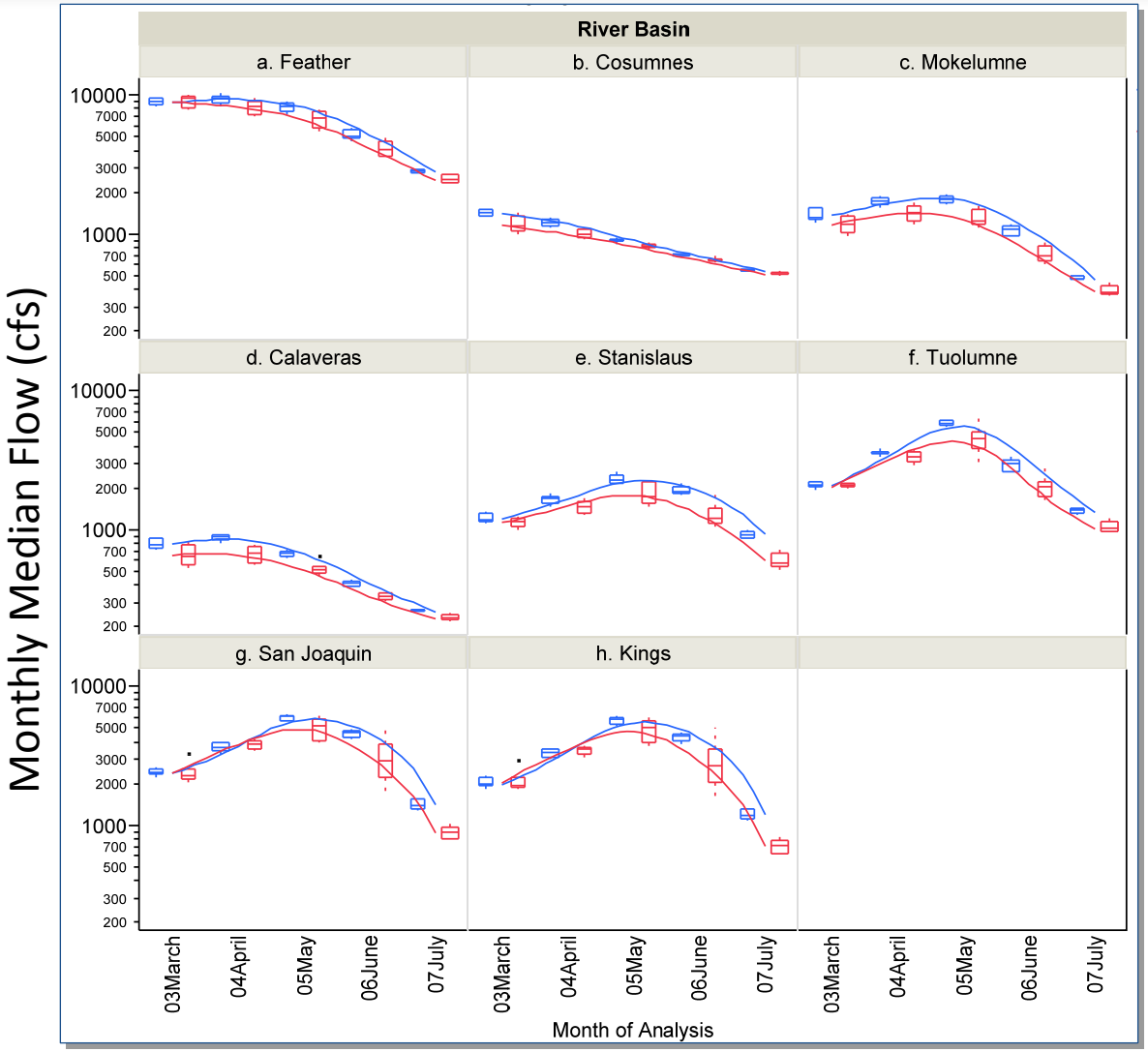
River Name and Location of Flow Measurement	
Cosumnes R. at Michigan Bar	Calaveras R. at New Hogan
Tuolumne R. at New Don Pedro	Feather R. at Oroville
Stanislaus R. at New Melones Dam	Mokelumne R. at Pardee
San Joaquin R. at Millerton Lake	King R. at Pine Flat Dam

IHA Results

Low Flow Parameters | Median Monthly | Maximum Parameters

IHA Statistic	No. of Sig. Decreases	No. of Sig. Increases	Avg. Historic Across Rivers/GCMs (median cfs)	Avg. Future Across Rivers/GCMs (median cfs)	Sign. Difference Across Rivers/GCMs
May	25	0	4026	2758	***
June	35	0	2860	1568	***
July	39	0	1254	810	***
August	37	0	715	605	***
September	34	0	581	512	***
October	31	0	531	467	***
X1.day.min	36	0	452	401	***
X3.day.min	35	0	454	403	***
X7.day.min	35	0	460	408	***
X30.day.min	37	0	505	440	***
X90.day.min	35	0	757	617	***
June.lowf	23	0	1663	1216	***
July.lowf	38	0	1083	807	***
Aug.lowf	37	0	717	611	***
Sept.lowf	29	0	587	537	***

GCM Ensemble Results



Month	GCM x BASIN Sig Decrease (n=48)
March	3
April	10
May	20
June	32
July	37

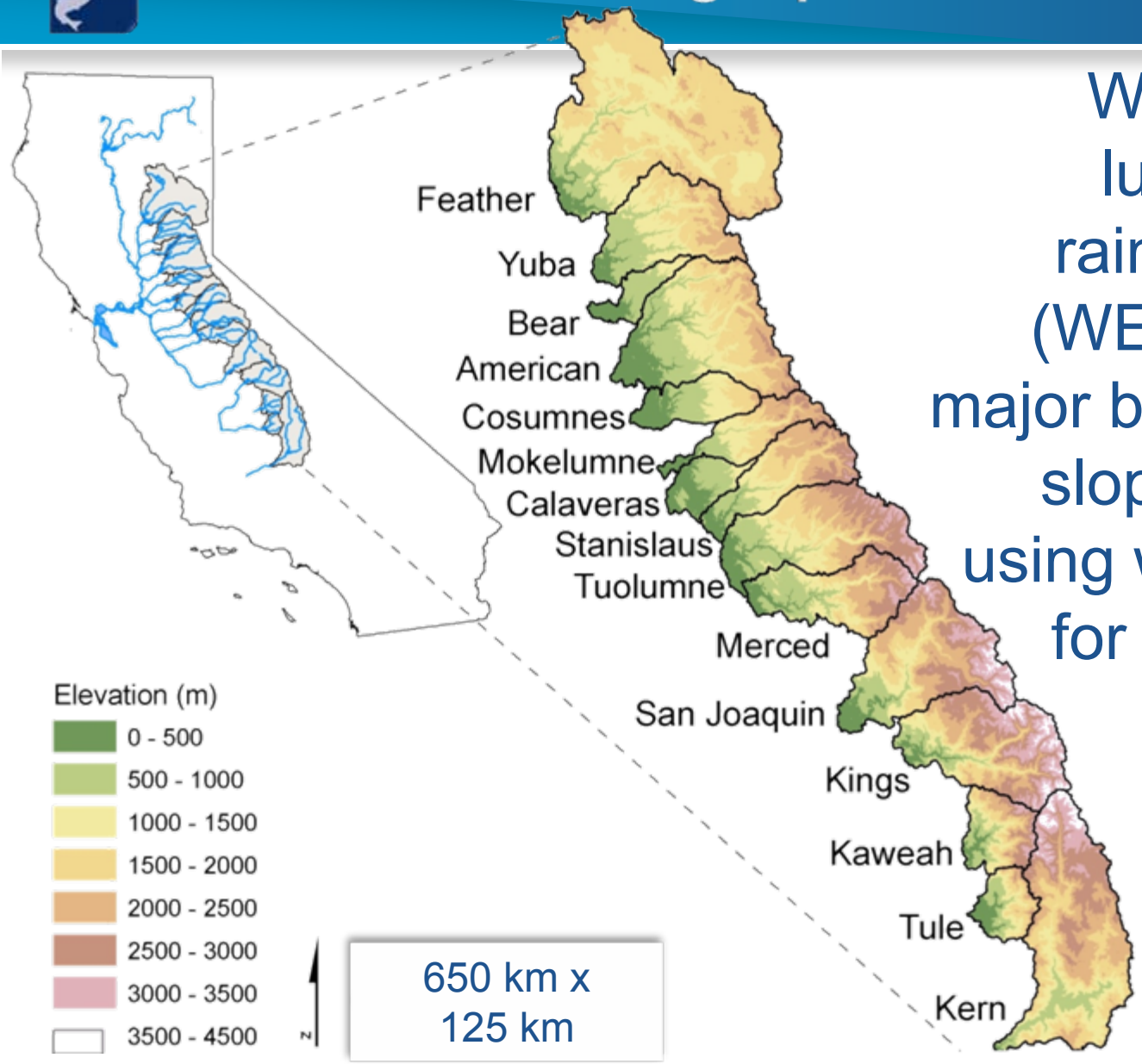
MODELING THE HYDROLOGY OF CLIMATE CHANGE IN CALIFORNIA'S SIERRA NEVADA FOR SUB-WATERSHED SCALE ADAPTATION

2009

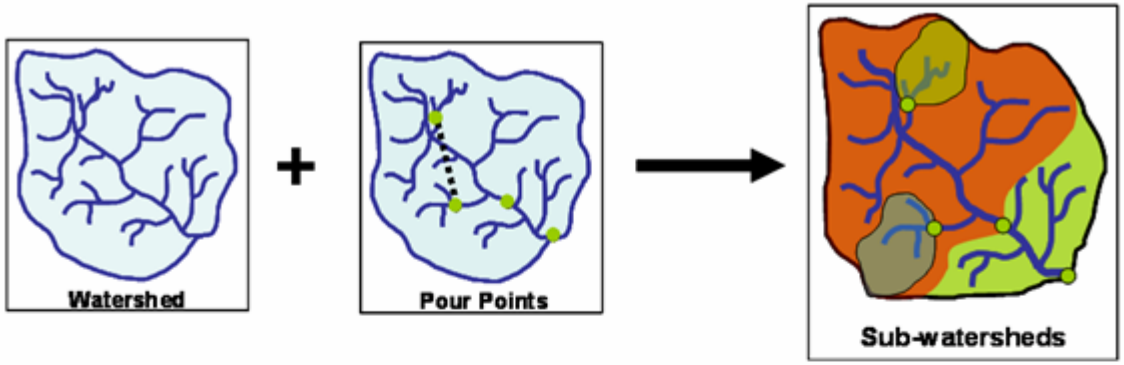
Journal of the American Water Resources Association
(45)6: 1409-1423

CA Young, M Escobar, M Fernandes, B Joyce, M Kiparsky, JF Mount, V Mehta, D Purkey, JH Viers, and D Yates

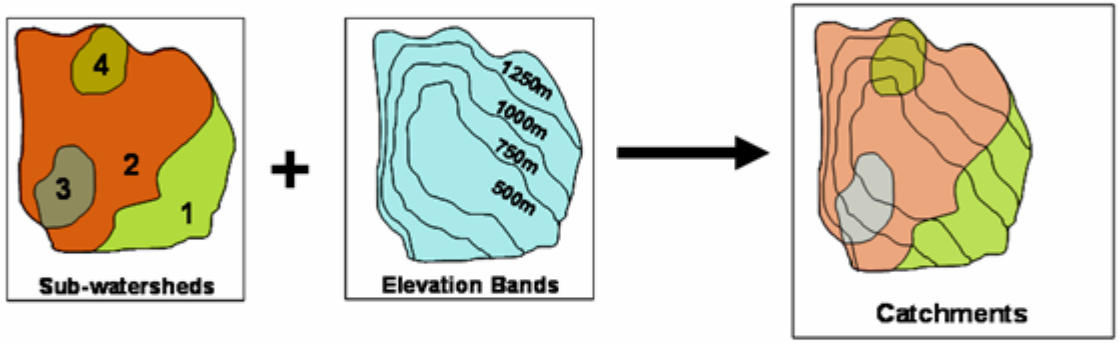
Scaling Up Snowmelt



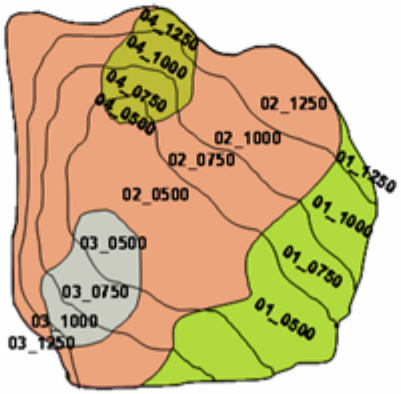
We implemented a lumped parameter rainfall-runoff model (WEAP21) for the 15 major basins of the west slope Sierra Nevada using weekly timesteps for 1980-2001 WYs.



