Flow Trends

A suite of restoration actions targeting multiple stressors using a variety of available approaches would be most effective at restoring biological functions.

- The CVP-SWP are highly regulated for multiple benefits; changes in the outflow can have unintended environmental consequences.

  (CVP-SWP Operations Tables; CVP-SWP operational constraints slide; NAS Report, p. 53 ["The [Fall X2] action also may have high water requirements and may adversely affect salmon and steelhead under some conditions (memorandum from FWS and NMFS, January 15, 2010)."]; Modeling of potential impacts of SWRCB Flow Criteria, December 2011, p. 7.)

- There is no statistically significant trend in outflow over the 91 year hydrologic record.

  (Hanson presentation, slide 5; Enright and Culberson (2010), p. 20 ["…seasonal outflow and salinity variability is primarily climate driven"]; Fox *et al.* 1990).

- The 91 year hydrologic record is the most appropriate dataset for analyzing post-development outflow patterns, as application of the entire record avoids selective use of data and provides a range of wet and dry hydrology both pre and post project. However, a baseline prior to 1850 would be more appropriate for analysis of "natural" conditions within which native species evolved, as by 1850 significant physical changes had already occurred in the Delta.

  (Hanson presentation, slide 5 [showing wet and dry hydrology pre and post dam development]; SFEI Report, pp.20-28)

- The unimpaired outflow calculation is not a useful estimate of "natural" pre-development outflow conditions.

  (DWR submittal to SWRCB, 2012, sec. 6; DWR presentation, 2011.)[1]

- Current annual outflow is within the estimated range of "natural" predevelopment annual outflow.

  (Hutton CWEMF presentation, 2014; Howes CWEMF presentation, 2014; Hanson presentation, slides 6 and 7; Hutton and Schmutte CWEMF presentation, 2014)[2]

- The more useful comparison to the predevelopment period is not outflow, rather its changes in other physical and chemical factors. These factors include significant alterations of the physical environment including changes in hydrodynamics; sedimentation; land use (i.e., loss of floodplains, tidal marshes and wetlands); and channelization (i.e., riprapped concrete channels);

---

[1] Using the DWR unimpaired flow calculation as a surrogate for "natural" outflow is an egregious error that has been carried forward in at least two published works (Cloern and Jassby 2012, and Dynesius and Nilsso (1994). This misuse of the DWR calculation should not be repeated.

[2] The analyses described in these presentations are complete and ready to be submitted for publication. This information will be presented by P. Hutton at the CWEMF conference February 2014.

as well as changes in water quality and speciation such as increases in contaminants, changes in water temperatures, increases in predators, and increases in invasive species. These environmental factors cannot be restored by changing outflow patterns.

(PWA submittal to SWRCB, Ecosystem Change, 2012; Hanson Presentation, slide 4.)

- There are several programs seeking to develop better scientific information.

    - <u>Bay-Delta Natural Flow Hydrodynamics and Salinity Transport:</u>

      Modeling techniques will be used to evaluate the characteristics of Bay-Delta salinity transport associated with the "natural" Bay-Delta hydrology. Bathymetric/topographic digital elevation models (DEMs) are required to construct hydrodynamic models for the Bay-Delta. A DEM of the "natural" Bay-Delta (circa 1850) will be developed by UCD under the direction of Dr. William Fleenor. UCD will obtain a second DEM from DWR to represent the Bay-Delta under current conditions.

      This is a collaborative effort between MWD and UCD and Phase 1 should be wrapped up in the next month. Phase II is anticipated and UCD has agreed to continue collaboration.

    - <u>A Model to Estimate Delta Inflows and Outflows Under Natural Conditions:</u>

      A simple spreadsheet-based model that estimates "natural" predevelopment Delta inflows and outflows has been developed. The vegetation coverage classes and ET underlying the "natural" flow estimates in the model are based on extensive literature review, the results of which are about to be submitted for publication. This model is being refined to improve hydrologic routing and groundwater assumptions. This is funded by the state and federal water contractors.

    - <u>Salinity Trends in Suisun Bay and the Western Delta: October 1921-September 2012:</u>

      Historic salinity data is being compiled from a variety of resources across all of the Bay-Delta sampling stations. This data compilation will be the basis for future studies of salinity in Suisun Bay and the western Delta. This is funded by the state and federal water contractors.

      This is the first effort to assemble the extensive data set that was collected between the 1920s and 1960s. Enright and Culberson (2010) reported data at one station. This effort builds on their work.

Bay-Delta Standards

Contained in D-1641

DRAFT

CRITERIA	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
FLOW/OPERATIONAL												
• **Fish and Wildlife**												
SWP/CVP Export Limits					1,500cfs [1]							
Export/Inflow Ratio [2]	65%	35% of Delta Inflow [3]					65% of Delta Inflow					
Minimum Delta Outflow	[4]						3,000 - 8,000 cfs [4]					
Habitat Protection Outflow		7,100 - 29,200 cfs [5]										
Salinity Starting Condition [6]		[6]										
River Flows:												
@ Rio Vista									3,000 - 4,500 cfs [7]			
@ Vernalis - Base		710 - 3,420 cfs [8]				[8]						
- Pulse					[9]					+28TAF		
Delta Cross Channel Gates	[10]	Closed				[11]					Conditional [10]	
WATER QUALITY STANDARDS												
• **Municipal and Industrial**												
All Export Locations	≤ 250 mg/l Cl											
Contra Costa Canal	150 mg/l Cl for the required number of days [12]											
• **Agriculture**												
Western/Interior Delta				Max.14-day average EC mmhos/cm [13]								
Southern Delta [14]		1.0 mS		30 day running avg EC 0.7 mS					1.0 mS			
• **Fish and Wildlife**												
San Joaquin River Salinity [15]				14-day avg; 0.44 EC								
Suisun Marsh Salinity [16]	12.5 EC	8.0 EC		11.0 EC						19.0 EC	[17]	15.5 EC

[#] **See Footnotes**

Footnotes

[1] Maximum 3-day running average of combined export rate (cfs) which includes Tracy Pumping Plant and Clifton Court Forebay Inflow less Byron-Bethany pumping.

Year Type	All
Apr15 - May15*	The greater of 1,500 or 100% of 3-day avg. Vernalis flow

* This time period may need to be adjusted to coincide with fish migration. Maximum export rate may be varied by CalFed Op's group.

[2] The maximum percentage of average Delta inflow (use 3-day average for balanced conditions with storage withdrawal, otherwise use 14-day average) diverted at Clifton Court Forebay (excluding Byron-Bethany pumping) and Tracy Pumping Plant using a 3-day average. (These percentages may be adjusted upward or downward depending on biological conditions, providing there is no net water cost.)

[3] The maximum percent Delta inflow diverted for Feb may vary depending on the January 8RI.

Jan 8RI	Feb exp. limit
≤ 1.0 MAF	45%
between 1.0 & 1.5 MAF	35%-45%
> 1.5 MAF	35%

DRAFT

[4] Minimum monthly average Delta outflow (cfs). If monthly standard ≤ 5,000 cfs, then the 7-day average must be within 1,000 cfs of standard; if monthly standard > 5,000 cfs, then the 7-day average must be ≥ 80% of standard.

Year Type	All	W	AN	BN	D	C
Jan	4,500*					
Jul		8,000	8,000	6,500	5,000	4,000
Aug		4,000	4,000	4,000	3,500	3,000
Sep	3,000					
Oct		4,000	4,000	4,000	4,000	3,000
Nov-Dec		4,500	4,500	4,500	4,500	3,500

* Increase to 6,000 if the Dec 8RI is greater than 800 TAF

[5] Minimum 3-day running average of daily Delta outflow of 7,100 cfs OR: either the daily average or 14-day running average EC at Collinsville is less than 2.64 mmhos/cm (This standard for March may be relaxed if the Feb 8RI is less than 500 TAF. The standard does not apply in May and June if the May estimate of the SRI IS < 8.1 MAF at the 90% exceedence level in which case a minimum 14-day running average flow of 4,000 cfs is required.) For additional Delta outflow objectives, see **TABLE A**.

[6] February starting salinity: If Jan 8RI > 900 TAF, then the daily or 14-day running average EC @ Collinsville must be ≤ 2.64 mmhos/cm for at least one day between Feb 1-14. If Jan 8RI is between 650 TAF and 900 TAF, then the CalFed Op's group will determine if this requirement must be met.

[7] Rio Vista minimum monthly average flow rate in cfs (the 7-day running average shall not be less than 1,000 below the monthly objective).

Year Type	All	W	AN	BN	D	C
Sep	3,000					
Oct		4,000	4,000	4,000	4,000	3,000
Nov-Dec		4,500	4,500	4,500	4,500	3,500

[8] BASE Vernalis minimum monthly average flow rate in cfs (the 7-day running average shall not be less than 20% below the objective). Take the higher objective if X2 is required to be west of Chipps Island.

Year Type	All	W	AN	BN	D	C
Feb-Apr14 and May16-Jun		2,130 or 3,420	2,130 or 3,420	1,420 or 2,280	1,420 or 2,280	710 or 1,140

[9] PULSE Vernalis minimum monthly average flow rate in cfs. Take the higher objective if X2 is required to be at or west of Chipps Island.

Year Type	All	W	AN	BN	D	C
Apr15 - May15		7,330 or 8,620	5,730 or 7,020	4,620 or 5,480	4,020 or 4,880	3,110 or 3,540
Oct	1,000*					

* Up to an additional 28 TAF pulse/attraction flow to bring flows up to a monthly average of 2,000 cfs except for a critical year following a critical year. Time period based on real-time monitoring and determined by CalFed Op's group.

[10] For the Nov-Jan period, Delta Cross Channel gates may be closed for up to a total of 45 days.

[11] For the May 21-June 15 period, close Delta Cross Channel gates for a total of 14 days per CALFED Op's group. During the period the Delta cross channel gates may close 4 consecutive days each week, excluding weekends.

[12] Minimum # of days that the mean daily chlorides ≤ 150 mg/l must be provided in intervals of not less than 2 weeks duration. Standard applies at Contra Costa Canal Intake or Antioch Water Works Intake.

Year Type	W	AN	BN	D	C
# Days	240	190	175	165	155

[13] The maximum14-day running average of mean daily EC (mmhos/cm) depends on water year type.

	WESTERN DELTA				INTERIOR DELTA			
	Sac River @ Emmaton		SJR @ Jersey Point		Mokelumne R @ Terminous		SJR @ San Andreas	
Year Type	0.45 EC from April 1 to date shown	EC value from date shown to Aug15 *	0.45 EC from April 1 to date shown	EC value from date shown to Aug15 *	0.45 EC from April 1 to date shown	EC value from date shown to Aug15 *	0.45 EC from April 1 to date shown	EC value from date shown to Aug15 *
W	Aug 15		Aug 15		Aug 15		Aug 15	
AN	Jul 1	0.63	Aug 15		Aug 15		Aug 15	
BN	Jun 20	1.14	Jun 20	0.74	Aug 15		Aug 15	
D	Jun 15	1.67	Jun 15	1.35	Aug 15		Jun 25	0.58
C		2.78		2.20		0.54		0.87

* When no date is shown, EC limit continues from April 1.

[14] As per D-1641, for San Joaquin River at Vernalis: however, the April through August maximum 30- day running average EC for San Joaquin River at Brandt Bridge,Old River near Middle River, and Old River at Tracy Road Bridge shall be 1.0 EC until April 1, 2005 when the value will be 0.7 EC.

[15] Compliance will be determined between Jersey Point & Prisoners Point. Does not apply in critical years or in May when the May 90% forecast of SRI ≤ 8.1 MAF.

[16] During deficiency period, the maximum monthly average mhtEC at Western Suisun Marsh stations as per SMPA is:

Month	mhtEC
Oct	19.0
Nov	16.5
Dec-Mar	15.6
Apr	14.0
May	12.5

[17] In November, maximum monthly average mhtEC = 16.5 for Western Marsh stations and maximum monthly average mhtEC = 15.5 for Eastern Marsh stations in all periods types.

TABLE A

Number of Days When Max. Daily Average Electrical Conductivity of 2.64 mmhos/cm Must Be Maintained at Chipps Island and Port Chicago. (This can also be met with a maximum 14-day running average EC of 2.64 mmhos/cm, or 3-day running average Delta outflows of 11,400 cfs and 29,200 cfs, respectively.) Port Chicago Standard is triggered only when the 14-day average EC for the last day of the previous month is 2.64 mmhos/cm or less. PMI is previous month's 8RI. If salinity/flow objectives are met for a greater number of days than required for any month, the excess days shall be applied towards the following month's requirement. The number of day's for values of the PMI between those specified below shall be determined by linear interpolation.

PMI (TAF)	Chipps Island (Chipps Island Station D10) FEB	MAR	APR	MAY	JUN
≤ 500	0	0	0	0	0
750	0	0	0	0	0
1000	28*	12	2	0	0
1250	28	31	6	0	0
1500	28	31	13	0	0
1750	28	31	20	0	0
2000	28	31	25	1	0
2250	28	31	27	3	0
2500	28	31	29	11	1
2750	28	31	29	20	2
3000	28	31	30	27	4
3250	28	31	30	29	8
3500	28	31	30	30	13
3750	28	31	30	31	18
4000	28	31	30	31	23
4250	28	31	30	31	25
4500	28	31	30	31	27
4750	28	31	30	31	28
5000	28	31	30	31	29
5250	28	31	30	31	29
≥ 5500	28	31	30	31	30

*When 800 TAF < PMI < 1000 TAF, the number of days is determined by linear interpolation between 0 and 28 days.

PMI (TAF)	Port Chicago (continuous recorder at Port Chicago) FEB	MAR	APR	MAY	JUN
0	0	0	0	0	0
250	1	0	0	0	0
500	4	1	0	0	0
750	8	2	0	0	0
1000	12	4	0	0	0
1250	15	6	1	0	0
1500	18	9	1	0	0
1750	20	12	2	0	0
2000	21	15	4	0	0
2250	22	17	5	1	0
2500	23	19	8	1	0
2750	24	21	10	2	0
3000	25	23	12	4	0
3250	25	24	14	6	0
3500	25	25	16	9	0
3750	26	26	18	12	0
4000	26	27	20	15	0
4250	26	27	21	18	1
4500	26	28	23	21	2
4750	27	28	24	23	3
5000	27	28	25	25	4
5250	27	29	25	26	6
5500	27	29	26	28	9
5750	27	29	27	28	13
6000	27	29	27	29	16
6250	27	30	27	29	19
6500	27	30	28	30	22
6750	27	30	28	30	24
7000	27	30	28	30	26
7250	27	30	28	30	27
7500	27	30	29	30	28
7750	27	30	29	31	28
8000	27	30	29	31	29
8250	28	30	29	31	29
8500	28	30	29	31	29
8750	28	30	29	31	30
9000	28	30	29	31	30
9250	28	30	29	31	30
9500	28	31	29	31	30
9750	28	31	29	31	30
10000	28	31	30	31	30
> 10000	28	31	30	31	30

When Regulations Affect the CVP & SWP

plus NMFS Temperature and Flow Standards

Management Standard	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Delta Minimum Outflow												
Delta "Habitat" Outflow (S X2)												
Diversion Rate Limit												
Diversion to Inflow Ratio												
Sacramento River Min. Flow												
San Joaquin River Min. Flow												
Delta Water Quality												

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A Scientific Assessment of Alternatives for Reducing Water Management Effects on Threatened and Endangered Fishes in California's Bay–Delta

Committee on Sustainable Water and Environmental Management in the California Bay-Delta

Water Science and Technology Board

Ocean Studies Board

Division on Earth and Life Studies

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COMMITTEE ON SUSTAINABLE WATER AND ENVIRONMENTAL MANAGEMENT IN THE CALIFORNIA BAY-DELTA*

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Preface

California, like many states, faces challenges related to water. Much of the state is too dry to support many human activities, such as municipal and industrial water use and irrigated agriculture, without supplementing the natural water supply. It has done this through an extensive series of engineering projects that include reservoirs, canals, levees, and pumps, largely to move water from the more humid north to the more arid and densely populated south. Much of California's natural surface-water supply flows into and through the Sacramento and San Joaquin watersheds into California's Bay-Delta, and from there through San Francisco Bay into the ocean. The delta itself is a biologically diverse estuarine ecosystem, and is the main point of diversion for water that is transported to the south.

As California's population and economic activity have increased, along with water diversions from the delta, conflicts over various water uses have increased as well, especially surrounding the bay-delta. Those conflicts have been brought to a head by restrictions on water diversions that have been required by two biological opinions, one by the U.S. Fish and Wildlife Service, covering delta smelt, and one by the National Marine Fisheries Service, covering salmon, steelhead, and sturgeon, to protect those fishes, which are listed as threatened or endangered under the federal Endangered Species Act. In addition, several recent dry years have exacerbated the situation. Conflicts over water are not new in California, but the current conflicts over the bay-delta appear to be unprecedented in their scale. Few parts of the state are unaffected by what happens to delta water.

Protecting all the listed species and preserving existing and projected uses of the region's water is a serious challenge. The complexity of the problem and the difficulty of identifying solutions have been highlighted by a plethora of scientific publications and arguments, in which many qualified and distinguished experts have reached differing conclusions. Nobody disagrees that engineering changes; the introduction of many exotic species, the addition of contaminants to the system, and the general effects of an increasing human population have contributed to the fishes' declines. There are, however, disagreements

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about the relative contributions of those factors and the appropriate remedies for them. This is the context in which the National Research Council was asked by Congress and the Department of the Interior to help resolve the issue by evaluating the scientific bases of the biological opinions. In response, the NRC appointed a special committee of experts to carry out a complex and challenging study in two phases.

In its first phase, the committee was tasked to focus on the scientific bases of the reasonable and prudent alternatives (RPAs) in the two biological opinions. The committee also assessed whether the RPAs might be in conflict with one another, as well as whether other options might be available that would protect the fishes with lesser impacts on other water uses. Finally, we were asked to consider the effects of "other stressors" on the fishes if sufficient time were available. The results of this first-phase analysis are the subject of this report. The committee did consider other stressors, but it did not evaluate them in depth. They will be more thoroughly addressed in a second report, scheduled to be published late in 2011, which will focus on broader issues surrounding attempts to provide more sustainable water supplies and to improve the ecological sustainability of the delta, including consideration of what ecological goals might be attainable.

The committee met in Davis, California for five days in January 2010. The committee heard presentations from representatives of federal and state agencies and a variety of other experts, and from members of several stakeholder groups and the public (see Appendix D). The information gathering sessions of this meeting were open to the public and widely advertised. The committee sought to hear from as many groups and individuals as possible within the time constraints. All speakers, guests, and members of the public were encouraged to provide written comments during and after the meeting. All presentations and written materials submitted were considered by the committee as time allowed. The committee thanks all the individuals who provided information.

This report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise in accordance with the procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the NRC in making its published report as sound as possible, and to ensure that the report meets NRC institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following for their reviews of this report: Joan G. Ehrenfeld, Rutgers University; Mary C. Fabrizio, Virginia Institute of Marine Science; Peter Gleick, Pacific Institute; William P. Horn, Birch, Horton, Bittner & Cherot;

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D. Peter Loucks, Cornell University; Jay Lund, University of California, Davis; Tammy Newcomb, Michigan Department of Natural Resources; and Andrew A. Rosenberg, Conservation International.

Although these reviewers provided constructive comments and suggestions, they were not asked to endorse the report's conclusions and recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Michael Kavanaugh, Malcolm Pirnie, Inc., who was appointed by the NRC's Report Review Committee and by Leo Eisel, Brown and Caldwell, who was appointed by the NRC's Division on Earth and Life Studies. They were responsible for ensuring that an independent examination of this report was conducted in accordance with NRC institutional procedures and that all review comments received full consideration. Responsibility for this report's final contents rests entirely with the authoring committee and the NRC.

I am enormously grateful to my committee colleagues for their diligence, enthusiasm, persistence, and hard work. The schedule for the preparation of this report was short, and without everyone's engagement, it could not have been completed. I also am grateful to David Policansky, Stephen Parker, Laura Helsabeck, Heather Chiarello, Ellen de Guzman, and Susan Roberts of the NRC staff for their efforts in facilitating the committee's meeting and for their work in helping to get this report completed on schedule in the face of historic snowstorms.

California will continue to face great challenges in managing, allocating, and using water, including managing California's Bay-Delta. We hope the committee's reports can help in that difficult process.

Robert J. Huggett
Chair

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Acronyms and Abbreviations

AF	Acre-feet
BA	Biological Assessment
BO	Biological Opinion
(C)DFG	California Department of Fish and Game
(C)DWR	California Department of Water Resources
C.F.R.	Code of Federal Regulations
Cir	Circuit Court (federal system)
CVP	Central Valley Project
CVPIA	Central Valley Project Improvement Act
DCC	Delta Cross Channel
DOI	(U.S.) Department of the Interior
DSM2	Delta Simulation Model II
EDT	Ecosystem Diagnosis and Treatment
ESA	Endangered Species Act
EWA	Environmental Water Account
FMT	Fall Midwater Trawl (survey)
FWS	(U.S.) Fish and Wildlife Service
HORB	Head of Old River Barrier
MAF	Million acre-feet
M&I	Municipal and Industrial
NAS	National Academy of Sciences
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
OCAP	Operations Criteria And Plan
OMR	Old and Middle River
OSB	Ocean Studies Board of the NRC
PTM	Particle-Tracking Model
RBDD	Red Bluff Diversion Dam
RPA	Reasonable and Prudent Alternative
SWP	State Water Project
TAF	Thousand acre-feet
USBR	United States Bureau of Reclamation
U.S.C.	United States Code
USGS	United States Geological Survey
VAMP	Vernalis Adaptive Management Plan
WSTB	Water Science and Technology Board of the NRC
X2	Contour line of salinity 2

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Summary

California's Bay-Delta estuary is a biologically diverse estuarine ecosystem that plays a central role in the distribution of California's water from the state's wetter northern regions to its southern, arid, and populous cities and agricultural areas. In addition to its ecological functioning and the ecosystem services it provides, there are numerous withdrawals of freshwater from the delta, the largest being pumping stations that divert water into the federal Central Valley Project (CVP) and the State Water Project (SWP), primarily for agriculture and metropolitan areas. Most former wetland and marsh areas of the delta have been drained for agriculture, and are protected by an aging collection of levees. Some of those areas also contain small urban settlements.