A. Sub-watershed Delineation



B. Elevation Banding



C. Final Catchments

Physical Parameters:

Watershed Delineation
(USGS 10m DEM-based)

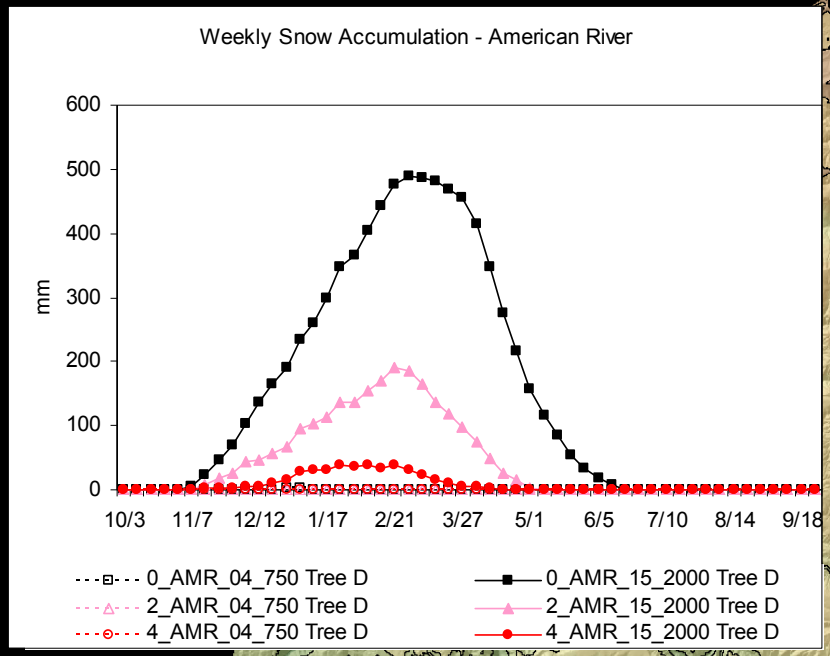
Elevation Banding (250m)

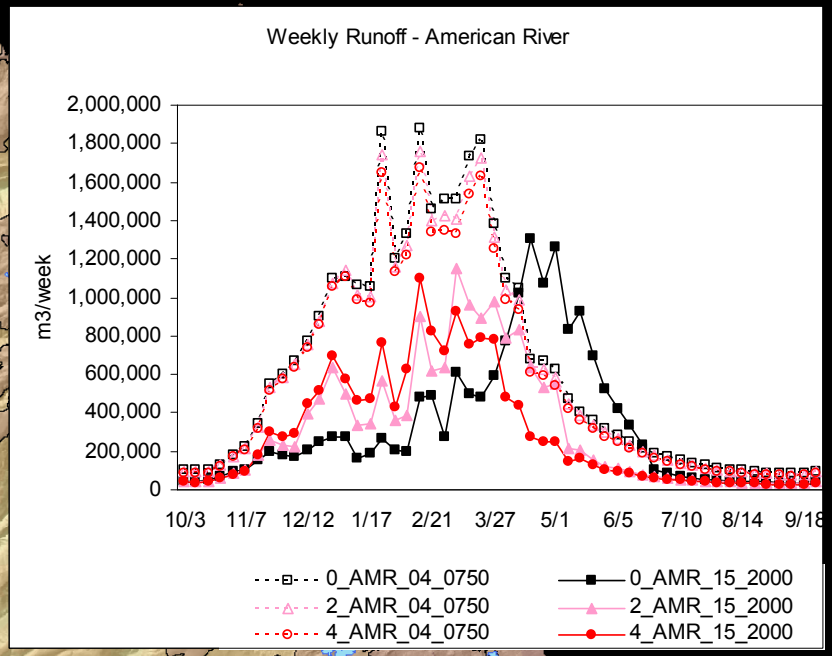
Existing Climate
(DAYMET '81 – '01 for Precipitation, Air Temperature, Wind Speed, etc)

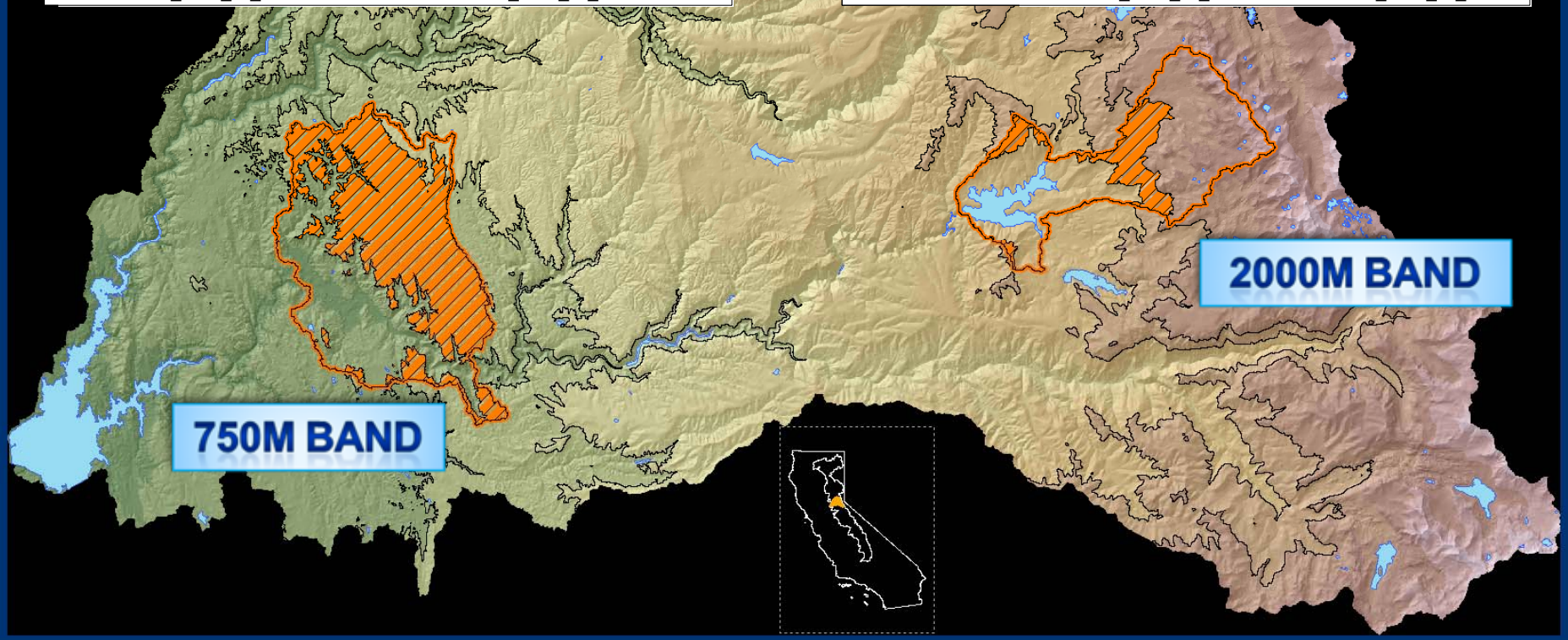
Soil Depth (SSURGO/STATSGO)

Terrestrial Vegetation (NLCD)

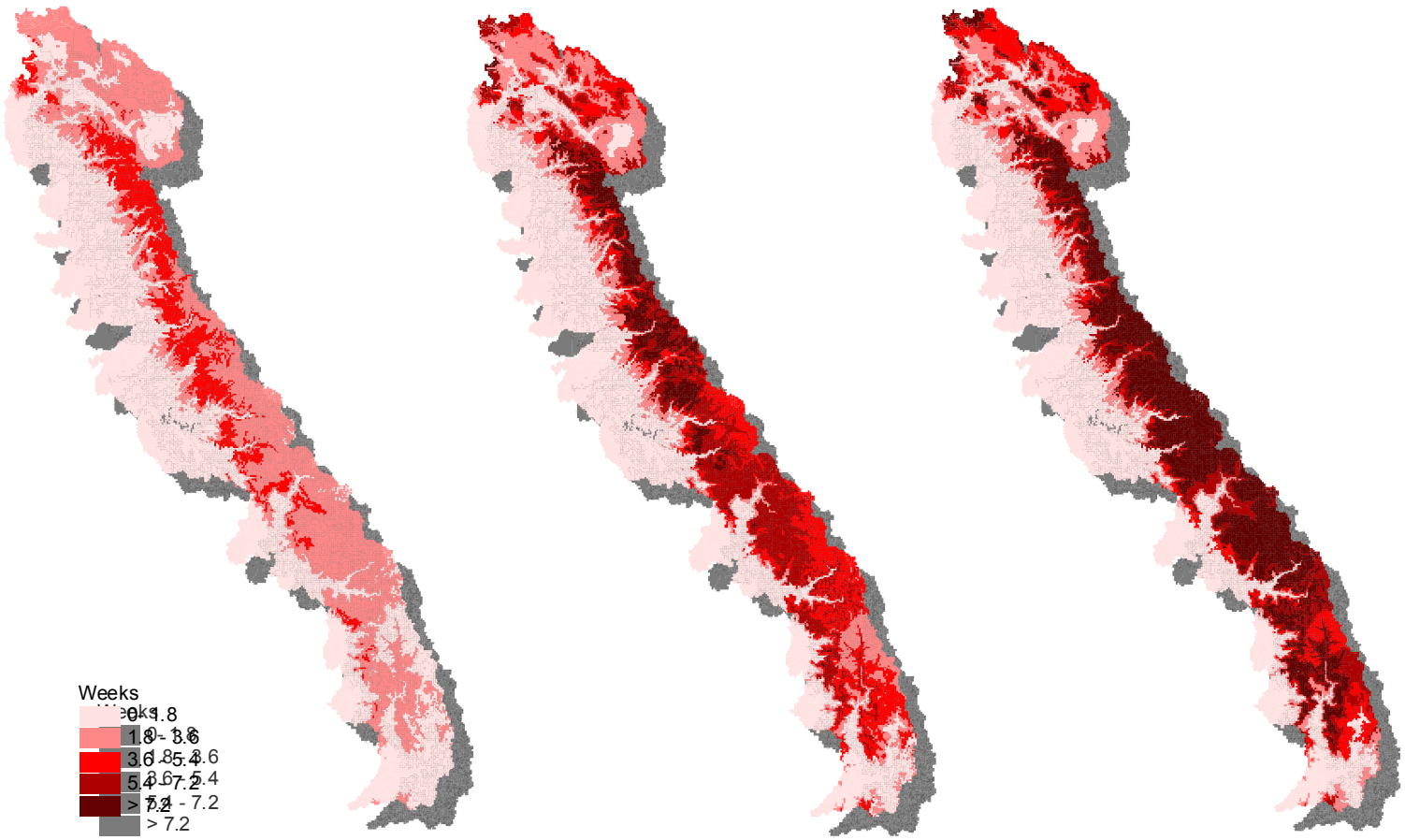
15 Watersheds
267 Subwatersheds
1267 Catchments
7 x 2 Land Cover by Soil Depth


Weekly Snow Accumulation - American River
mm
600
500
400
300
200
100
0
10/3
11/7
12/12
1/17
2/21
3/27
5/1
6/5
7/10
8/14
9/18
0_AMR_04_750 Tree D
2_AMR_04_750 Tree D
4_AMR_04_750 Tree D
0_AMR_15_2000 Tree D
2_AMR_15_2000 Tree D
4_AMR_15_2000 Tree D

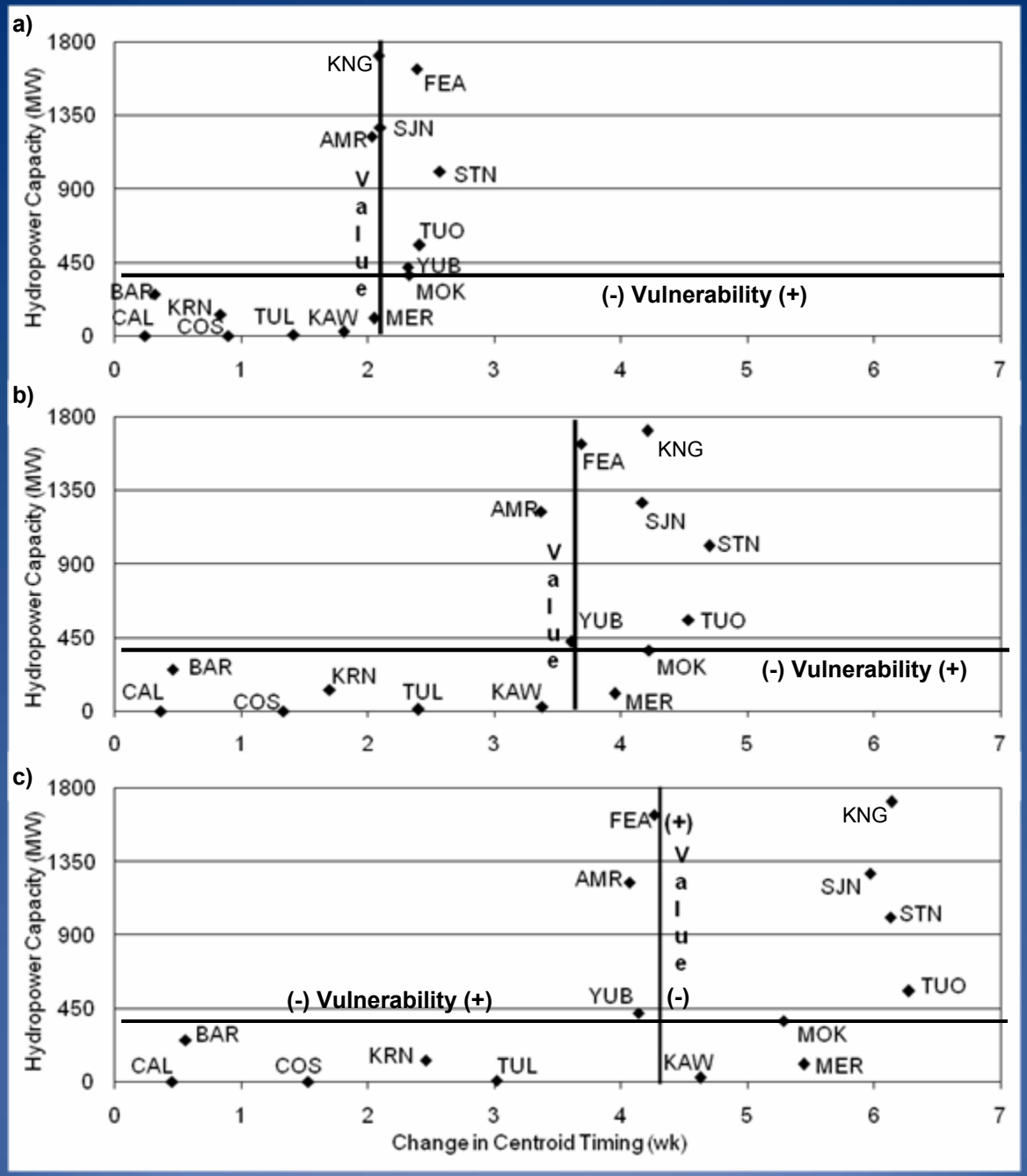

Weekly Runoff - American River
m3/week
2,000,000
1,800,000
1,600,000
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
10/3
11/7
12/12
1/17
2/21
3/27
5/1
6/5
7/10
8/14
9/18
0_AMR_04_0750
2_AMR_04_0750
4_AMR_04_0750
0_AMR_15_2000
2_AMR_15_2000
4_AMR_15_2000