This hydrologic and engineered system has met the diverse water-related needs of Californians for decades. But operation of the engineered system, along with the effects of an increasing population of humans and their activities, has substantially altered the ecosystem. These ecosystem changes have contributed to changes in the abundance, distribution, and composition of species in the delta, including the decline of many native species and the successful establishment of many species not native to the region.

Recently, the Fish and Wildlife Service (FWS) and the National Marine Fisheries Service (NMFS) issued biological opinions under the federal Endangered Species Act (ESA) that required changes ("reasonable and prudent alternatives," or RPAs) in water operations and related actions to avoid jeopardizing the continued existence and potential for recovery of delta smelt, winter-run and fall-run Chinook salmon, Central Valley steelhead, and green sturgeon. Those changes have reduced the amount of water available for other uses, and the tensions that resulted have been exacerbated by recent dry years.

The RPAs are divided into many separate actions. The RPA in the FWS opinion, divided into six actions, applies to delta smelt and thus focuses primarily on managing flow regimes to reduce entrainment of smelt and on extent of suitable water conditions in the delta, as well as on construction or restoration of

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habitat. The NMFS RPA, divided into five actions with a total of 72 subsidiary actions, applies to the requirements of Chinook salmon, steelhead, and green sturgeon in the delta and farther upstream. In addition to its focus on flow regimes and passage, it includes purchasing water to enhance in-stream flow, habitat restoration, a new study of acoustic-tagged steelhead, and development of hatchery genetics management plans. This committee did not evaluate all 78 actions and subsidiary actions in the two RPAs in detail. It spent most of its time on the elements of the RPAs that have the greatest potential to affect water diversions. It also spent time on elements whose scientific justifications appear to raise some questions.

Protecting all the listed species, as required by the ESA, while simultaneously trying to minimize impacts on existing and projected uses of the region's water, is a serious challenge. In addition, many anthropogenic and other factors, including pollutants; introduced species; and engineered structures such as dams, canals, levees, gates, and pumps adversely affect the fishes in the region, but they are not under the direct control of the CVP or the SWP, and thus are not subjects of the biological opinions.

The complexity of the problem of the decline of the listed species and the difficulty of identifying viable solutions have led to disagreements, including concerns that some of the actions in the RPAs might be ineffective and might cause harm and economic disruptions to water users, and that some of the actions specified in the RPAs to help one or more of the listed species might harm others. In addition, some have suggested that the agencies might be able to meet their legal obligation to protect species with less economic disruptions to other water users. Those concerns led the Department of the Interior and Congress to ask for advice from the National Research Council (NRC), which appointed a special committee of experts to carry out this study.

THE COMMITTEE'S CHARGE

The committee's charge includes the following tasks (the full statement of task is in Appendix A).

The committee was asked to undertake two main projects over a term of two years resulting in two reports. The first report, prepared on a very short timeline, was to address scientific questions, assumptions, and conclusions underlying water-management alternatives (i.e., the RPAs) in the two biological opinions mentioned above, and this is where the committee focused most of its attention. In addition, three specific issues were to be addressed. First, are there any "reasonable and prudent alternatives" (RPAs) that, based on the best avail-

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able scientific data and analysis, would provide equal or greater protection for the listed species and their habitat while having lesser impacts to other water uses than those adopted in the biological opinions? Second, are there provisions in the biological opinions to resolve the potential for actions that would benefit one listed species while causing negative impacts on another? And finally, to the extent that time permits, the committee was asked to consider the effects of other stressors (e.g., pesticides, ammonia discharges, invasive species) on federally listed and other at-risk species in the Bay-Delta. The committee's second report, due in late 2011, will address how to most effectively incorporate science and adaptive management concepts into holistic programs for management and restoration of the Bay-Delta.

The committee's charge was to provide a scientific evaluation, not a legal one, and that is what the committee did. **Nothing in this report should be interpreted as a legal judgment as to whether the agencies have met their legal requirements under the ESA.** The committee's report is intended to provide a scientific evaluation of agency actions, to help refine them, and to help the general attempt to better understand the dynamics of the delta ecosystem, including the listed fishes.

THE COMMITTEE'S PRINCIPAL CONCLUSIONS

Context

The California Bay-Delta is a system that has undergone significant anthropogenic changes for more than a century. Those changes include water withdrawals; draining of wetlands; introduction of many nonnative species of plants and animals, some deliberate; construction of canals, gates, marinas, roads, levees, pumps, dams, and other structures that affect the hydrology of the system; the damming of almost all the major rivers and tributaries to the system, which also has altered the seasonal flow regime and other hydrologic aspects of the system; and the release of contaminants, pollutants, and nutrients into the system as a result of the above changes and the increase of agriculture, industrial and residential development, and other human activities. All these changes have affected the distribution, abundance, and composition of species in the delta, some of which have increased dramatically and some, including the species listed under the Endangered Species Act (Chinook salmon, delta smelt, steelhead, and green sturgeon), which have declined precipitously. The biological opinions with their associated RPAs that the committee has reviewed relate only to proposed changes in operations of the CVP and the SWP in the delta and

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methods to reduce the adverse effects on the listed species of those changes. Some restrictions on CVP and SWP water diversions have been initiated to protect the listed fish species, but so far have not produced measurable effects in slowing their declines.

The committee concludes that reversing or even slowing the declines of the listed species cannot be accomplished immediately. Even the best-targeted methods of reversing the fish declines will need time to take effect amid changing environmental conditions such as multi-year droughts and continued pressures on the system from other human-caused stresses. Especially for fishes whose populations are very low already, the effects of any actions will be difficult to detect at first, and detecting them will be made more difficult by the effects of other environmental changes and uncertainties inherent in sampling small populations.

The FWS Biological Opinion and RPA

The committee considered the six actions contained within the RPA, most of which were judged to have a sound conceptual basis. The committee then focused on the RPA actions that involved Old and Middle River (OMR) flows, the management of the mean position of the contour where salinity is 2[1] (X2), and the creation or restoration of tidal habitat for smelt. The first two actions involve significant requirements for water; the third does not.

The management of OMR flows is predicated on the concept that pumping of water for export from the south delta creates net negative (toward the pumps) flows, averaged over the tidal cycle, that cause delta smelt (and some juvenile salmon) to be experience increased mortality in the south delta, especially in winter. The RPA action limits the net OMR flows to levels that depend on conditions during this period, with a variety of environmental triggers and adaptive-management procedures. **Although there are scientifically based arguments that raise legitimate questions about this action, the committee concludes that until better monitoring data and comprehensive life-cycle models are available, it is scientifically reasonable to conclude that high negative OMR flows in winter probably adversely affect smelt populations. Thus, the concept of reducing OMR negative flows to reduce mortality of smelt at the SWP and CVP facilities is scientifically justified.**

[1] This is often expressed as a concentration, e.g., "2 parts per thousand," but more recently it has been expressed as a ratio of electrical conductivities, hence it has no units.

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However, there is substantial uncertainty regarding the amount of flow that should trigger a reduction in exports. In other words, the specific choice of the negative flow threshold for initiating the RPA is less clearly supported by scientific analyses. The biological benefits and the water requirements of this action are likely to be sensitive to the precise values of trigger and threshold values. There clearly is a relationship between negative OMR flows and mortality of smelt at the pumps, but the data do not permit a confident identification of the threshold values to use in the action, and they do not permit a confident assessment of the benefits to the population of the action. As a result, the implementation of this action needs to be accompanied by careful monitoring, adaptive management, and additional analyses that permit regular review and adjustment of strategies as knowledge improves.

The management of the mean position of X2 during the fall (Action 4 of the FWS RPA) is based on observations that relate smelt use of spawning habitat with various salinity regimes. X2 is interpreted by the agencies not as a single line, but rather as an indicator of the spatial pattern of salinity in the delta and thus as indicative of the extent of habitat favorable for delta smelt.

The relationships among smelt abundance, habitat extent, and the mean position of X2 as an indicator of available habitat are complex. The controversy about the action arises from the poor and sometimes confounding relationship between indirect measures of delta smelt populations (indices) and X2. Although there is evidence that the position of X2 affects the distribution of smelt, the weak statistical relationship between the location of X2 and the size of smelt populations makes the justification for this action difficult to understand. In addition, although the position of X2 is correlated with the distribution of salinity and turbidity regimes, the relationship of that distribution and smelt abundance indices is unclear. **The X2 action is conceptually sound in that to the degree that the amount of habitat available for smelt limits their abundance, the provision of more or better habitat would be helpful. However, the derivation of the details of this action lacks rigor.** The action is based on a series of linked statistical analyses (e.g., the relationship of presence/absence data to environmental variables, the relationship of environmental variables to habitat, the relationship of habitat to X2, the relationship of X2 to smelt abundance). Each step of this logical train of relationships is uncertain. The relationships are correlative with substantial variance left unexplained at each step, yet the analyses do not carry the uncertainty at each step to the next step. The action also may have high water requirements and may adversely affect salmon and steelhead under some conditions. **As a result, the committee concludes that how specific X2 targets were chosen and their likely beneficial effects need further clarification. It also is critical that the adaptive-management requirements**

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included in the RPA be implemented in light of the uncertainty about the biological effectiveness of the action and its possibly high water requirements.

The tidal habitat management action in the RPA requires creation or restoration of 8,000 acres of intertidal and subtidal habitat in the delta and in Suisun Marsh. This action has not been controversial because it does not affect other water users. **The committee finds that the conceptual foundation for this action (Action 6) is weak because the relationship between tidal habitats and food availability for smelt is poorly understood. The details of its implementation are not fully justified in the biological opinion. The committee recommends that this action be implemented in phases, with the first phase to include the development of an implementation and adaptive management plan (similar to the approach used for the floodplain habitat action in the NMFS biological opinion), but also to explicitly consider the sustainability of the resulting habitats, especially those dependent on emergent vegetation, in the face of expected sea-level rise.** In addition, there should be consideration of the types and amounts of tidal habitats necessary to produce the expected outcomes and how they can be achieved and sustained in the long term. The committee supports the monitoring program referred to in Action 6, and appropriate adaptive management triggers and actions.

The NMFS Biological Opinion and RPA

The NMFS RPA for salmon, steelhead, and green sturgeon is a broad complex of diverse actions spanning three habitat realms: tributary watersheds, the mainstem Sacramento and San Joaquin Rivers, and the delta. **On balance, the committee concludes that the actions, which are primarily crafted to improve life-stage-specific survival rates for salmon and steelhead, with the recognition that the benefits also will accrue to sturgeon, are scientifically justified.** The strategies underpinning many of the individual actions are generally well supported by more than a decade of conceptual model building about the requirements of salmonids in the region, although the extent to which the intended responses are likely to be realized is not always clearly addressed in the RPA. Given the absence of a transparent, quantitative framework for analyzing the effects of individual and collective actions, it is difficult to make definitive statements regarding the merits of such a complex RPA. Indeed, absent such an analysis, the controversial aspects of some of the RPA actions could detract from the merits of the rest of the RPA.

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In general, as described in detail in Chapter 6, the committee concludes that although most, if not all, of the actions in this RPA had a sound conceptual basis, the biological benefits and water requirements of several of the actions are, as with the delta smelt actions, likely quite sensitive to the specific triggers, thresholds, and flows specified. As a result, the committee recommends that the specific triggers, thresholds, and flows receive additional evaluation that is integrated with the analyses of similar actions for delta smelt.