750M BAND
2000M BAND

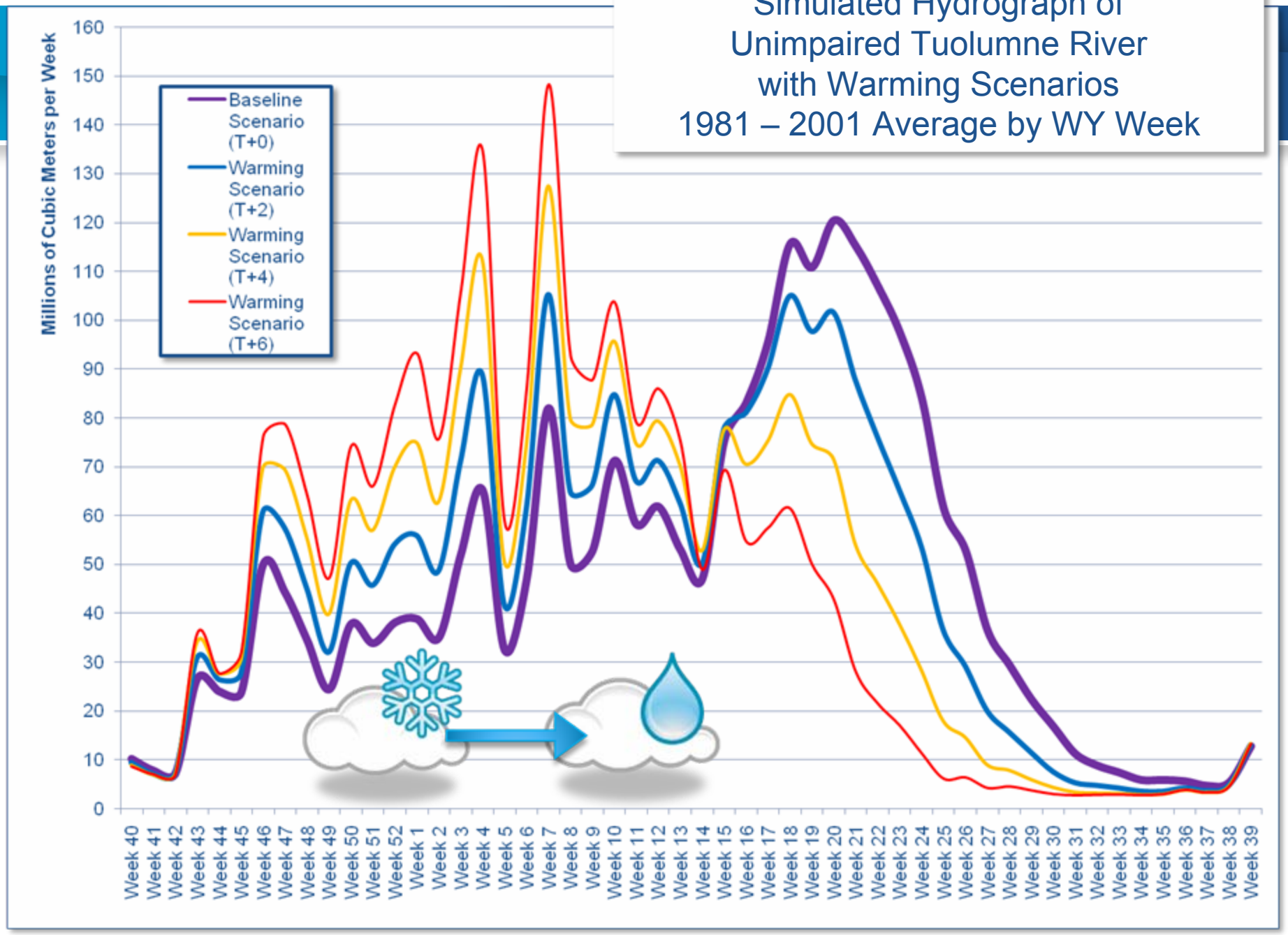
Strong altitudinal and latitudinal gradients in timing of runoff



Shift in runoff center of mass for 2, 4, and 6 degree increases in temperature (from left to right). Values are averages for 1981 – 2001.


a)
Hydropower Capacity (MW)
1800
1350
900
450
0
KNG
FEA
AMR
SJN
STN
TUO
YUB
MOK
BAR
CAL
KRN
COS
TUL
KAW
MER
Value
(-) Vulnerability (+)
0
1
2
3
4
5
6
7
b)
Hydropower Capacity (MW)
1800
1350
900
450
0
FEA
KNG
AMR
SJN
STN
YUB
TUO
MOK
BAR
CAL
COS
KRN
TUL
KAW
MER
Value
(-) Vulnerability (+)
0
1
2
3
4
5
6
7
c)
Hydropower Capacity (MW)
1800
1350
900
450
0
FEA
(+)
KNG
AMR
SJN
STN
Value
TUO
(-) Vulnerability (+)
YUB
(-)
MOK
BAR
CAL
COS
KRN
TUL
KAW
MER
0
1
2
3
4
5
6
7
Change in Centroid Timing (wk)

Simulated Hydrograph of Unimpaired Tuolumne River with Warming Scenarios 1981 – 2001 Average by WY Week

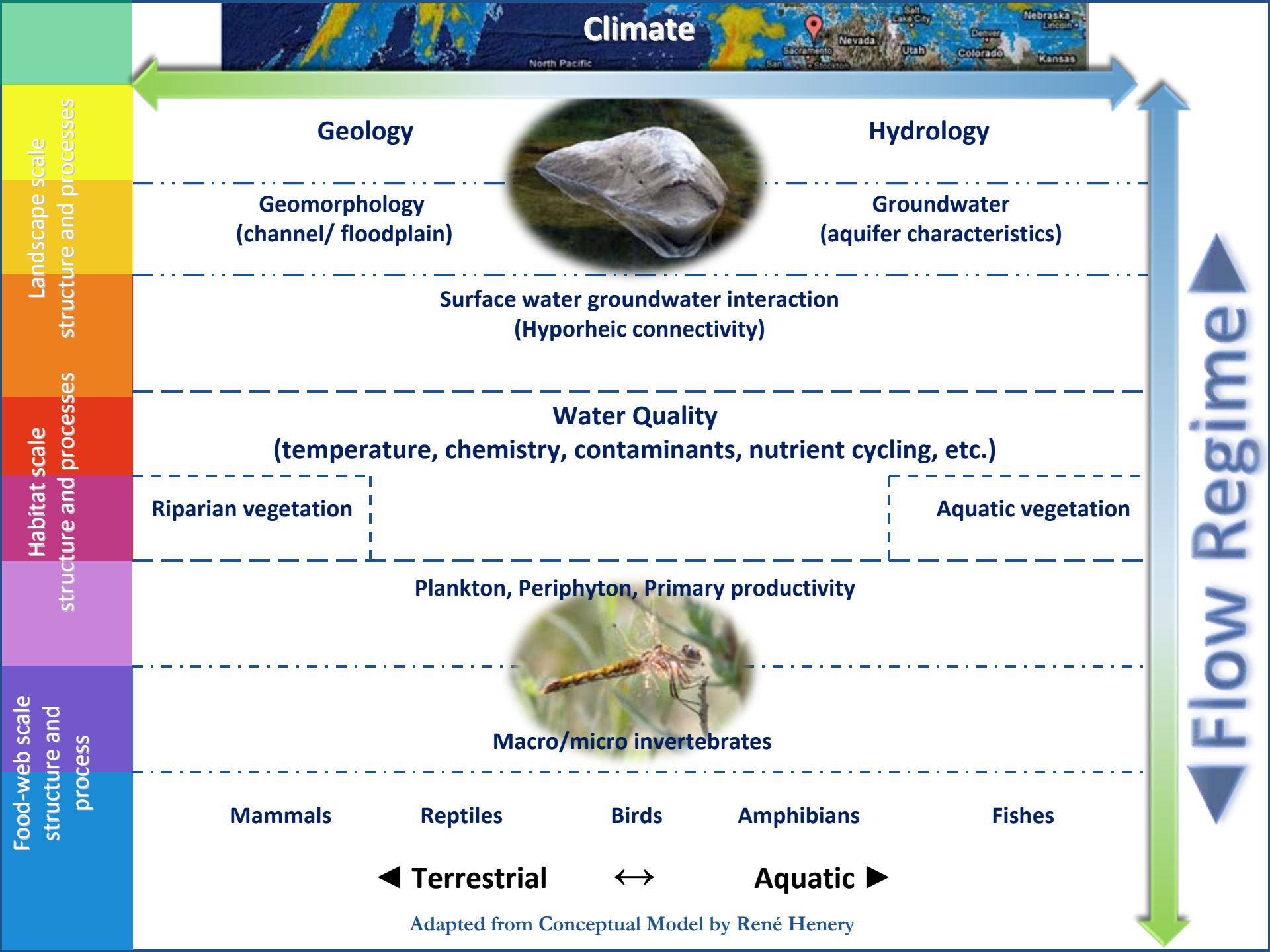


ECOLOGY AND MANAGEMENT OF THE SPRING SNOWMELT RECESSION

2010

BioScience

S Yarnell, JH Viers, and JF Mount



Adapted from Conceptual Model by René Henery

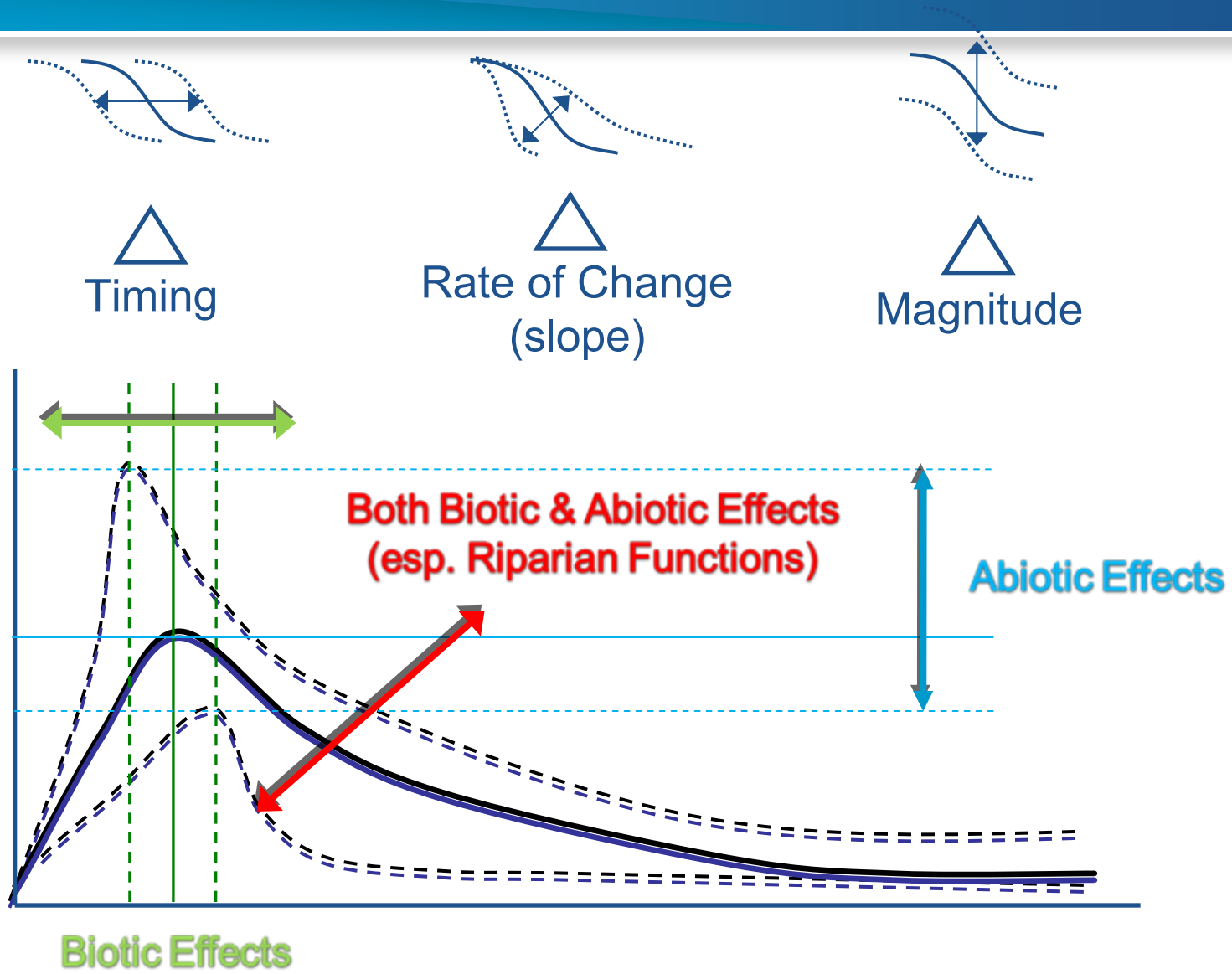
Spring Snowmelt Recession

the physical, chemical and biological impact of this spring-time pulse of water is profound…

Important to both geomorphic and ecological processes...

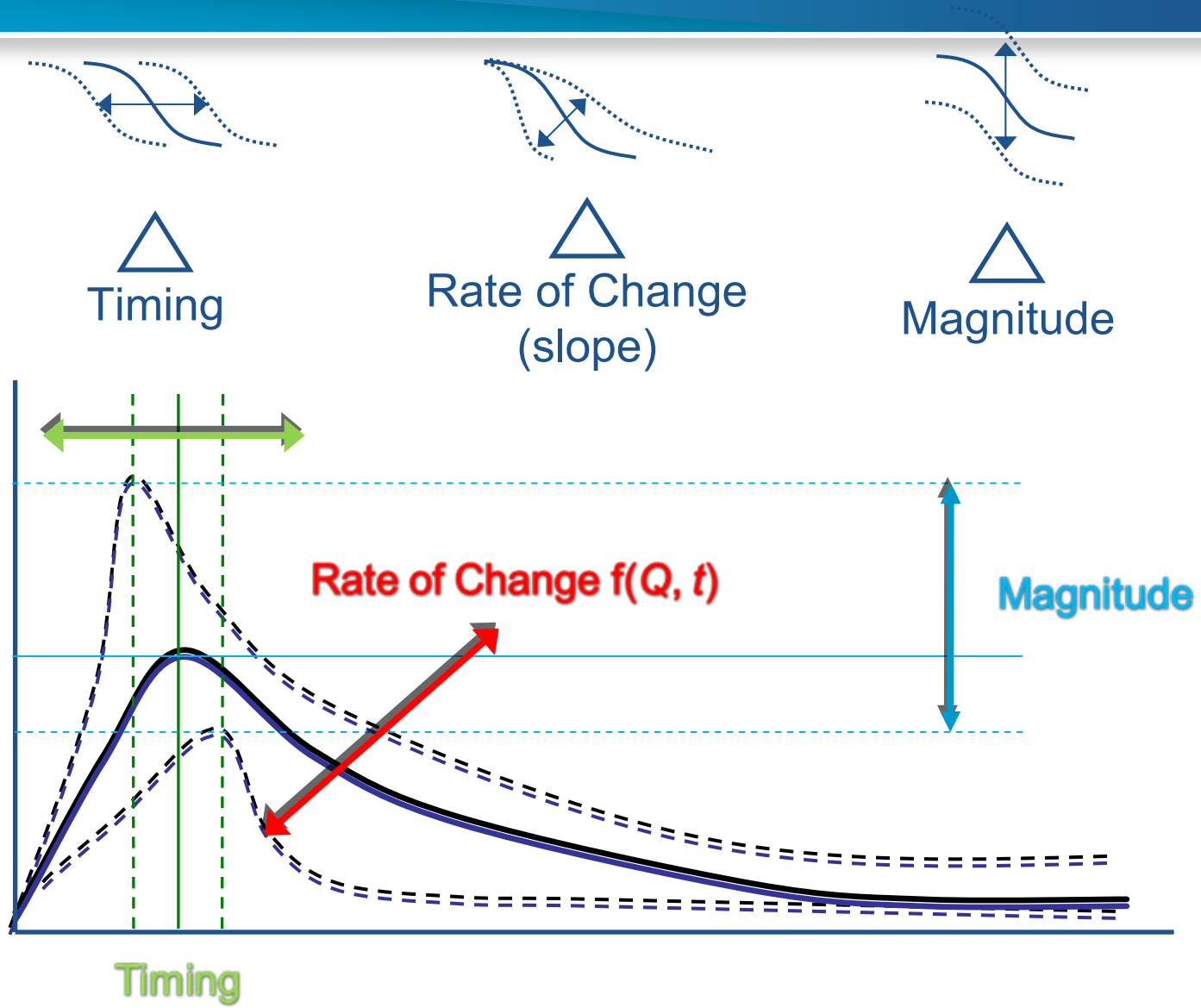
- ***Montane*** ► bulk of the total annual discharge, often delivering more than 70% of annual streamflow
  - (Hauer et al. 1997).
- ***Mediterranean-montane*** ► summer low flows dominate for up to six months of the year and at least 65% of annual precipitation falls in the three months of winter
  - (Gasith and Resh 1999).

Recession Limb Ecology

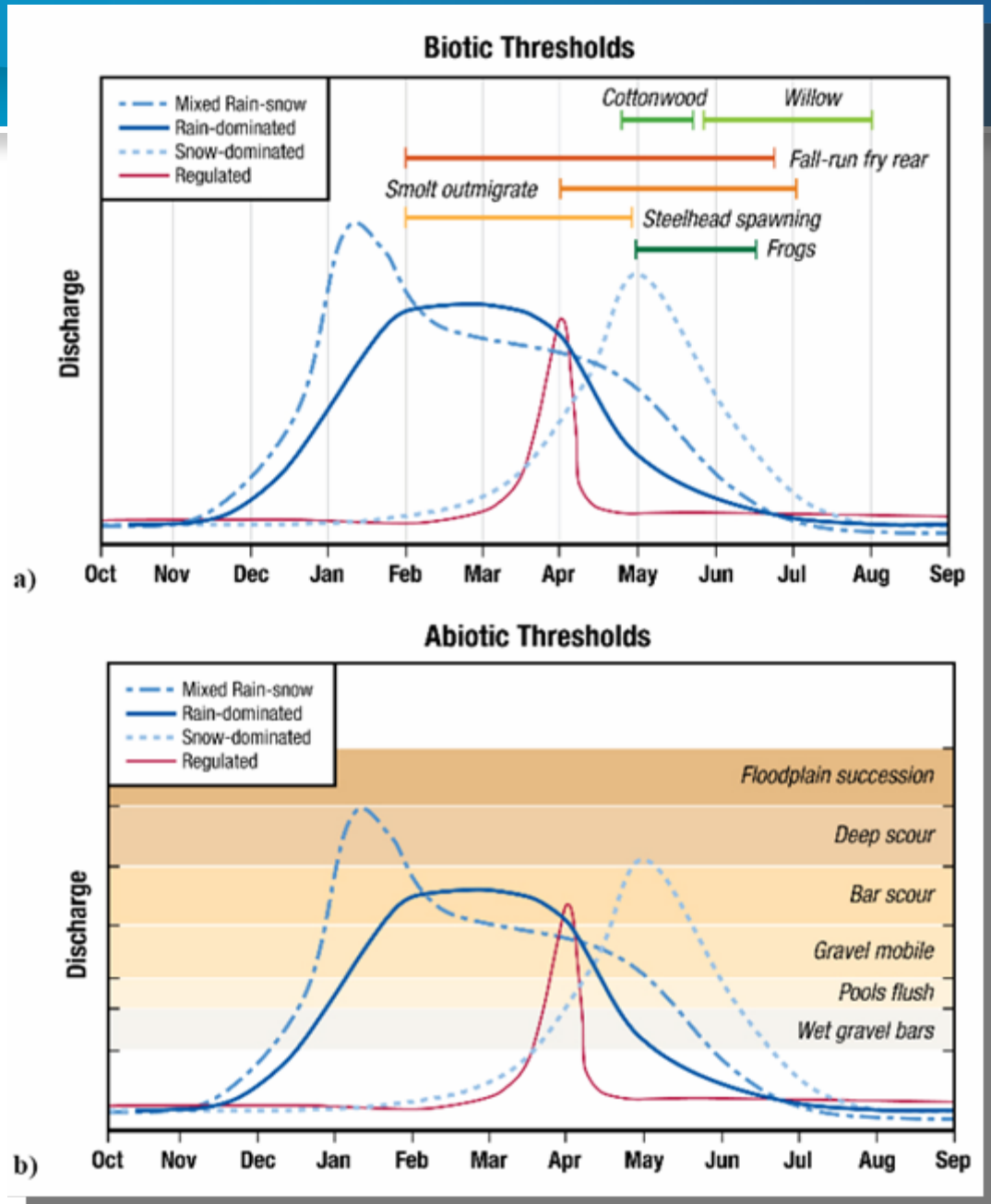


Yarnell, Viers, and Mount (2010)

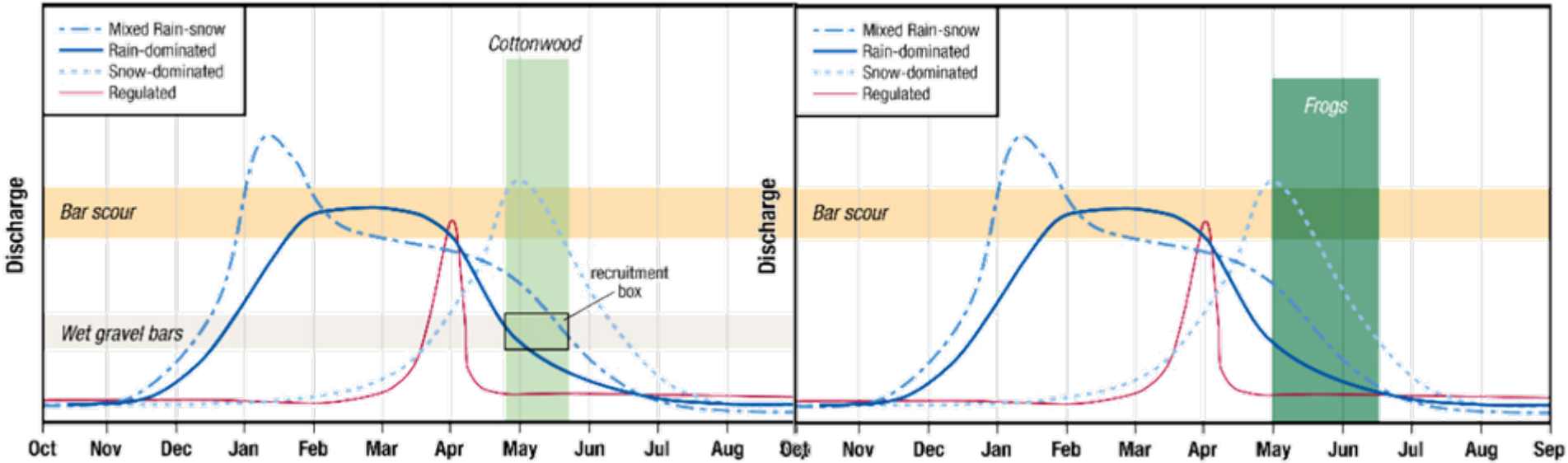
Recession Limb Mechanics



Yarnell, Viers, and Mount (2010)


Biotic Thresholds
Mixed Rain-snow
Rain-dominated
Snow-dominated
Regulated
Cottonwood
Willow
Fall-run fry rear
Smolt outmigrate
Steelhead spawning
Frogs
Discharge
a)
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Abiotic Thresholds
Mixed Rain-snow
Rain-dominated
Snow-dominated
Regulated
Floodplain succession
Deep scour
Bar scour
Gravel mobile
Pools flush
Wet gravel bars
Discharge
b)
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep

Recession Ecology



CHARACTERIZATION OF THE UNREGULATED SPRING SNOWMELT RECESSION AND POTENTIAL CHANGES WITH CLIMATE WARMING

In Prep

JH Viers, GE Epke, SM Yarnell, and JF Mount

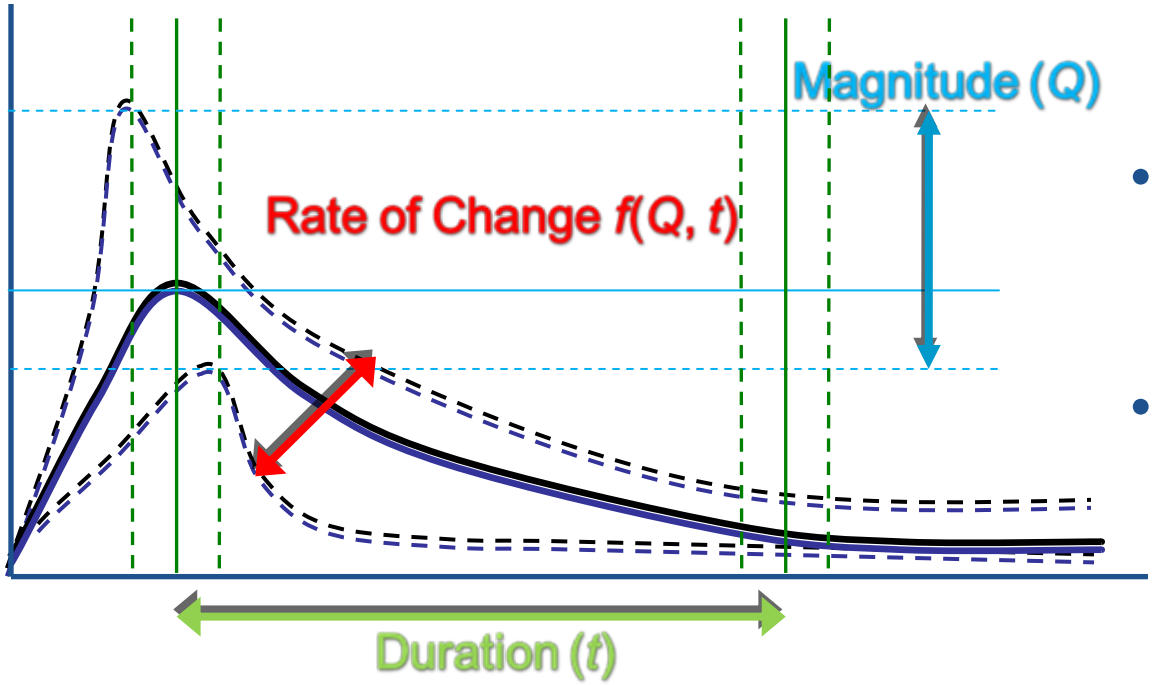
Recession Limb

Timing

Rate of Change (slope)

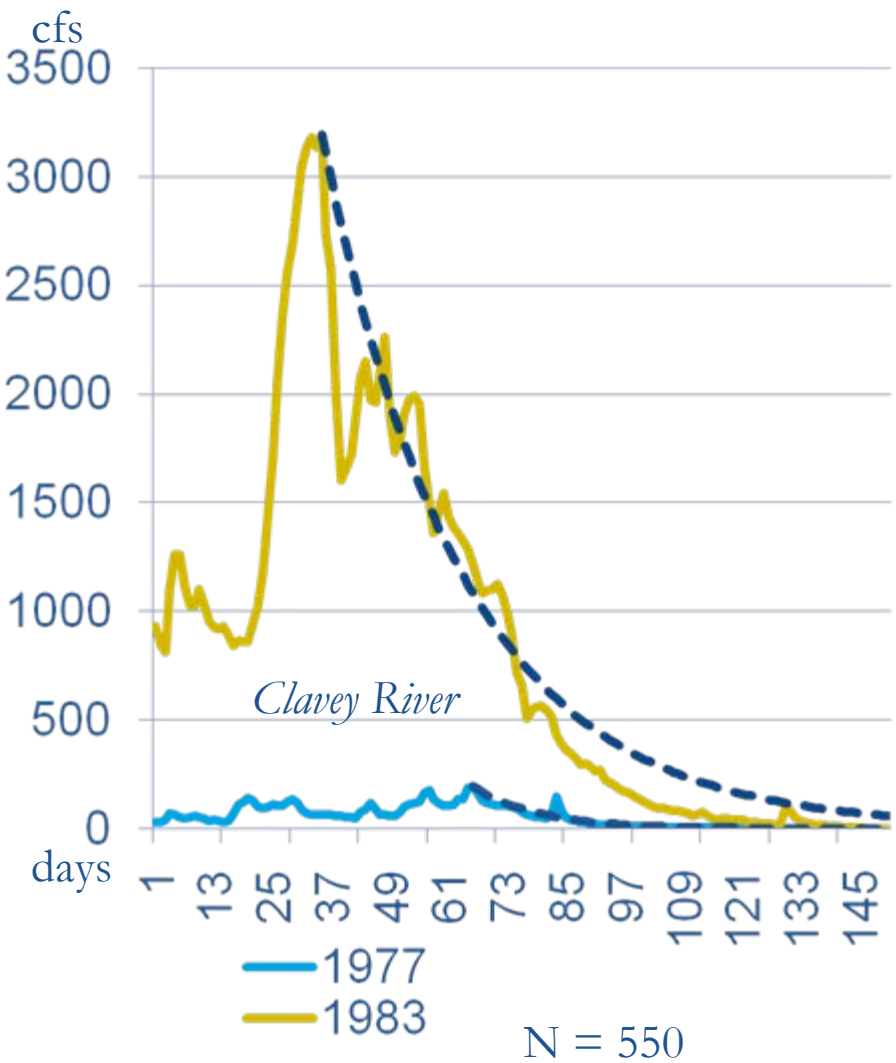
Magnitude

$$Q_i = Q_0 e^{-kt}$$



- Simplicity of decay function is most parsimonious
- Can be used at multiple spatial and temporal scales
- Can be used by water managers as rule of thumb to better mimic natural flow regime

Recession Method

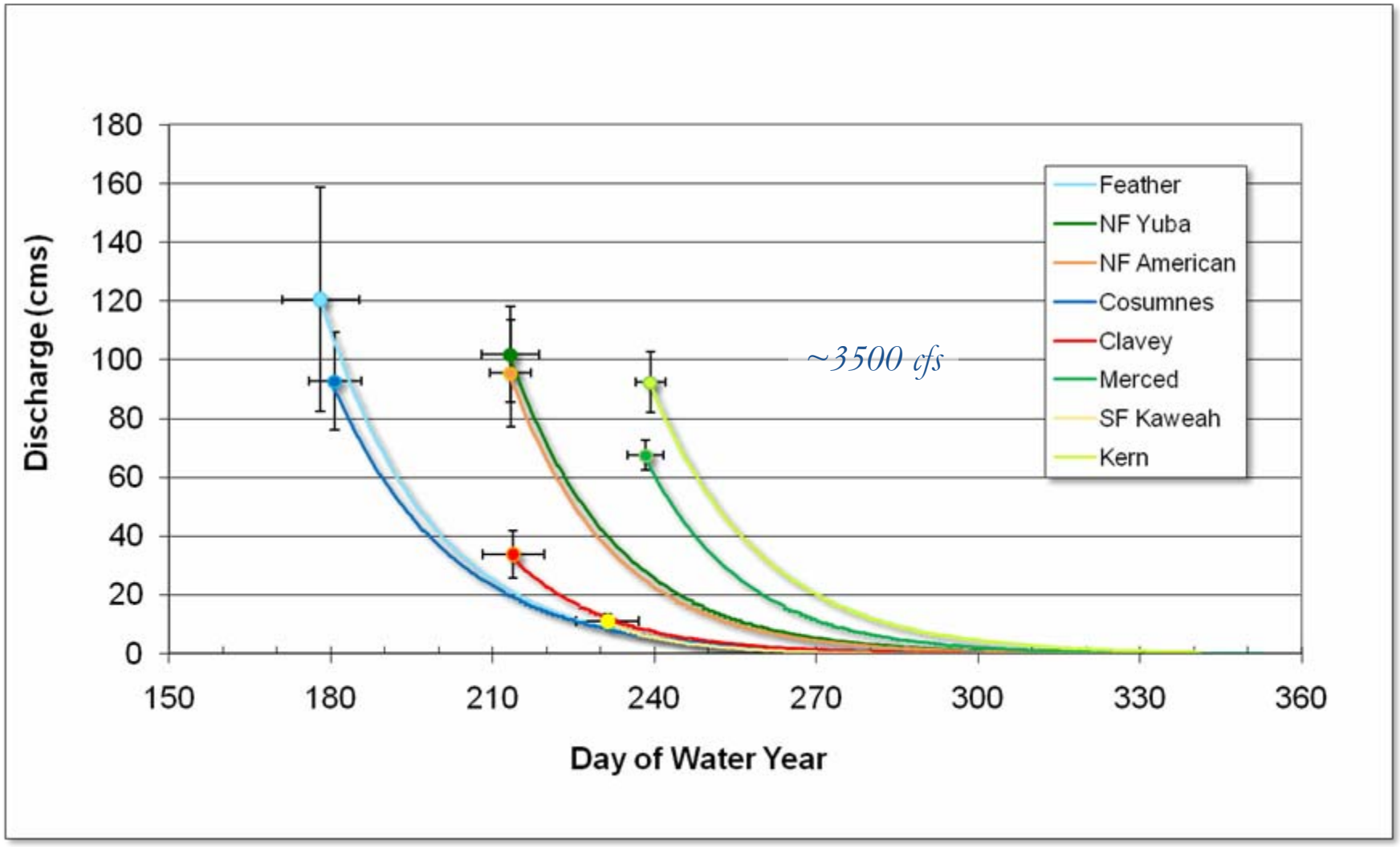


1. Identify beginning of low flow period / end of snowmelt recession, as either:
   - First day of four consecutive day period without change in discharge
   - Day of both minimum flow and minimum rate of change
2. Identify day of maximum discharge within 150 days of end of snowmelt recession period to establish time series
3. Fit semi-log ordinary least squares regression against time (*t*); determine slope (*k*)
4. Evaluate modeled fit of slope (k_{mod}) with Nash-Sutcliffe Model Efficiency (NSME)

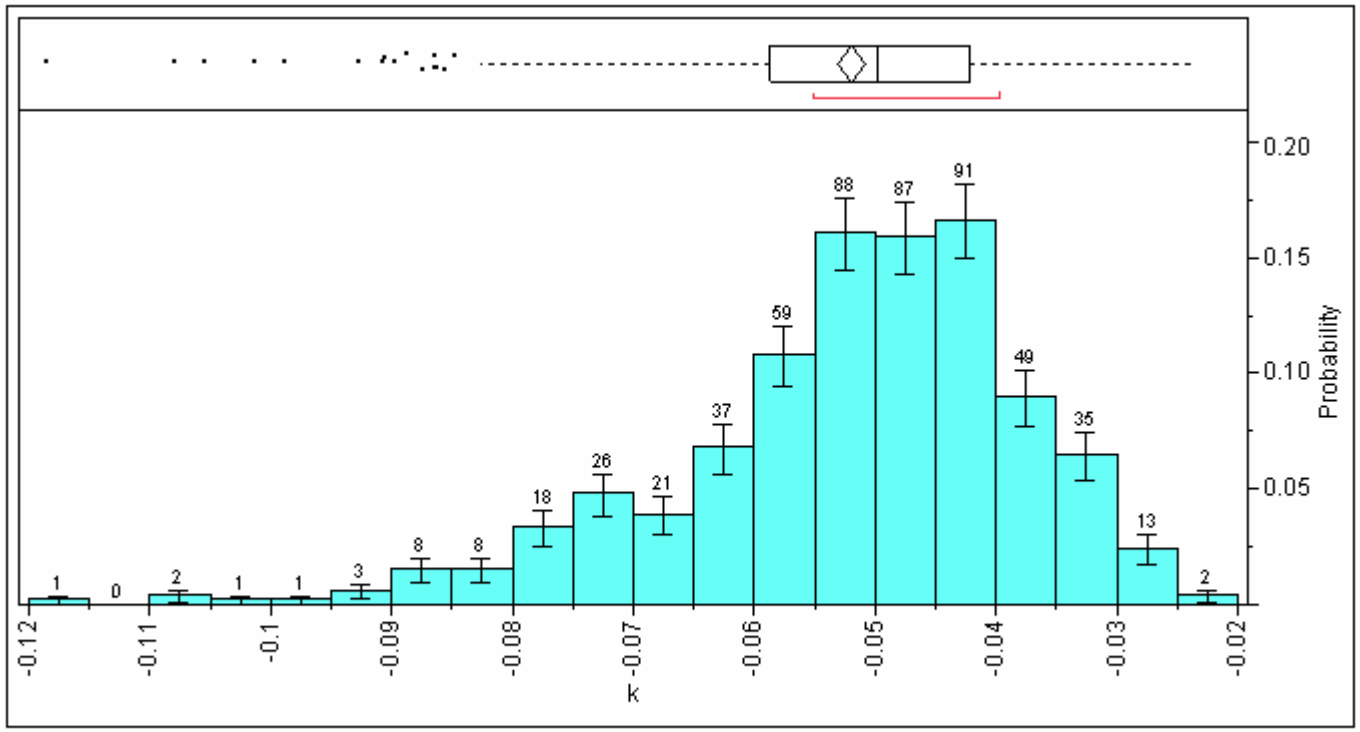
Site Descriptors

Watershed	Site (USGS #)	Elevation (m)	Drainage Area (km^2)	Record (yrs)	Latitude (° N)
Feather	Indian C. nr Crescent Mill (11401500)	1067	1914	63	40.08
NF Yuba	Goodyears Bar (11413000)	748	647	77	39.53
NF American	North Fork (11427000)	218	886	66	38.94
Cosumnes	Michigan Bar (11335000)	51	1388	100	38.50
Clavey	Buck Meadows (11283500)	724	373	34	38.90
Merced	Happy Isles Br. (11264500)	1224	469	93	37.73
SF Kaweah	Three Rivers (11210100)	246	223	31	36.42
Kern	Comb. Kern & No 3 (11186001)	831	2191	96	35.95