In particular, the committee concludes that it is difficult to ascertain to what extent the collective watershed and tributary actions will appreciably improve survival within the watershed or throughout the entire river system. The committee concludes that the actions to improve mainstem passage for salmonids and sturgeon, in particular those concerning the Red Bluff Diversion Dam, are well justified scientifically. The committee recommends some kind of quantitative assessment framework for assessing survival be developed and implemented.

The management of OMR flows to reduce entrainment mortality of salmon smolts is similar in concept to the smelt OMR action, and like that action, **the committee concludes that its conceptual basis is scientifically justified, but the scientific support for specific flow targets is less certain. Uncertainty in the effect of the triggers should be reduced, and more-flexible triggers that might require less water should be evaluated.**

Another set of actions in this RPA focuses on managing exports and flows in the San Joaquin River to benefit outmigrating steelhead smolts. The actions are intended to reduce the smolts' vulnerability to entrainment into the channels of the south delta and the pumps by increasing the inflow-to-export ratio of water in the San Joaquin River. It thus has two components: reducing exports and increasing San Joaquin River inflows into the delta. **The committee concludes that the rationale for increasing San Joaquin River flows has a stronger foundation than does the prescribed export action. We further conclude that the action involving a six-year study of smolt survival would provide useful insight into the effectiveness of the actions as a long-term solution.**

The final two actions considered here were improving the migratory passage of salmon and sturgeon through the Yolo Bypass and the inundation of additional floodplain lands to provide additional rearing habitat for juvenile salmon. **The committee concludes that both actions are scientifically justified, but the implications for the system as a whole of routing additional flows through the Yolo Bypass for the system were not clearly analyzed.** In particular, the consequences of the action for Sacramento River flows and for the potential mobilization of mercury were not clearly described.

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Other Possible RPAs

The committee's charge requires the identification, if possible, of additional potential RPAs that might have the potential to provide equal or greater protection to the fishes than the current RPAs while costing less in terms of water availability for other uses. **The committee considered a variety of possible actions not in the RPAs (see Chapter 6), and concluded that none of them had received sufficient documentation or evaluation to be confident at present that any of them would have the potential to provide equal or greater protections for the species while requiring less disruption of delta water diversions.**

Other Stressors

Based on the evidence the committee has reviewed, the committee agreed that the adverse effects of all the other stressors on the listed fishes are potentially large. Time did not permit full exploration of the issue in this first report, but examples of how such stressors may affect the fishes are described. The committee will explore this issue more thoroughly in its second report.

Modeling

The committee reviewed the models the agencies used to understand the basis for the resource agencies' jeopardy opinion and to determine to what degree they used the models in developing the RPAs. **The committee concluded that as far as they went, despite flaws, the individual models were scientifically justified, but that they needed improvements and that they did not go far enough toward an integrated analysis of the RPAs. Thus the committee concluded that improving the models by making them more realistic and by better matching the scale of their outputs to the scale of the actions, and by extending the modeling framework to be more comprehensive and to include features such as fish life cycles would improve the agencies' abilities to assess risks to the fishes, to fine-tune various actions, and to predict the effects of the actions.**

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Potential Conflicts Between RPAs and Integration of RPAs

The committee concludes that the RPAs lack an integrated quantitative analytical framework that ties the various actions together within species, between smelt and salmonid species, and across the watershed. This type of systematic, formalized analysis, although likely beyond the two agencies' legal obligations when rendering two separate biological opinions, is necessary to provide an objective determination of the net effect of all their actions on the listed species and on water users.

An additional overall, systematic, coordinated analysis of the effect of all actions taken together and a process for implementing the optimized, combined set of actions is required to establish the credibility of the effort overall. The committee is aware that instances of coordination among the agencies certainly exist, including modification of actions to reduce or eliminate conflicting effects on the species. Indeed, the committee did not find any clear example of an action in one of the RPAs causing significant harm to the species covered in the other RPA. But coordination is not integration. The lack of a systematic, well-framed overall analysis is a serious scientific deficiency, and it likely is related to the ESA's practical limitations as to the scope of actions that can or must be considered in a single biological opinion. The interagency effort to clearly reach consensus on implications of the combined RPAs for their effects on all the species and on water quality and quantity within the delta and on water operations and deliveries should use scientific principles and methods in a collaborative and integrative manner. Similarly, this committee's efforts to evaluate potential harmful effects of each RPA on the species covered in the other RPA were hampered by the lack of a systematic, integrated analysis covering all the species together. Full documentation of decisions should be part of such an effort, as should inclusion of the environmental water needs of specific actions and for the entire RPA.

It is clear that integrative tools that, for example, combine the effect over life stages into a population-level response would greatly help the development and evaluation of the combined actions. There has been significant investment in hydrological and hydrodynamic models for the system, which have been invaluable for understanding and managing the system. An investment in ecological models that complement and are integrated with the hydrological and hydrodynamics models is sorely needed. Clear and well-documented consideration of water requirements also would seem well advised because some of the actions have significant water requirements. Credible documentation of the water needed to implement each action and the combined actions, would enable an even clearer and more logical formulation of how the suite of actions might be

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coordinated to simultaneously benefit the species and ensure water efficiency. **This recommendation for integration of models and across species responds to the committee's broad charge of advising on how to most effectively incorporate scientific and adaptive-management concepts into holistic programs for managing the delta, and likely goes beyond the agencies' legal obligations under the ESA, and will be addressed more thoroughly in the committee's second report.**

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1
Introduction

California's Bay-Delta estuary is a biologically diverse estuarine ecosystem that plays a central role in the distribution of California's water from the state's wetter northern regions to its southern, arid, and populous cities and agricultural areas (Figure 1-1). The Bay-Delta region receives water flows from the Sacramento and San Joaquin Rivers and their tributaries, which drain the east slopes of the Coast Range, the Trinity Alps and Trinity Mountains in northern California, and the west slopes of the Sierra Nevada Mountains. Outflows from the Bay-Delta, through San Francisco Bay and into the Pacific Ocean, are met by tidal inflows, resulting in a brackish water ecosystem in many reaches of the Bay-Delta. In addition to its ecological functioning and the ecosystem services it provides, there are numerous withdrawals of freshwater from the Bay-Delta, the largest being pumping stations that divert water into the federal Central Valley Project (CVP), primarily for Central Valley agriculture, and the State Water Project (SWP), primarily for southern California metropolitan areas. Other water is extracted from Bay-Delta waterways for consumptive use within the delta region itself, and for municipal and industrial use around the margins of the delta, and returned to its waterways diminished in quantity and quality. Most former wetland and marsh areas of the delta have been drained for agriculture, and are protected by an aging collection of levees (Moyle et al., 2010). Some of those areas also contain small urban settlements.

This hydrologic and engineered system has met the diverse water-related needs of Californians for decades. But construction and operation of the engineered system, along with the effects of an increasing population of humans and their activities, have substantially altered the ecosystem. Current conditions include altered water-quality and salinity regimes and the magnitude and direction of flows in the delta, with rigorous management of the location of the contour where salinity is 2[1] (known as X2) through flow releases from upstream reservoirs. Consequent changes in the abundance, distribution, and composition of species in the delta have been compounded by the introduction and invasion

[1] This is often expressed as a concentration, e.g., "2 parts per thousand," but more recently it has been expressed as a ratio of electrical conductivities, hence it has no units.

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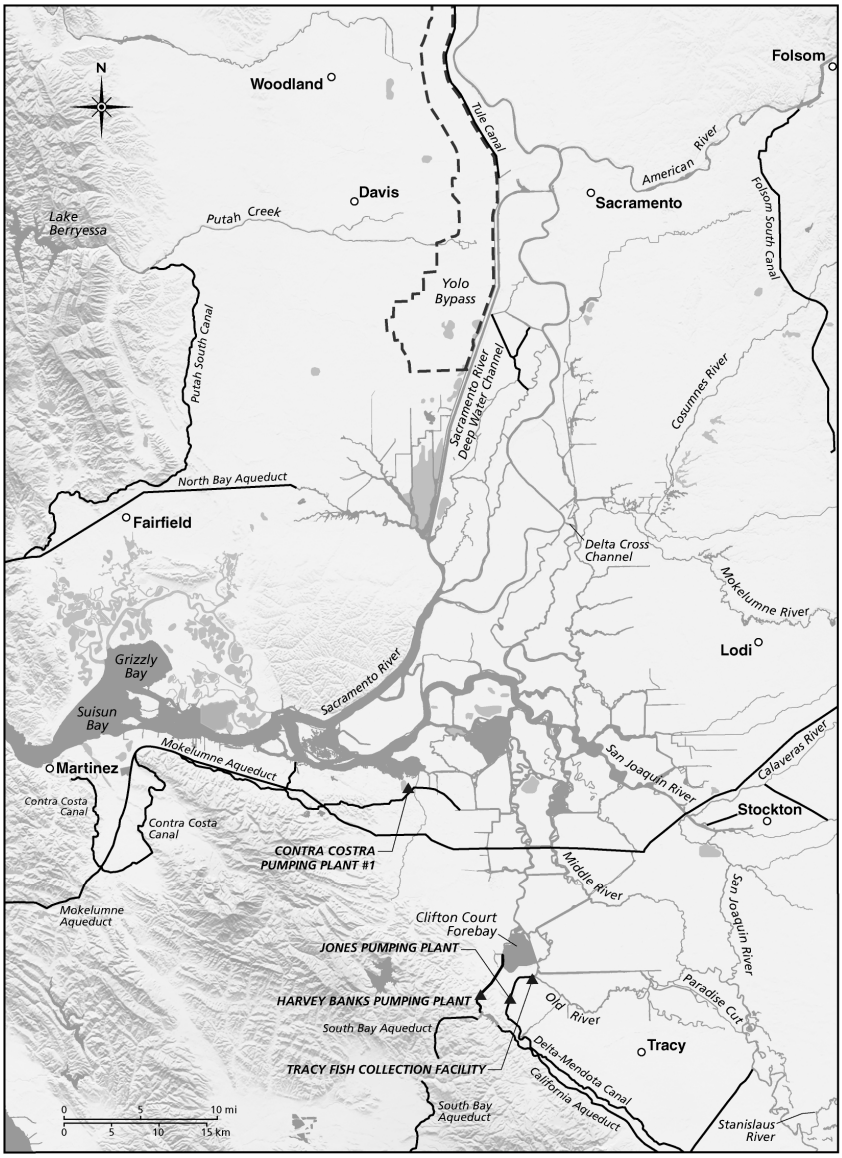

FIGURE 1-1 Map of the delta. SOURCE: Modified from FWS (2008).

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of many species not native to the region.

Recently, several species of native fishes have been listed as threatened or endangered under the federal Endangered Species Act (ESA) and the California Endangered Species Act. This study focuses only on the federal ESA. The federal listings have led to Section 7 (of the ESA) consultations between the operators of the CVP (the U.S. Bureau of Reclamation, or USBR) and of the SWP (the California Department of Water Resources, or DWR) and the Fish and Wildlife Service (FWS), the National Marine Fisheries Service (NMFS), and the California Department of Fish and Game (DFG). Those consultations led to the issuance of opinions by the Services that required changes ("reasonable and prudent alternatives," or RPAs) in water operations and related actions to avoid jeopardizing the continued existence and potential for recovery of delta smelt (*Hypomesus transpacificus*), winter-run and fall-run Chinook salmon (*Oncorhynchus tshawytscha*), Central Valley steelhead (*Oncorhynchus mykiss*), and green sturgeon (*Acipenser medirostris*). The impacts of the RPAs on water users and the tensions that resulted have been exacerbated recently by series of dry years. In the longer term, climate change presents uncertainties and challenges with its anticipated impact on precipitation, snowpack, streamflow, and rising sea level, which will affect not only salinity and riparian habitats in the delta but likely also will threaten the integrity of the extensive system of levees (1,100 miles in length).