Spring Snowmelt Recession Curves

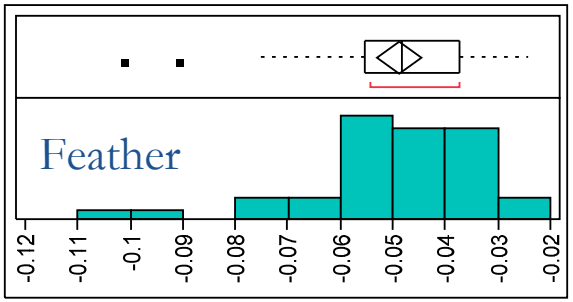


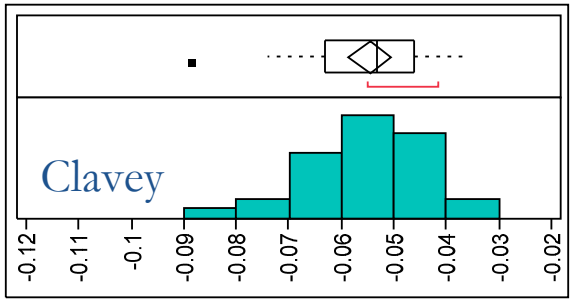
Recession (k_{mod})Distribution

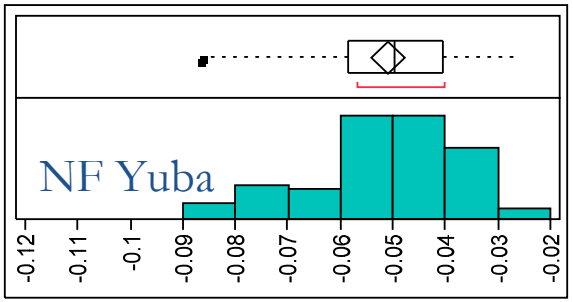


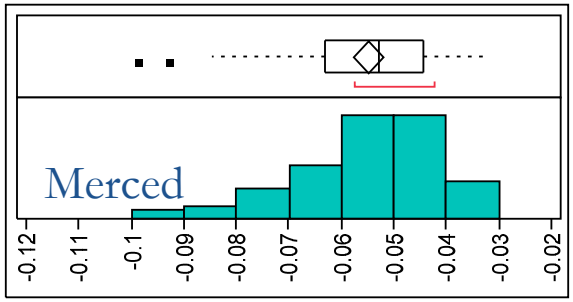
Mean	-0.051955	N	550
Std Dev	0.0143595	Variance	0.0002062
Std Err Mean	0.0006123	Skewness	-0.933088
Upper 95% Mean	-0.050752	Kurtosis	1.4124287
Lower 95% Mean	-0.053158		

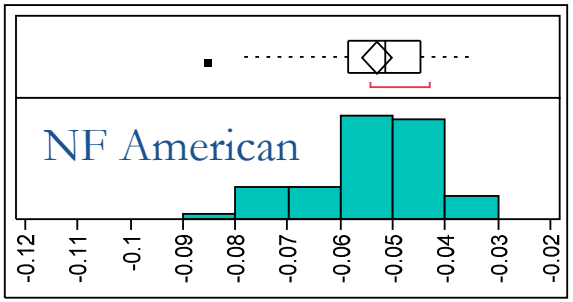
Basin Distributions

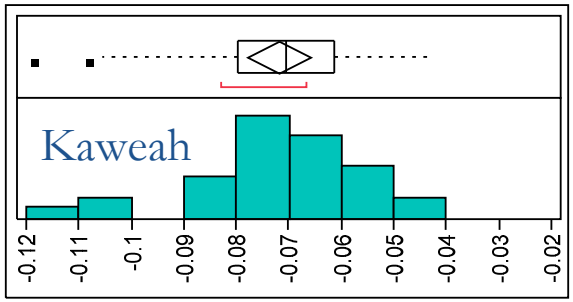


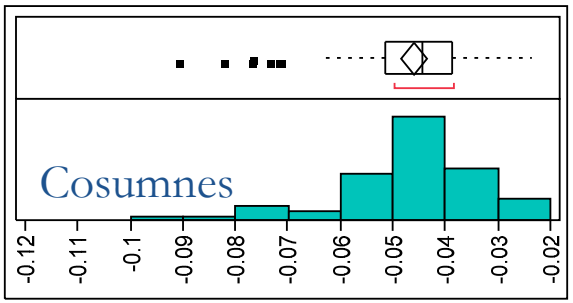


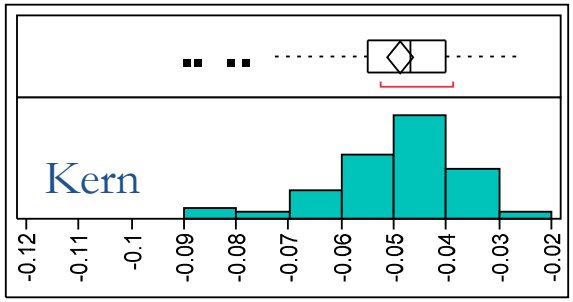












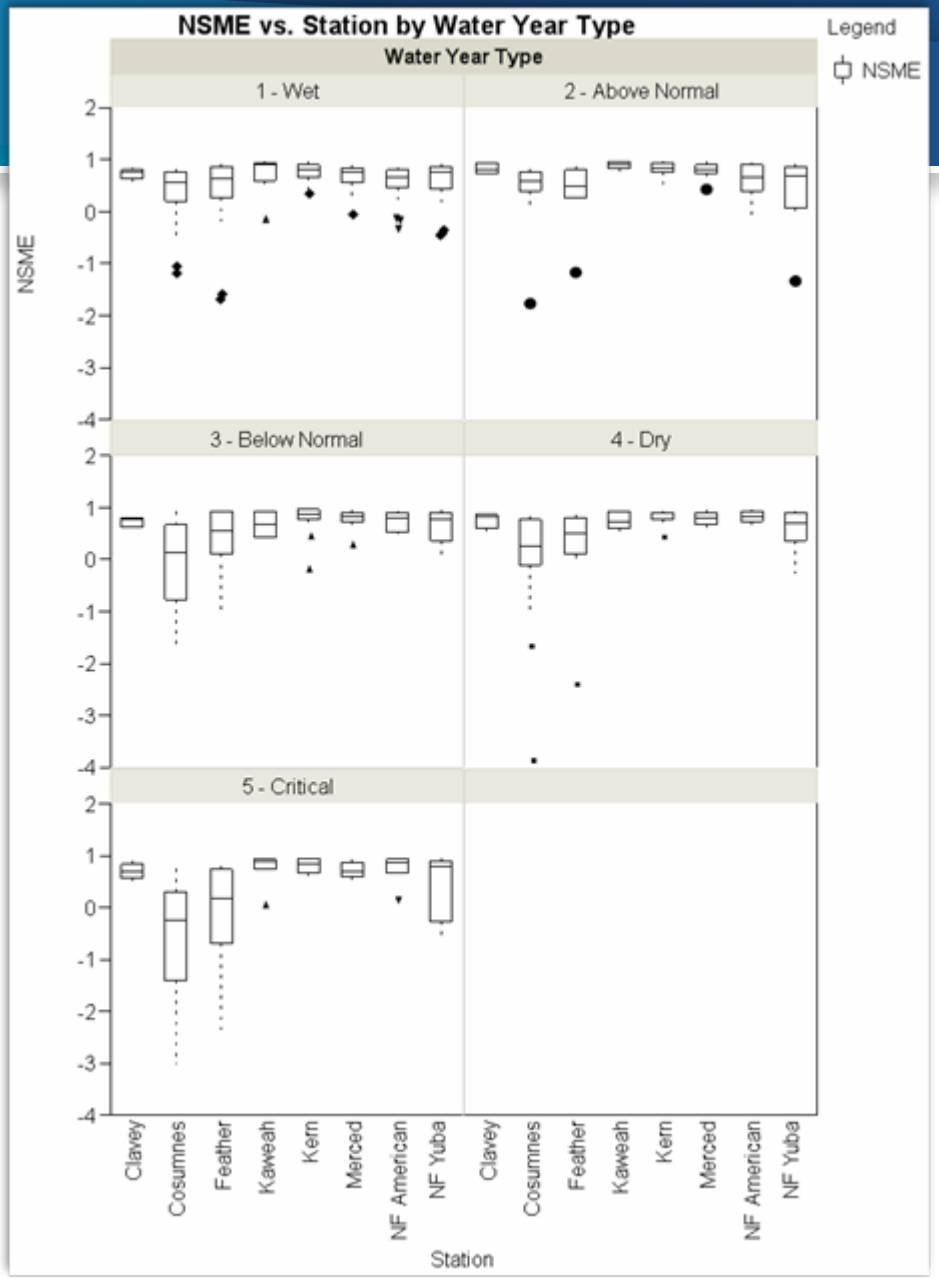
NSME Trends

Means for Oneway Anova of NSME Scores across Stations

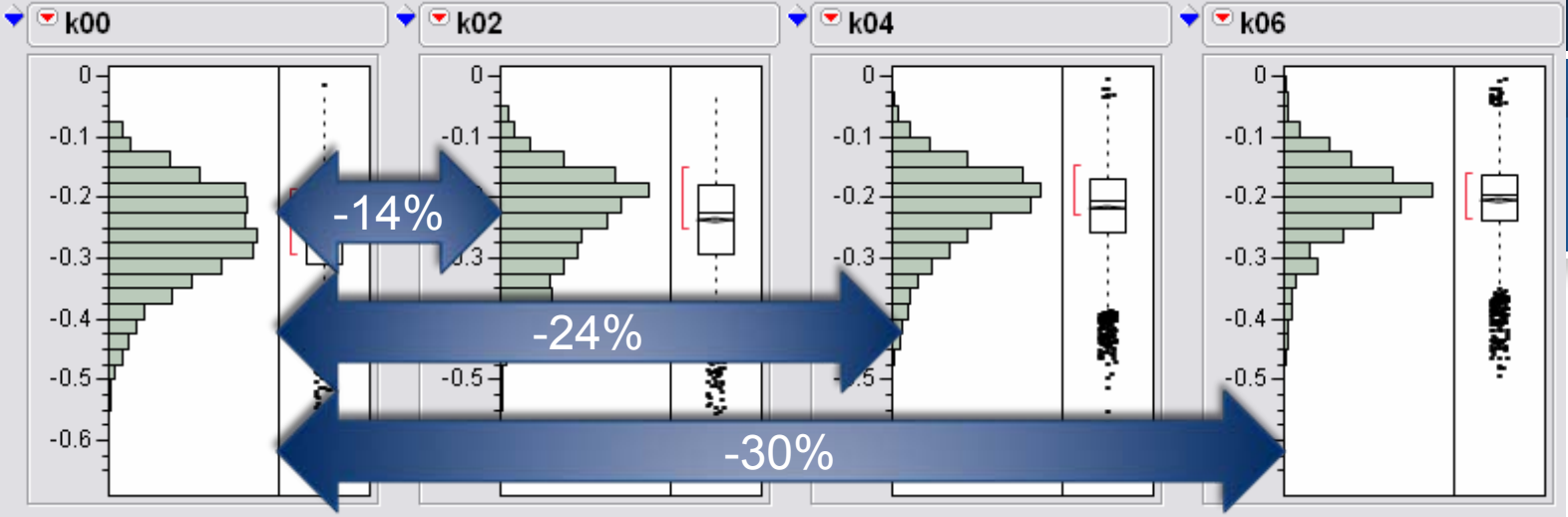
Level	N	Mean	Std Error	Lower 95%	Upper 95%
Kern	96	0.79	0.05	0.69	0.89
Kaweah	32	0.77	0.09	0.59	0.95
Merced	93	0.75	0.05	0.64	0.85
Clavey	32	0.73	0.09	0.55	0.91
NF American	67	0.70	0.06	0.55	0.80
NF Yuba	77	0.55	0.06	0.43	0.66
Feather	52	0.30	0.07	0.16	0.44
Cosumnes	101	0.12	0.05	0.02	0.22

Cosumnes River NSME by Water Year Type

Level	Level	Diff	Std Err Diff	p-Value
Above Normal	Critical	0.94	0.31	0.0284
Wet	Critical	0.91	0.27	0.0095