The RPAs are divided into many separate actions. The RPA in the FWS opinion (FWS, 2008), divided into six actions, focuses primarily on the flow and storage regimes as affected by diversions (pumping water to the south) and on reducing entrainment, with some focus on habitat. The NMFS RPA (NMFS, 2009) is divided into five actions with a total of 72 subsidiary actions. In addition to its focus on flow regimes, storage, and passage, it includes purchasing water to enhance in-stream flow, habitat restoration, a new study of acoustic-tagged steelhead, and development of hatchery genetics management plans. This committee did not evaluate all 78 actions and subsidiary actions in the two RPAs in detail. It spent most of its time on the elements of the RPAs that have the greatest potential to affect water diversions. It also spent time on elements whose scientific justifications appear to raise some questions.

Protecting all the listed species and preserving existing and projected uses of the region's water is a serious challenge. As the NMFS biological opinion (NMFS, 2009) says, "the current status of the affected species is precarious," and "it has been difficult to formulate an RPA that is likely to avoid jeopardy to all listed species and meets all regulatory requirements." Adding to this difficulty is the existence of the many anthropogenic and other factors that adversely affect the fishes in the region but which are not under the direct control of the

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CVP or the SWP, and thus are not subjects of the biological opinions[2]. These include other human modifications to the system, including pollutants; invasive species and altered species composition; and engineered structures such as dams, canals, gates, pumps, and levees.

The complexity of the problem of the decline of the listed species and the difficulty of identifying solutions to it have led to disagreements, including concerns that some of the actions in the RPAs might cause harm and economic disruptions to many water users, and that some of the actions specified in the RPAs to help one or more of the listed species might harm others.

SYSTEM OVERVIEW

Overview of System Hydrology

We briefly describe the Sacramento-San Joaquin delta (Figure 1-1) and the two massive water storage and delivery projects that affect the area. Several publications go into great detail describing the delta and the operations of the federal and state water systems (DWR, 2006, 2009a, 2009b; USBR, 2006).

The Central Valley Project (CVP) operated by the U.S. Bureau of Reclamation and the State Water Project operated by the California Department of Water Resources provide water to farms and cities in an area encompassing the majority of the land and population of California. The two projects constitute the largest agriculture and municipal water-supply system in the United States. Water supplying both projects ultimately comes mainly from California's two major river systems—the Sacramento and the San Joaquin—with substantial imports from the Trinity River. Water also is stored in several major reservoirs as well, including Shasta (capacity 4.6 million acre-feet[3], or MAF), Oroville (3.4 MAF), Trinity (2.4 MAF), New Melones (2.4 MAF), San Luis (2 MAF), Don Pedro (2 MAF), McClure (Exchequer) (1 MAF), and Folsom (1 MAF), as well as many smaller ones. Releases from those reservoirs are used to help manage flows and salinity in the delta, as well as being used for agriculture, municipal and industrial uses, recreation, flood protection, and hydropower.

The CVP provides about 5 MAF of water to agriculture each year (about 70 percent of the CVP's supply), 0.6 MAF for municipal and industrial (M&I) use

[2] Those other mainly adverse changes are considered as part of the "environmental baseline."

[3] An acre-foot is the amount of water required to cover an acre of land to a depth of one foot; it is equal to 43,560 cubic feet, 325,851 gallons, or 1,234 cubic meters of water.

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(serving about 2 million people) and 1.4 MAF to sustain fish, wildlife, and their habitats. The SWP provides about 70 percent of its water to M&I customers (about 20 million people) and 30 percent to agriculture (about 660,000 acres of irrigated farmland). The largest SWP contractor is the Metropolitan Water District of Southern California, which receives about 50 percent of SWP deliveries in any one year. At least two-thirds of the population of California depends on water delivered from these projects as a primary or supplemental source of supply. Other important functions provided by both projects include flood protection, recreation, power generation, and water quality to preserve fish and wildlife.

Both projects preceded and accommodated the explosive growth of California's economy and population. The CVP was begun in the mid to late 1930s and the SWP was begun in the 1960s. Dozens of reservoirs and lakes, pumping facilities, and over 1,200 miles of pipelines and canals make up the two interdependent water-supply and delivery systems.

The Sacramento-San Joaquin Delta

In the middle of both systems and connecting the northern water supply reservoirs and southern water demands is the Sacramento-San Joaquin Delta (Figure 1-1). Thus, the delta is an integral part of the water-delivery infrastructure for both the SWP and CVP. While the focus of this report is the determination of the effects of water allocations for fish, there are many other requirements that must be met in the delta to maintain flows and quality for the many uses of water delivered by the SWP and CVP projects.

Two major pumping plants draw water from the channels and rivers feeding the delta. The SWP pumping plant (Banks Pumping Plant) can deliver an average flow of nearly 6,700 cubic feet per second (cfs) to Clifton Court Forebay for transport to users south of the delta. The Jones Pumping Plant withdraws water primarily from Old River and has the capability of 4,600 cfs to contractors in southern California. Relatively small amounts of water are extracted for the Contra Costa canal (up to 195,000 af or 195 thousand acre-feet {TAF} per year) and the North Bay Aqueduct (up to 71 TAF per year) (FWS, 2008). In addition, diversions occur upstream of the delta. These diversions affect the location of X2, the amount of water that can be withdrawn at the pumps, the flow in the San Joaquin River, and other factors.

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THE PRESENT STUDY

The statement of task (Appendix A) charges the NRC committee to review the scientific basis of the Services' RPAs and advise on how to most effectively incorporate science and adaptive management concepts into holistic programs for management and restoration of the delta. To balance the need to inform near-term decisions with the need for an integrated view of water and environmental management challenges over the longer-term, the committee was tasked to produce two reports. This first report focuses on the scientific bases of the water-management alternatives (RPAs) in the two biological opinions and whether there might be possible alternative RPAs that would be as or more protective of the fishes with lesser impacts on other water uses. The committee also has considered "other stressors," as specified in its statement of task. These are stressors not necessarily directly associated with the water projects; they are part of the "environmental baseline," a concept related to the Endangered Species Act that refers to other anthropogenic modifications of the environment. As such, they are not addressed by the RPAs, because RPAs must address operations of the water projects.

In this first report, most of the committee's focus has been on the question of the scientific bases of the water-management alternatives (RPAs) in the biological opinions, with a smaller focus on potential conflicts between the RPAs, potential alternative RPAs, and other stressors. The committee's second report will focus on broader issues surrounding attempts to provide more sustainable water supplies and to improve the ecological sustainability of the delta, including consideration of what ecological goals might be attainable.

To prepare this report, the committee met in Davis, California for five days in January 2010. It heard presentations from representatives of federal and state agencies and a variety of other experts, and from members of the public, and began work on the report. The committee was able to consider information received by February 8, 2010. Additional writing and two teleconferences occurred in February, and the report was reviewed according to the NRC's report-review procedure (the reviewers are acknowledged in the preface).

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2

The Legal Context of This Report

SCOPE OF THE COMMITTEE'S TASK

The committee was asked "to review the scientific basis of actions that have been and could be taken to simultaneously achieve both an environmentally sustainable Bay-Delta and a reliable water supply." While this committee's review is scientific, and not legal, the committee nonetheless recognizes the importance of the legal context within which its evaluation takes place. The standard of review applicable in legal challenges to the opinions and associated RPAs provides a useful reference. In such lawsuits, courts will invalidate the RPAs only if they are demonstrated to be "arbitrary, capricious, an abuse of discretion, or otherwise not in accordance with law" (Administrative Procedure Act, 5 U.S.C. § 706(2)(A)). Courts are reluctant to second-guess technical agency judgments and may not substitute their judgment for that of the agency, particularly in cases where there are scientific uncertainty and differing scientific views. *See* Aluminum Co. of America v. Bonneville Power Administration, 175 F.3d 1156 (9th Cir. 1999); Trout Unlimited v. Lohn, 559 F.3d 946 (9th Cir. 2009). Thus, while the committee can come to different conclusions than the agencies did in their biological opinions, that would not be a *legal* justification for deeming them inadequate, as long as the agencies adequately considered the available scientific data and their conclusions are supportable by the evidence. Similarly, the RPAs should not be considered *legally* inadequate simply because different alternatives could be scientifically justified, as long as the agencies could reasonably believe that their RPAs would avoid the likelihood of jeopardy.

Some aspects of the committee's task require it to make determinations beyond the scope of the agencies' legal obligations or authority when issuing a biological opinion and RPAs. For example, the committee's charge includes consideration of the effects of stressors such as pesticides, ammonium, and invasive species on federally listed and other at-risk species in the Bay-Delta—stressors likely beyond the action agencies' legal authority to regulate, unless the effects are indirectly changed by the RPAs. Any such considerations by this

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committee in this or in its second report would have no bearing on the question of whether or not the biological opinions and RPAs are legally adequate. Instead, such considerations should be interpreted in contexts apart from the biological opinion and RPAs, such as the Bay-Delta Conservation Program (development of a habitat conservation plan); the State Water Resources Control Board's development of flow criteria for the delta; the Delta Stewardship Council's development of a delta plan; and others.

POTENTIAL VIOLATIONS OF ESA SECTION 7 AND SECTION 9

In each biological opinion, the relevant wildlife agency concluded that the proposed federal action—implementation of the water projects' operations plan—was likely to "jeopardize" the continued existence of species listed as endangered and to adversely modify their critical habitat. This would violate Section 7 of the Endangered Species Act (ESA), which requires agencies to "insure" that any actions they authorize, fund, or carry out are not likely to jeopardize endangered species or to destroy or adversely modify the species' critical habitat (16 U.S.C. § 1536 (a) (2)). As defined by agency regulations, "jeopardy" means that the proposed action "reasonably would be expected, directly or indirectly, to reduce appreciably the likelihood of both the survival and recovery of [relevant endangered species] in the wild by reducing the reproduction, numbers, or distribution of that species" (50 C.F.R. § 402.02). As required by the ESA, the wildlife agencies suggested "reasonable and prudent alternatives" (RPAs) that would allow the action to go forward without violating Section 7 (16 U.S.C. § 1536 (B) (3) (A)).

In addition to the jeopardy determinations (generally, applying to species as a whole), both biological opinions found that the proposed action would "take" individual members of the endangered populations in violation of Section 9 of the ESA. By regulation, the "take" of an endangered species includes "an act which actually kills or injures wildlife" and may include "significant habitat modification or degradation where it actually kills or injures wildlife by significantly impairing essential behavioral patterns, including breeding, feeding, or sheltering" (Babbitt v. Sweet Home Chapter of Communities, 515 U.S. 687 (1995)).

The resource agencies, the National Marine Fisheries Service and the Fish and Wildlife Service, issued an "incidental take statement," in the present case, setting forth reasonable and prudent measures necessary and appropriate to minimize the effect of the proposed action on endangered species. If the action agencies (the Bureau of Reclamation and the California Department of Water

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Resources) comply with those measures, including monitoring and reporting requirements, then any "takes" that result from project operations will be deemed "incidental," and they will be exempt from the prohibitions of Section 9.