Simulated Unimpaired Flows for 20 Water Years



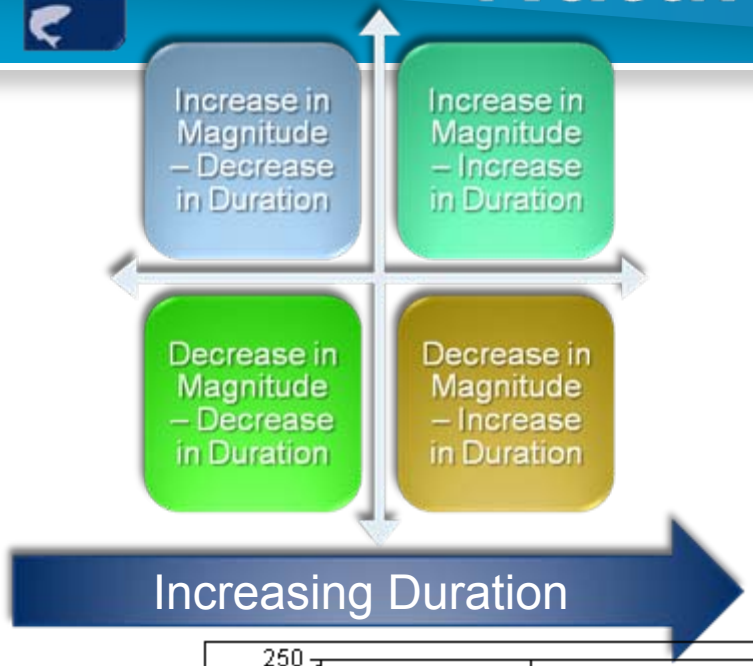
Quantiles

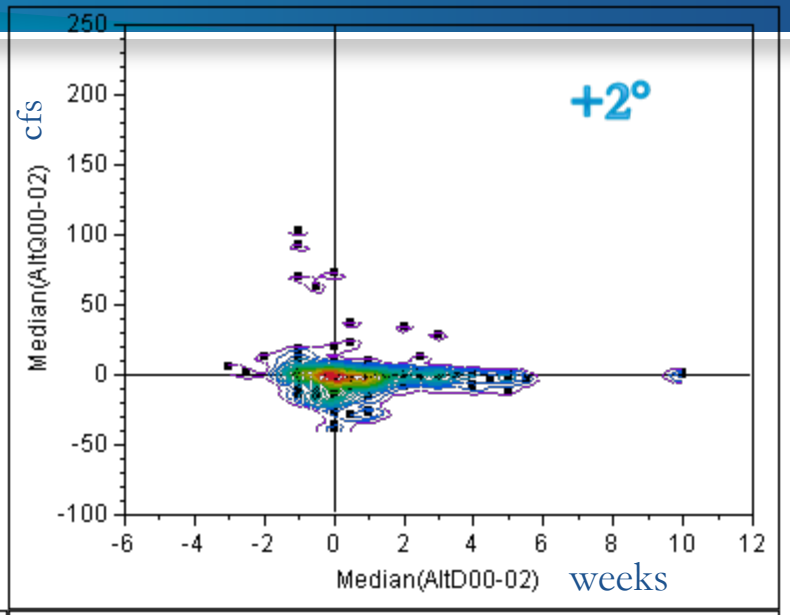
		k00	k02	k04	k06
100.0%	maximum	-0.0168	-0.0219	-0.0068	-0.0074
99.5%		-0.0906	-0.0698	-0.0584	-0.0449
97.5%		-0.1215	-0.1037	-0.0952	-0.0917
90.0%		-0.1587	-0.1444	-0.1353	-0.1291
75.0%	quartile	-0.1984	-0.1779	-0.1687	-0.1632
50.0%	median	-0.2554	-0.2243	-0.2063	-0.1972
25.0%	quartile	-0.3110	-0.2929	-0.2568	-0.2389
10.0%		-0.3668	-0.3547	-0.3193	-0.2957
2.5%		-0.4387	-0.4191	-0.3964	-0.3722
0.5%		-0.4939	-0.4922	-0.4477	-0.4421
0.0%	minimum	-0.6542	-0.6504	-0.5738	-0.4949

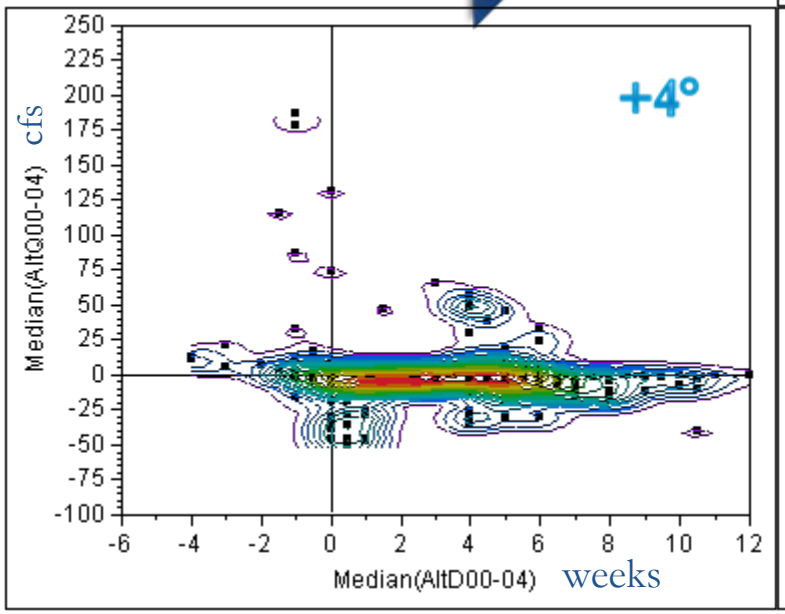
Moments

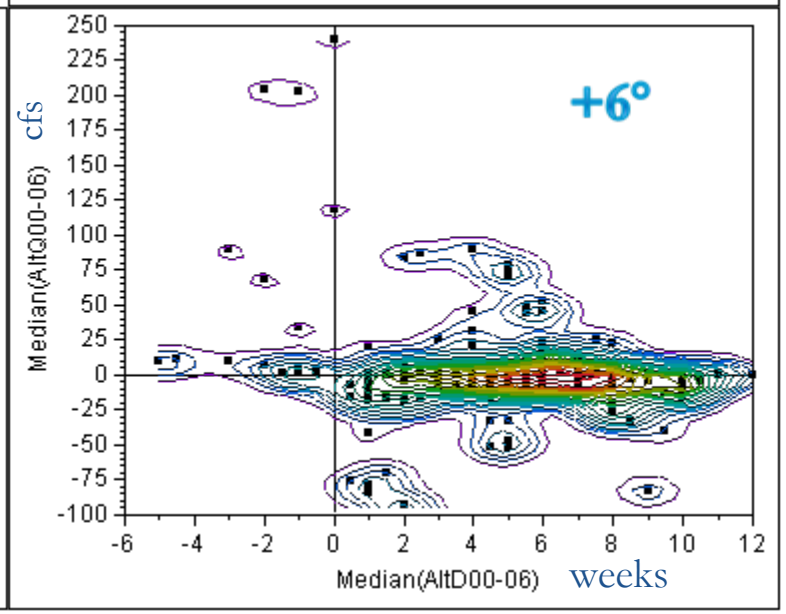
	k00	k02	k04	k06
Mean	-0.259622	-0.238092	-0.217567	-0.205492
Std Dev	0.0816614	0.0826156	0.0737997	0.0669995
Std Err Mean	0.0011886	0.0012088	0.0011003	0.0010209
Upper 95% Mean	-0.257292	-0.235722	-0.21541	-0.203491
Lower 95% Mean	-0.261952	-0.240462	-0.219724	-0.207494
N	4720	4671	4499	4307
Sum Wgt	4720	4671	4499	4307
Sum	-1225.415	-1112.126	-978.8322	-885.0541
Variance	0.0066686	0.0068253	0.0054464	0.0044889
Skewness	-0.440453	-0.617471	-0.75601	-0.76397
Kurtosis	0.1420303	0.2778851	0.8090187	1.3765095
CV	-31.45396	-34.69909	-33.92049	-32.60442
N Missing	500	549	721	913

Nature of Change

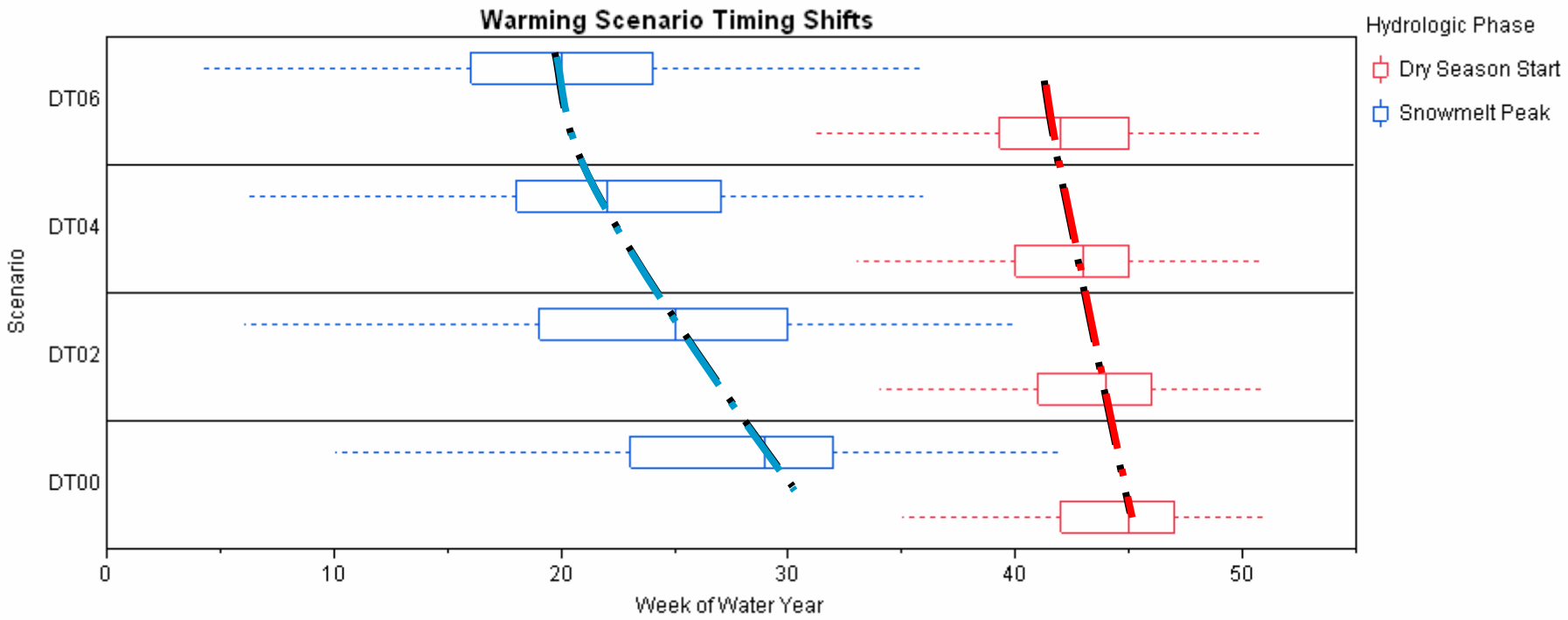








Increase in Duration



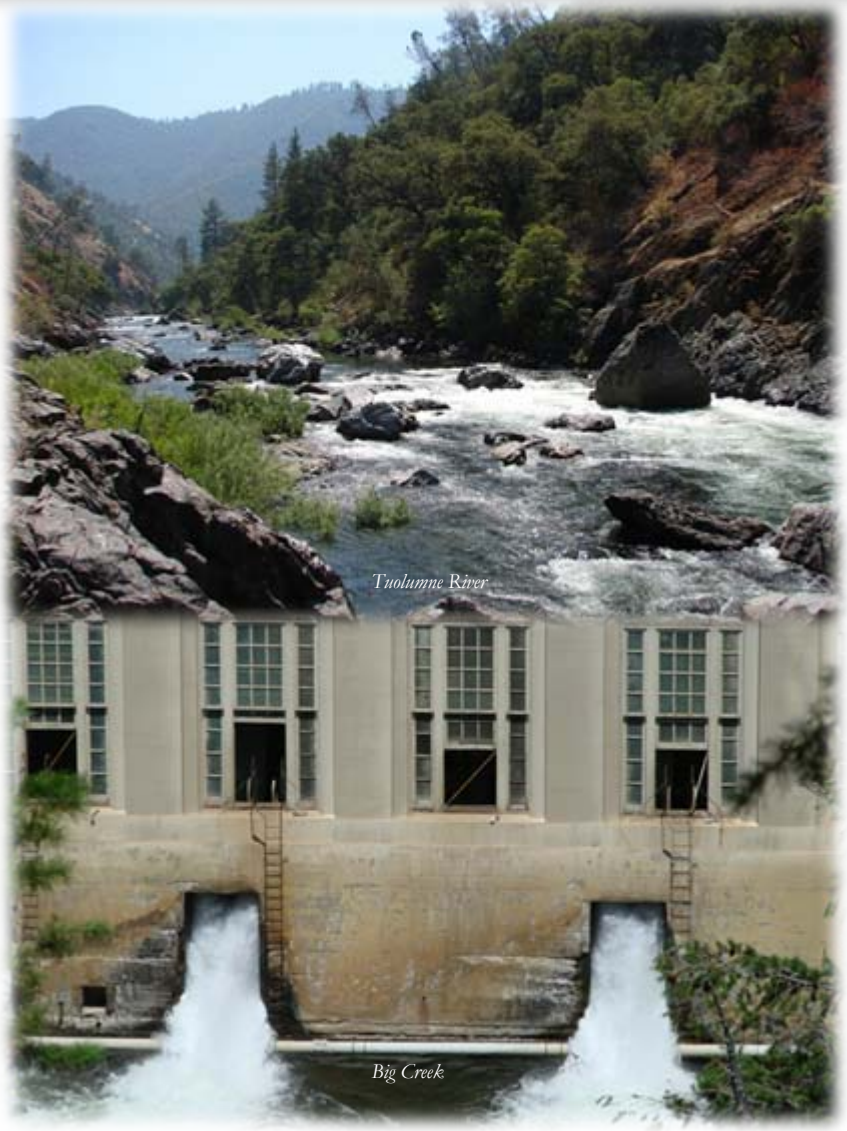
261 Individual Watersheds modeled for 20 Water Years of Unimpaired Flows across 15 Sierra Nevada Basins with 3 Warming Scenarios (+2,+4, +6° C)

changes in the hydrologic system are likely to have significant impacts on watersheds, aquatic & riparian ecosystems, and ecosystem services