STANDARDS FOR THE PREPARATION OF BIOLOGICAL OPINIONS

Best Available Data

Under the ESA, the agencies must develop their biological opinions and associated RPAs using the "best scientific and commercial data available" (16 U.S.C. § 1536 (a) (2)). Courts have emphasized the qualifier *available,* explaining that perfect data are not required. Action can be taken based on imperfect data, so long as the data are the best available. In addition, the above requirement does not remove the agency's discretion to rely on the reasonable judgments of its own qualified experts, even if others, even a court, might find alternative views more persuasive (see Aluminum Co. v. Bonneville Power Admin., 175 F.3d 1156 (9th Cir. 1999).

Thus, the courts afford the agencies significant deference in determining the best data available for developing the RPAs. Therefore, even if this committee might have relied on different data or come to different conclusions than the agencies did, it does not follow that the RPAs are legally insufficient. Rather, this committee's conclusions and recommendations should be seen as applying to future work beyond the scope of the agencies' legal obligations.

Economic Considerations

Although the economic impact of species protections may be relevant under the ESA, its influence is limited. For example, economic concerns *may not* be part of the decision whether or not to list species as endangered or threatened, but *must be* considered when the agencies designate critical habitat (16 U.S.C. § 1533). When developing biological opinions and RPAs, the Ninth Circuit acknowledged that the wildlife agencies may go beyond "apolitical considerations" and that if two proposed RPAs would avoid jeopardy to the relevant species, the agencies "must be permitted to choose the one that best suits all of its interests, including political or business interests." Southwest Center for Biological Diversity v. U.S. Bureau of Reclamation, 143 F.3d 515 (9th Cir. 1998); *See also* Bennett v. Spear, 520 U.S. 154 (1997) (asserting that the "best scientific and commercial data" provision is . . . intended, at least in part, to prevent

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uneconomic [because erroneous] jeopardy determinations"). Nevertheless, the lower courts have been reluctant to second-guess agency opinions on the basis of economic arguments (Aluminum Co. cited above).

Effects of the Proposed Action and the Environmental Baseline

In preparing biological opinions, agencies must evaluate the "effects of the [proposed] action" on the species or its critical habitat. Other adverse modifications of the species' habitats or negative effects on their populations are considered part of the "environmental baseline." The agencies' analysis includes consideration of:

1) direct effects;
2) indirect effects ("those that are caused by the proposed action and are later in time, but still are reasonably certain to occur");
3) interrelated actions ("those that are part of a larger action and depend on the larger action for their justification");
4) interdependent actions ("those that have no independent utility apart from the action under consideration"); and
5) cumulative effects ("those effects of future State or private activities, not involving Federal activities, that are reasonably certain to occur within the action area of the Federal action subject to consultation") (50 C.F.R. §§ 402.02 and 402.14(g)(3-4)).

STANDARDS FOR THE PREPARATION OF REASONABLE AND PRUDENT ALTERNATIVES (RPAs)

Although RPAs are not binding on the action agency, adherence to the RPAs provides the agency with a safe harbor from claimed violations of the ESA. As the U.S. Supreme Court explained, "the action agency is technically free to disregard the Biological Opinion and proceed with its proposed action, but it does so at its own peril (and that of its employees), for 'any person' who knowingly 'takes' an endangered or threatened species is subject to substantial civil and criminal penalties, including imprisonment" (Bennett v. Spear, 520 U.S. 154 (1997)).

Under agency regulations, the RPAs must satisfy each of the following four requirements:

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1) Project purpose: RPAs must be capable of implementation in a manner consistent with the intended purpose of the action.
2) Scope of agency authority: RPAs must be consistent with the scope of the action agencies' legal authority and jurisdiction.
3) Feasibility: RPAs must be economically and technologically feasible; and
4) Avoid jeopardy: The directors of FWS and NMFS must believe that the RPAs would avoid the likelihood of jeopardizing the continued existence of listed species or resulting in the destruction or adverse modification of critical habitat (50 C.F.R. § 402.02).

Although RPAs must avoid the likelihood of jeopardy, they are not required to promote recovery of the affected species. In other words, no RPA has the responsibility of mitigating all the adverse effects—the "environmental baseline"—that may be causing the decline of a listed species. They must only avoid the likelihood that the *proposed action* will cause jeopardy.

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3

The Life Histories of the Fishes

INTRODUCTION

Chinook salmon (*Oncorhynchus tshawytscha*), steelhead (*Oncorhynchus mykiss*), and green sturgeon (*Acipenser medirostris*) are anadromous species; that is, they spawn in freshwater but spend a portion of their life in saltwater. Delta smelt (*Hypomesus transpacificus*) are resident within the brackish and freshwater habitats of the delta. In both anadromous and resident life-history strategies the fish migrate from their natal habitat into their adult habitat and then back to the spawning habitat, completing the life cycle. The fish do not simply drift between their habitats, but have evolved specific life-stage behaviors to meet the challenges they confront. These behaviors are cued by the fishes' physiology and by environmental conditions, which together drive the timing and movement of the individuals through their life cycle. Because all species spend time in the delta, they share some environmental conditions and challenges, but their different life histories cause them also to face unique challenges. Many of the challenges are the result of anthropogenic modifications to the delta and river habitats, and these challenges are of particular concern (see Chapter 5). Some, but not all, of them are addressed in the RPAs. The information on the fishes' life histories presented below illustrates the complexity of their interactions with their environments and the potential importance of apparently small changes in the timing, direction, and magnitude of variations in flow, salinity, turbidity, water temperature, and other environmental conditions.

FISHES OF THE SALMON FAMILY

The delta provides habitat for two species of Pacific salmon, Chinook salmon (hereafter "salmon") and the rainbow trout-steelhead complex. Pacific salmon typically are anadromous. There are many exceptions, however, such as rainbow trout, which although apparently genetically identical to steelhead, are

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not anadromous; and there is a great deal of variation in their life histories (Williams, 2006).

When adult salmon, steelhead, and sturgeon return from the ocean and begin their upriver migration, they experience several challenges, including physical and water-quality blockages. Here the delta water system has had a great impact on populations, for 80 percent of the historical spawning habitat for Chinook salmon (Clark, 1929) and much of it for the other species has been blocked by the storage reservoirs of the Central Valley (Lindley et al., 2006). Summer temperatures in the Central Valley waterways can reach potentially lethal levels for salmon, increasing their susceptibility to disease and decreasing metabolic efficiency (Myrick and Cech, 2001, 2004). The timing of adult salmon runs leads them to avoid most of the detrimental effects of high summer temperatures because they enter the delta and swim upriver to their spawning habitats and hatcheries in the spring, autumn, and winter. Wild spawning fish excavate redds in stream reaches with loose gravel in shallow riffles or along the margins of deeper runs (NMFS, 2009), where temperatures are cooler and eggs buried in the gravel receive a sufficient flux of oxygenated water through interstitial flow. The eggs incubate for several months and after emerging the young fry either immediately begin their migration back to the ocean or spend several weeks to a year in freshwater before migrating. Because of this diversity, juvenile salmon and steelhead pass through the delta throughout the year; however, the timing and size of the migrants generally corresponds to specific runs (Lindley et al., 2006; Williams, 2006).

Salmon and steelhead undergo a complex set of physiological changes in preparation for their migration to the ocean known as "smoltification," after which the young fish are known as "smolts." The alteration of the fish's physiology to successfully osmoregulate in saltwater after beginning life in freshwater is a significant challenge that can be exacerbated by human-caused environmental changes (e.g., NRC, 2004b). Most Central Valley Chinook salmon migrate to the ocean within a few months of hatching and the smolts are less than 10 cm long, although some remain in freshwater for up to a year. Juvenile steelhead migrate to sea after one to three years in freshwater, and can be as large as 25 cm in length. Young migrating Chinook are much more vulnerable to entrainment in adverse flows than the stronger-swimming steelhead smolts.

Juvenile salmon migrants experience predation during their downstream migration through the Sacramento River or through the interior delta on their way to the sea. Fish that enter the central delta, driven by the strong tidal and pumping-induced flows, are moved through a labyrinth of channels, which further delays their migration and exposes them to additional predators (Perry et al., 2010). Finally, fish that enter the Old and Middle Rivers (OMR) can be drawn

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towards the SWP and CVP pumps (Kimmerer, 2008a). Juvenile salmon that successfully pass through the delta enter the ocean and spend one or more years there before returning to freshwater to spawn. Ocean survival is particularly dependent on the conditions the fish experience during the first few months they enter the saltwater (Lindley et al., 2009). Fish that are drawn into the central and southern delta by reverse flows are more vulnerable to predation than those that take a more direct path to the ocean, and other aspects of changed environmental conditions also expose them to predators (for more detail, see Chapter 5).

GREEN STURGEON

The Central Valley green sturgeon (*Acipenser medirostris*) is an anadromous fish that can reach 270 cm (nearly nine feet) in length with a maximum age of 60 to 70 years (Moyle et al., 2002). The historical distribution of green sturgeon is poorly documented, but they may have been distributed above the locations of present-day dams on the Sacramento and Feather Rivers (Beamesderfer et al., 2007). Information on the distribution of green sturgeon in the San Joaquin River is lacking. Mature green sturgeon enter the Sacramento River from the ocean in March and April. The Red Bluff Diversion Dam can impede their migrations (Heublein et al., 2009). After spawning, green sturgeon may immediately leave the river or hold over in deep pools until the onset of winter rains (Erikson et al., 2002; Heublein et al., 2009). Individuals then migrate back to the ocean and return to freshwater to spawn every two to four years (Erickson and Webb, 2007; Lindley et al., 2008)

Based on adult spawning behavior and the habitats required for green sturgeon embryo development, reproductive females likely select spawning areas with turbulent, high velocities near low-velocity resting areas. Green sturgeon spawning areas are presumed to be characterized by coarser substrates upstream of lower gradient reaches, which usually have slower velocities. Eggs and milt are released in turbulent water above deep, complex habitats; fertilized eggs drift into deeper areas and stick onto the substrate. Eggs require cool temperatures for development and hatch after approximately a week. Larval and juvenile green sturgeons are bottom-oriented and nocturnally active until a few months of age (Kynard et al., 2005). Juvenile green sturgeon migrate into seawater portions of natal estuaries as early as one and a half years old (Allen and Cech, 2007), and eventually emigrate to nearshore coastal waters by three years old. Subadults are migratory, spending their next 12 to16 years foraging in the coastal ocean and entering western estuaries during the summer (Moser and Lindley, 2007). In the ocean, green sturgeon inhabit the coastal shelf out to 100m depth with occa-

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sional, rapid vertical ascents near or to the surface (Erickson and Hightower, 2006).

DELTA SMELT

The delta smelt is a near-annual species; most individuals complete their life cycle in one year, but some survive for two years and reproduce again. Delta smelt reside in brackish waters around the western delta and Suisun Bay region of the estuary, being commonly found in salinities of 2 to 7, but the range they occupy extends from 0 (freshwater) to 15 or more (Moyle, 2002). In the winter (December to April), pre-spawning delta smelt migrate to tidal freshwater habitats for spawning, and larvae rear in these areas before emigrating down to the brackish water (Bennett, 2005). Delta smelt inhabit open waters away from the bottom and shore-associated structural features. Although delta smelt spawning has never been observed in the wild, information about related members of the smelt family suggests that delta smelt use bottom substrate and nearshore features during spawning. Juvenile and adult stages, 20-70 mm in length, are generally caught in the western delta and Suisun Bay in the landward margin of the brackish salinity zone, which may extend upstream of the confluence zone of the Sacramento and San Joaquin Rivers. Historically pre- and post-spawned fish were observed throughout the delta. In wet years, spawning adults often were observed in the channels and sloughs in Suisun Marsh and the lower Napa River.

In the brackish habitat of the western delta the flow is tidal with a net seaward movement, and so to maintain position, the juvenile fish appear to coordinate swimming behavior with the tides, occurring near the surface on the flood tides and at depth on the ebbs. However, in other regions, adaptive tidal behavior has not been observed and fish simply move with the tides, which may promote horizontal exchange to adjacent shallow water habitats. The FWS biological opinion emphasizes the complexity of this behavior (p. 651) and thus the above description is a general one that does not capture details that might be important.

The brackish zone also has higher densities of other fishes and zooplankton, suggesting that it may serve as a nursery habitat for delta smelt and other fishes (Bennett, 2005). The spawning movement of adults from their brackish habitat in the western delta landward to the freshwater portions of the delta is triggered by high flows and turbidity pulses.

This diversity of paths from the low-salinity (brackish) zone to the freshwater spawning habitats suggests that delta smelt do not have fidelity to specific

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structural habitats as do salmon. Instead, their upstream movement is directed by a combination of physiological and environmental cues that involve salinity, turbidity, and both net and tidal flows through the channels of the delta and its tributaries. Additionally, since 2005, approximately 42 percent of the current delta smelt population is in the Cache Slough complex north of the delta, and may represent an alternative life-history strategy in which the fish remain upstream through maturity (Sommer et al., 2009).

Historically, the complete delta-smelt life cycle occurred unobstructed throughout the delta. Human-caused changes in delta water quality and hydrodynamics have disrupted the cycle and since 2005, delta-smelt population densities have been extremely low in the traditional habitats in the central and south delta (*http://www.dfg.ca.gov/delta/data/*), and pump salvage[1] also has been extremely low, about four percent of the 50-year average index (*http://www.dfg.ca.gov/delta/data/townet/indices.asp?species=3*). Analyses seeking causes for the declines to the present condition have focused on relationships between abundance, salvage, water exports, delta flows, turbidity, and food. Kimmerer (2008b) found that delta-smelt survival between summer (juvenile) and fall (adult) was related to zooplankton biomass, suggesting that high zooplankton abundances contributed to delta-smelt abundance and residence time in the southern delta, and thus increased entrainment risk at the pumps. Grimaldo et al. (2009) found that between 1995 and 2005 the inter-annual variation in adult delta-smelt salvage was best correlated with turbidity and the interaction of OMR[2] flows and X2[3]. The annual salvage of age-0 delta smelt (fish hatched in that year, around 27 mm in length) was best correlated with spring abundance of zooplankton, OMR flows, and turbidity. Additionally, Grimaldo et al. suggested that differences in temporal patterns of entrainment of delta smelt between years may be a measure of the degree to which their physical habitat overlapped with the hydrodynamic footprint of negative OMR flows towards the pumps. However, the year-class strength of adult delta smelt was not related to salvage, al-

[1] "Salvage" refers to fish caught in the pumps and retrieved alive to be released elsewhere in the system. It often is used as a surrogate estimate for "take" by the pumps.

[2] The term "OMR flows" refers to flows in the Old and Middle Rivers (see Figure 1-1), which are affected by the pumping of water for export. At high negative flows, that is, flows away from the sea towards the pumps in the south, the normal seaward flow associated with ebb tides can be completely eliminated.

[3] "X2" refers to the salinity isohaline of salinity 2 (a contour line of equal salinity). Sometimes X2 is used as shorthand for the mean position of that isohaline, measured in kilometers upstream from the Golden Gate Bridge over the outlet of San Francisco Bay. Managing the position of X2 is a major aspect of the delta smelt Biological Opinion and RPA; it is managed by adjusting flows of fresh water from delta reservoirs, as well as by adjusting pumping rates.

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though the position of X2 was correlated with salvage at an intra-annual scale when OMR flows were negative. Other analyses showed a similar correlation (e.g., FWS, 2008).

While the correlation between OMR flows and salvage is substantial (Kimmerer, 2008b), their effect on population dynamics is not clear (Bennett, 2005; Grimaldo et al., 2009). Indirect factors could have contributed to population declines through a reduction in the size and abundance of food in the brackish zone. Overall zooplankton abundance is correlated with delta smelt survival (Feyrer et al., 2007; Grimaldo et al., 2009; Kimmerer, 2008b). Zooplankton abundance has been reduced through several factors, including the introduction of the overbite clam (*Corbula amurensis*), an efficient grazer of zooplankton in the low-salinity zone, and changes in nutrients that have altered the phytoplankton population so that cyanobacteria, which can reduce the food supply for zooplankton, have increased while diatoms have declined (FWS, 2008). The change in zooplankton species, associated with the success of invasive species in changed environmental conditions, also is probably important. It has been suggested that the position of X2 affects the size of delta smelt habitat and thus it affects the susceptibility of juvenile and adult delta smelt to pump entrainment (Feyrer et al., 2007, Kimmerer, 2008a). Furthermore, the mean position of X2 has moved inland about 10 km over the past 15 years (FWS, 2008, p. 180). However, there is no direct evidence relating these indirect effects to population numbers of smelt (Bennett, 2005; Kimmerer, 2002). In addition, delta smelt are now largely absent from the central and southern delta, while a significant portion of the remaining population exists in the Cache Slough complex to the north. These changes increase the uncertainty surrounding current estimates of delta smelt population changes in response to alterations in delta hydraulics.

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4

Use of Models

MODELING SCENARIOS

Modeling of baselines and future project actions is a standard practice of evaluating impacts. Both biological opinions relied on the use of modeling scenarios (known as Studies) provided by the Operations Criteria and Plan (OCAP) biological assessment (BA) (*http://www.usbr.gov/mp/cvo/ocap_page.html*), although the extent to which such results were used in each biological opinion and in the formulation of RPAs varied significantly. The "proposed action" with reference to ESA is the continued operation of the CVP and SWP with additional operational and structural changes (USBR, 2008, Table 2-1) to the system. The U.S. Bureau of Reclamation (USBR) and the California Department of Water Resources (DWR) provided the results of the modeling conducted for simulating baseline conditions, future system components, operational strategies, and the water supply demands. In addition to simulating the water-supply deliveries of the project, the modeling also attempted to mimic the project operations associated with the regulatory environments described in operating criteria described in D-1485, D-1641,CVPIA Section 3406 (b)(2) and the Environmental Water Account (EWA) (USBR, 2008). A major difference in the current and future scenarios is the extent to which EWA is used. The purpose of EWA was to enable diversion of water by the SWP and CVP from the delta to be reduced at times to benefit fish species while minimizing uncompensated loss of water to SWP and CVP contractors (USBR, 2008, Chapter 2). The EWA is intended to replace the water loss due to pumping curtailments by purchasing surface water and groundwater from willing sellers and through increasing the flexibility of operations. The simulations include both a "full EWA" characterizing the full use of EWA assets as well as a "limited EWA" focusing only on a limited number of assets. The EWA is currently under review to determine its future (FWS, 2008, p. 34) and the RPA actions were not based on it.

Another factor that changed from current to future conditions is the way water demand by CVP/SWP users is simulated. Demands have been pre-

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processed using either contractual amounts and/or level of development (existing versus future). Some demands were assumed to be fixed at contractual amounts whereas in other cases they varied according to the hydrologic conditions. This topic will be considered in the committee's second report.

While several study scenarios were developed for the OCAP biological assessment (USBR, 2008), the use of modeling results in the biological opinions was largely limited to a smaller set of scenarios (Table 4-1).

Study 7.0 describes the existing condition (circa 2005), whereas Study 7.1 presents the existing condition demands with near future facilities as well as the projected modification to EWA. Study 8 describes the future condition corresponding to the year 2030 (USBR, 2008, pp. 9-33, 9-53, 9-54). Study series 9 constitutes a future condition representing modified hydrology (warm and warmer, dry and wet) along with a projected sea level rise of one foot.

CENTRAL ISSUES CONCERNING MODEL USE IN THE BIOLOGICAL OPINIONS

The USFWS and NMFS supplemented the modeling results provided by USBR and DWR with their own modeling efforts and available science on the implications of management actions on species. The primary suite of models provided to FWS and NMFS include (USBR, 2008, Chapter 9):

(a) Operations and hydrodynamic models: CalSim-II, CalLite, the Delta Simulation Model II (DSM2), including particle-tracking models (PTMs, which also are considered as surrogates for biological models)

TABLE 4-1 Key scenarios used for biological opinions of FWS and NMFS

Study	Level of Development (Year)	Environmental Water Account (EWA)	Future Project Facilities[1]	Climate and Sea Level Rise
7.0	2005	Full EWA	No	No
7.1	2005	Limited EWA	Yes	No
8.0	2030	Limited EWA	Yes	No
9.0-9.5	2030	Same as in Study 8.0[2]	Yes	Yes

[1] Future project features include South Delta Improvement Program (Stage 1), Freeport Regional Water Project, California Aqueduct and Delta-Mendota Canal intertie

[2] According to the OCAP BA (USBR, 2008), Study suite 9 is identical to Study 8.0 except for climate change and sea-level rise

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(b) Temperature models: Reclamation Temperature, SRWQM, and Feather River Mode
(c) Biological models: Reclamation Mortality, and SALMOD

The modeling framework used by the agencies is diagrammed in Figure 4-1.

The USFWS, in its biological opinion, used available results from a combination of tools and data sources, including CalSim-II, DSM2-PTM, DAYFLOW historical flows, and statistical models based on observational data and particle-tracking simulations (FWS, 2008, p. 204). NMFS analyses included results from coupled CalSim-II simulations with various water-quality and biological models for a few of the life stages (NMFS, 2009, p. 64).

The CalSim-II model, the primary tool used to evaluate the water-resources implication of the proposed actions, was developed by the DWR and the USBR to simulate water storage and supply, streamflows, and delta export capability for the Central Valley Project (CVP) and the State Water Project (SWP). CalSim-II simulates water deliveries and the regulatory environment associated with the water-resources system north of the delta and south of the delta using a

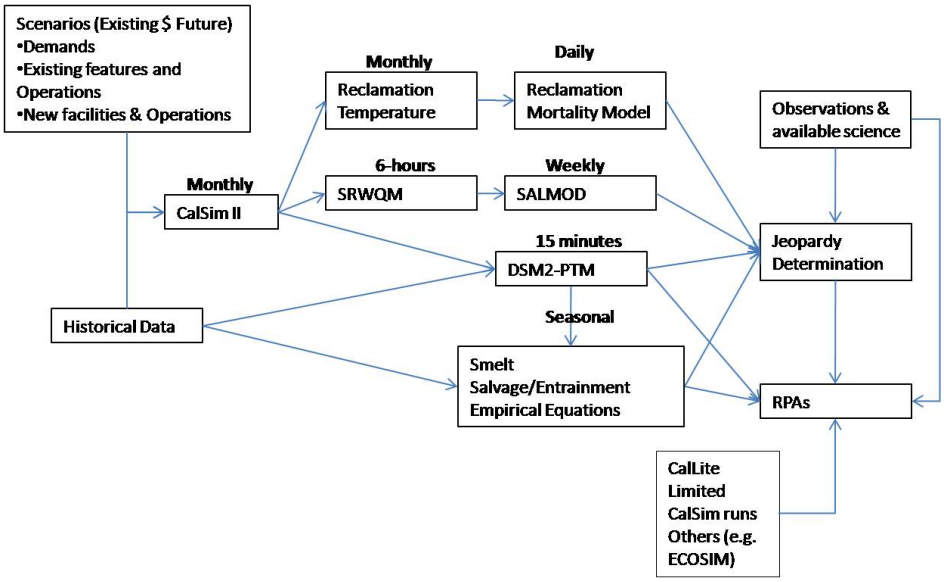

FIGURE 4-1 Modeling framework used in NMFS and USFWS biological opinions and RPAs.