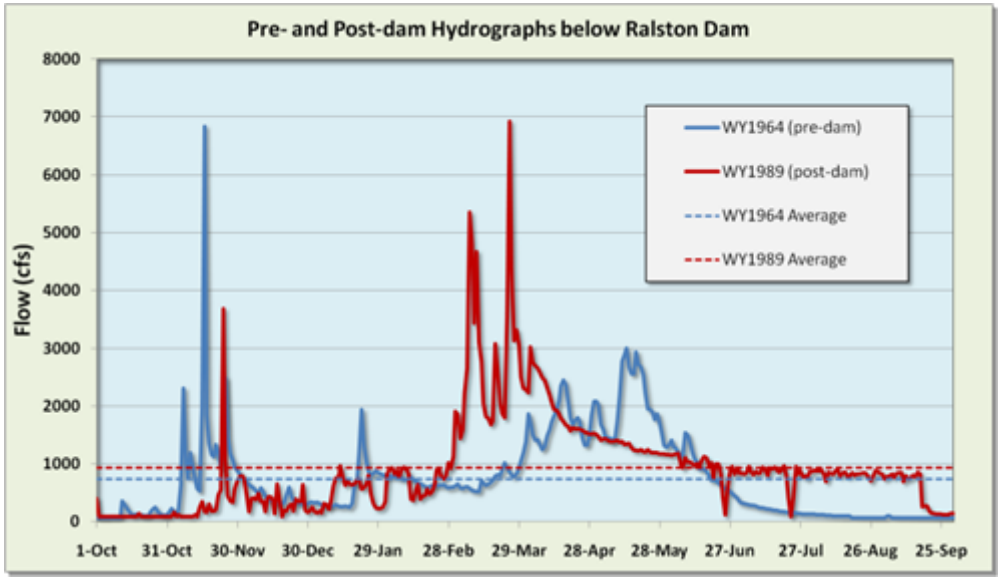
Potential Change	Cause	Potential Outcomes
Contraction and loss of meadows and wetlands	Loss of snow (and recharge) leading to lowering of water table; increased upland vegetation encroachment and potential Et losses to woody species	Increased erosion and sediment load due to incision; increased flashiness downstream; lower base flows in summer
Stream flow reduced for annual runoff	Changes in precipitation timing and type; increased losses to evapotranspiration	Reduces habitats (volume & niche space) of all aquatic species; increased water temperatures; due increased plant stress / desiccation / disease; shift in assemblages
Reduced summer low flows	Alteration of hydrologic regime; shift in timing of center of mass; increased losses to evapotranspiration	Reduction in physical habitat; increased water temperatures; increased physiological stress in some animals; due increased plant stress / desiccation / disease
Reduction in rate of snowmelt recession	Increased separation between peak snowmelt period and initiation of low flow season (duration) and decreased snowmelt magnitude	decreased disturbance with increased riparian establishment where substrate and hyporheic flows allow; channel hardening

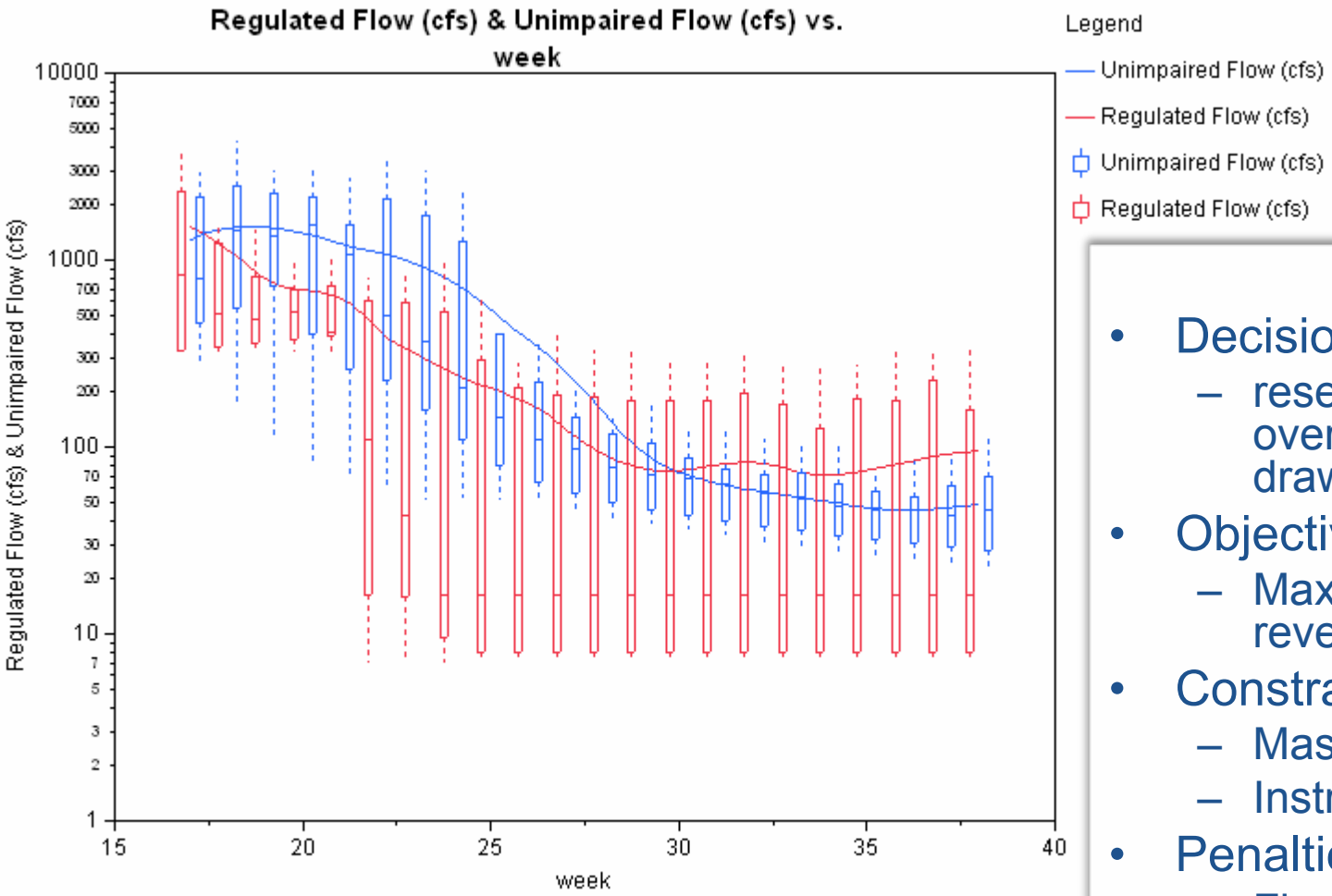
Natural Flow Regime

Poff et al. 1997



- magnitude
- timing
- duration
- frequency
- rate of change

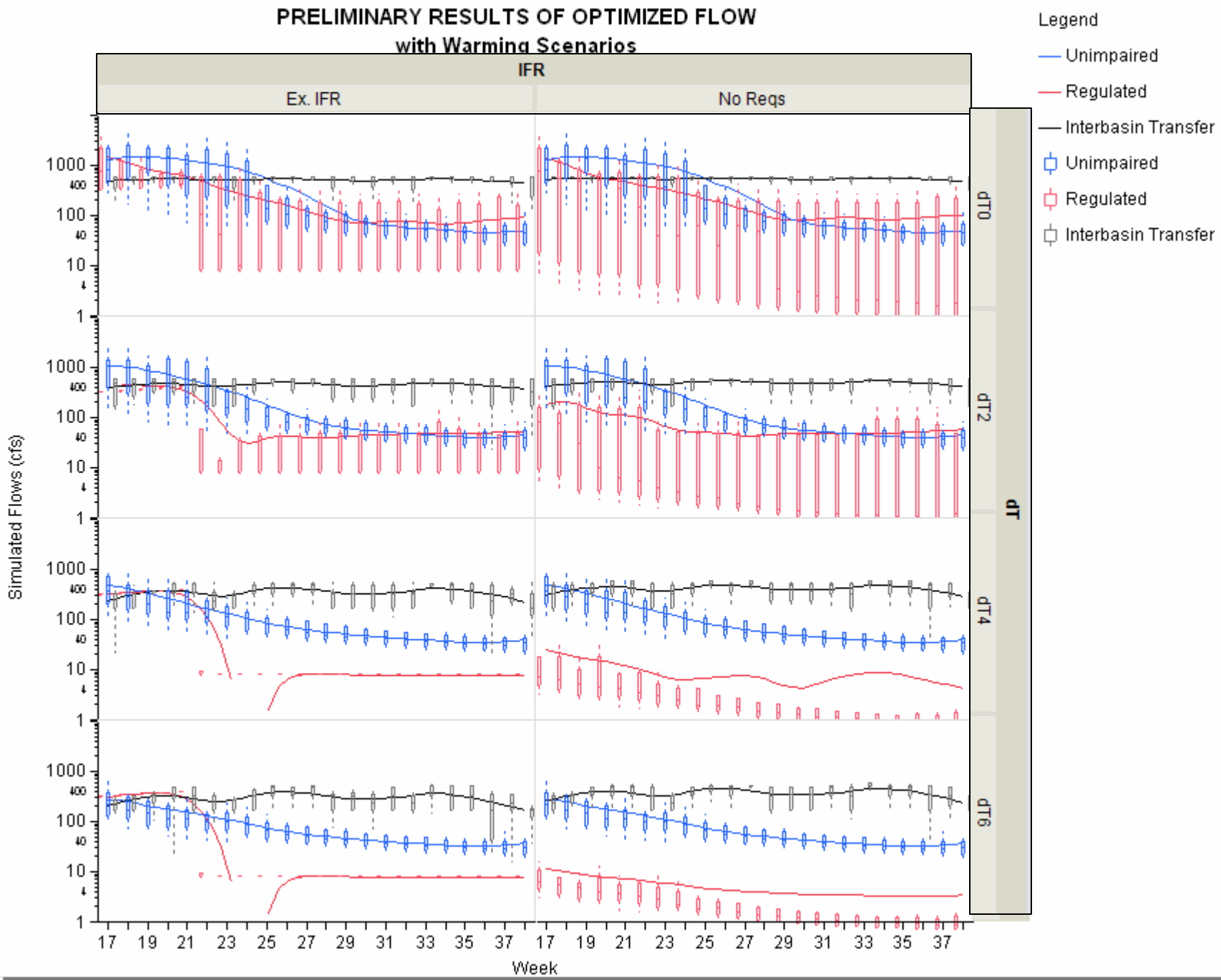




- Decision variable
  - reservoir releases over spring/summer drawdown period
- Objective
  - Maximize: benefit = revenue – penalties
- Constraints
  - Mass balance
  - Instream Flow Req
- Penalties
  - Flow deficits & excess flows (time specific, for now)
  - Spill (location, time specific)

Hydroeconomic Optimization with Linear Programming

DE Rheinheimer, JH Viers, JR Lund (In Prep)


PRELIMINARY RESULTS OF OPTIMIZED FLOW
with Warming Scenarios
IFR
Ex. IFR
No Reqs
dT
dT0
dT2
dT4
dT6
Simulated Flows (cfs)
1000
400
100
40
10
4
1
17 19 21 23 25 27 29 31 33 35 37
Week
Legend
Unimpaired
Regulated
Interbasin Transfer
Unimpaired
Regulated
Interbasin Transfer

Outcomes & Applications

- Ecological Outcomes:
  - Adaptation to stationary hydrological process balances abiotic disturbance (Q_{max}) with biotic stress (Q_{min})
  - Rate of change (k) facilitates reproduction and growth requirements of aquatic and riparian ecosystems
  - Hydrologic alteration with regional climate warming will likely have profound ecological consequences

- Water Management :
  - Environmental Flow Releases necessary to maintain ecosystem services
  - Simulation allows for accurate understanding of system sensitivity to warming
  - Forecasting under uncertainty possible (necessary)
  - Regulated river systems will be challenged to meet demands of all downstream users

Acknowledgements

Key Participants in Study:

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- ***Stockholm Environment Institute***: D. Purkey, C. Young, M. Escobar, & V. Mehta
- ***Watercourse Engineering Inc***: M. Deas, & S. Tanaka