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single time step (one month) optimization procedure based on a linear programming algorithm. CalSim-II represents the best available planning model for the CVP-SWP system, according to a CALFED Science Program peer review by Close et al. (2003) (USBR, 2008, p. 9-4). However, many users have suggested that its primary limitation is its monthly time step, and the model should be used primarily for comparative analysis between scenarios and discouraged its use for absolute predictions (Ferreira et al., 2005; USBR, 2008, Chapter 9). In response to the peer review by Close et al. (2003), DWR and USBR provided a list of development priorities (Table 2, DWR/USBR, 2004), including the use of a daily time step, but it is not clear how many of such planned improvements have been incorporated into the version of CalSim-II used in the biological opinions.

Several other tools and models were central in effects analysis and developing RPAs, including hydrodynamic and water-quality (DSM2, USBR's temperature, SRWQM), habitat (SALMOD), and statistical and particle-tracking models (salvage, DSM2-PTM). Some of these models have already been evaluated in the literature for their individual strengths and limitations, though some (SALMOD and USBR's mortality models) have not yet been formally peer reviewed. We first review some of the challenges of applying these individual models in the determination of RPAs, and then focus on examining the modeling process, including how the models contributed to the development of RPAs, and where the uncertainties and vulnerabilities in that process lie.

Model Scale and Management Implications

Very generally, the tiered modeling approach (Figure 4-1) applied the results of CalSim-II as input to various hydrodynamic and ecological models to predict impacts of project operations and, to a very limited extent, to explore RPAs. At one level, model simulations were also used or performed to investigate the feasibility of some proposed actions. For example, CalSim-II was used at the planning level to investigate whether the USBR could meet the 1.9 MAF (at the end of September) required by actions I.2.3 and I.2.4 (maintaining cold water supplies necessary for egg incubation for the following summer's cohort of winter-run), and to recommend storage conservation in severe and extended droughts (NMFS, 2009, p. 596). Similarly, examination of CalSim results and hydrologic records demonstrated to the agencies that the first year of a drought sequence is particularly critical to storage and operations in the following drought year (NMFS, 2009, p. 596). The benefits of using models at this planning level, especially given the importance of water-year types, is clear, and there is little controversy about this application of the models.

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At another level, model scenarios were examined to investigate the relationships between operations and impacts on various life stages of the fish across the water-year types and operations scenarios. For example, NMFS used DWR's Delta Survival Model (Greene, 2008) to estimate mortality of smolts associated with three CalSim-II Study scenarios (7.0, 7.1, 8.0). The USFWS used statistical models of salvage and total entrainment (Grimaldo et al., 2009; Kimmerer, 2008) to investigate the effects of proposed operations by comparing actual and predicted salvage and entrainment losses under modeled OMR flows (FWS, 2008, p. 211).

While some challenges exist in linking models in this tiered approach (see next section), concerns and controversies appear to be largely directed at the various forms of statistical relationships of salvage versus OMR flows, extrapolation of these relationships that describe impacts on single life stages to assess the population impacts on species, and the use of biological models without full consideration of their underlying uncertainties. In particular, this nested sequence of statistical models does not allow for uncertainties at one step to influence predictions at the next step. As a result, some of the RPA actions, especially those involving X2 and OMR flow triggers, are based on less reliable scientific and modeling foundations than others. In these cases, the incomplete data and resolution of the models do not closely match the resolution of the actions.

Adequacy of Current Models

Life-cycle Models

Both agencies have been criticized for the lack of adequate life-cycle models to address population level responses (e.g., Deriso, 2009; Hilborn, 2009; Manly, 2009). Nonlinear and compensatory relationships between different life-history stages are common in many fish species. Moreover, many life-history traits exhibit significant patterns of autocorrelation, such that changes in one life-history trait induce or cause related changes in others. These patterns can most effectively be understood through integrated analyses conducted in a modeling framework that represents the complete life cycle. However, complete life-cycle models were not used in either biological opinion to evaluate the effects of changes in operations. The agencies acknowledge that further model development is required, including the "cooperative development of a salmonid life-cycle model acceptable to NMFS, Reclamation (USBR), CDFG, and DWR" (NMSF biological opinion, p. 584). While one life-cycle model (Interactive Ob-

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ject-Oriented Salmon simulation) was available for winter-run salmon from the OCAP BA (USBR, 2008), this model was rejected based on model resolution and data limitation issues (NMFS, 2009, p. 65). Similarly, a better life-cycle model for delta smelt is critically needed (PBS&J, 2008). Such life-cycle models for delta smelt are currently under development. The committee recommends that development of such models be given a high priority within the agencies. The committee also encourages the agencies to develop several different modeling approaches to enable the results of models with different structure and assumptions to be compared. When multiple models agree, the confidence in their predictions is increased.

Particle-Tracking Models (PTMs)

Particle-tracking models (PTMs) are models that treat eggs and larval fishes as if they were particles and simulate their movements based on hydraulic models of flows. Criticisms have applied to the use of PTMs, which rely on some key assumptions (e.g., neutral buoyancy, no active swimming) that have been challenged at least for some life stages (Kimmerer and Nobriga, 2008) on the basis that fish live and move in three dimensions. Other limitations of the use of PTMs in this case include the reliance on the one-dimensional DSM2, use of random-walks to simulate lateral movements, and the lack of simulation of fish behavior. In view of these limitations, PTMs as used in this case may not be suitable for predicting the movement of fish of some life stages (juvenile and adults) where behavior becomes relevant to the question of potential entrainment (Kimmerer and Nobriga, 2008). The NMFS acknowledges these limitations, noting that "The acoustic tagging studies also indicate that fish behavior is complex, with fish exhibiting behavior that is not captured by the 'tidal surfing' model utilized as one of the options in the PTM simulations. Fish made their way downstream in a way that was more complicated than simply riding the tide, and no discernable phase of the tide had greater net downstream movement than another" (NMFS, 2009, p. 651).

However, while fish seldom behave like passive particles, results based on passive particles can provide insights. For example, the NMFS used a combination of models to simulate mortality rates of salmonids for three CalSim-II scenarios. The results were used to compare the inter- and intra-annual impacts of the three scenarios (NMFS, 2009, p. 381). Further, the agencies advocate improving the model through further study, such as Action iV.2.2, which includes an acoustic tag experiment in part to evaluate action benefits and in part to improve PTM results (USBR, 2008, p. 645). Thus, while there is uncertainty re-

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garding the accuracy of the mortality losses, the use of the models in a comparative way is probably acceptable. However, it should be made clear how the model is used, and the explicit consideration of the PTM assumptions and uncertainties should be more clearly documented in the biological opinions.

Although there has not been an assessment of the degree to which these limitations affect the conclusions, PTM results were used for RPA development. Although the DSM2 has been calibrated adequately for OMR flows, there is no clear evidence concerning the accuracy of the PTM's ability to simulate smelt entrainment in relation to how the models are used for jeopardy determination and RPA development. This is particularly important because a number of actions driven by the RPAs recommend trigger values for OMR to curtail exports. As discussed in a later section, the science surrounding these OMR triggers is less clear than for many other aspects of the RPAs, and this trigger may result in significant water requirements. The committee's recommendations for improving the modeling and associated science are intended to improve the best science available to the agencies. The committee will address such improvements in greater detail in its second report.

Other Biological Models

The NMFS used other biological models to simulate the effects of operations on various life stages of salmon. These models involve several key assumptions and data limitations that influence the reliability of their results.

For example, SALMOD, developed by the USGS, was used by the NMFS to investigate the population level responses of the freshwater life stages to habitat changes caused by project operations (NMFS, 2009, p. 269). A variety of weekly averaged inputs are required, including streamflow, water temperature, and number and distribution of adult spawners (USBR, 2008, p. 9-25). This model provides some valuable insight, but requires greater consideration of the model assumptions (e.g., linear stream, habitat as primary limiting factor, independence of food resources on flow and temperature, density independence for some life stages) and uncertainties. Otherwise, the use of this model is limited to comparative, rather than absolute, analysis of RPA actions. Further, it would be important to investigate the sensitivity of the model to initial conditions and input data, particularly those prone to measurement error (e.g., number and distribution of spawners) to provide some indication of the reliability of model outputs. While SALMOD has not been thoroughly peer-reviewed, criticisms of similar modeling approaches (e.g., NRC, 2008) have highlighted some key issues with habitat-suitability models (e.g., the need for greater clarity concerning

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the assumption that habitat is a limiting factor and the need for a thorough assessment of the representativeness of the areas sampled) and have provided extensive discussions of the use of models in an adaptive-management approach, which is relevant to this committee's recommendations. Finally, the NMFS acknowledges that SALMOD is most appropriately applied to large populations that are not sensitive to individual variability and environmental stochasticity (NMFS, 2009, p. 270), which means that the predictions for the relatively small population in the delta river system are subject to considerable uncertainty. The uncertainties again highlight the need for an adaptive management approach.

The NMFS also used results from the USBR's salmon mortality model (Hydrologic Consultants, Inc., 1996) to examine daily salmon spawning losses for early life stages (pre-spawned eggs, fertilized eggs, and pre-emergent fry) due to exposure of high temperatures. Temperature-exposure mortality criteria for the three life stages are combined with modeled temperature predictions and spawning distribution data to compute percents of salmon spawning losses. Because simulations of river temperatures are run on a daily or shorter time step, downscaling of monthly CalSim-II data is required (USBR, 2008, Attachment H-1). Moreover, the monthly temperature models do not adequately capture the range of daily temperature variability (USBR, 2008, pp. 9-109). In addition, several assumptions (e.g., density independence) and important data limitations (USBR, 2008, pp. L-6, L-7) challenge the reliability of this model. Finally, while this model has been applied in other systems, it is not thoroughly peer reviewed and no analysis of sensitivity or uncertainty has been performed. Addressing these model shortcomings would help increase confidence in the analyses.

Developing, Evaluating, and Applying Best Available Models

As the agencies work within the constraints of best available science, some recognition of the adequacy and reliability of the models should be reflected in the management decisions by making them adaptive. The following five factors, in particular, need better documentation.

1. *Incompatible temporal resolution and implications for management decisions.*

The individual models used in this tiered analysis approach have a broad range of temporal resolutions (Figure 4-1). Care must be exercised in such

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situations so that the linkages of models with different temporal and spatial resolutions do not result in propagation of large errors that may influence decisions derived from the modeling results. For example, CalSim-II uses a monthly time step whereas the DSM2 uses a 15-minute time step. Although the tidal boundary condition in DSM2 is pre-processed at 15-minutes, average monthly flow, simulated by CalSim-II, is provided as the upstream flow boundary condition at many delta inflow points. The linkage of CalSim-II and DSM2 attempts to smooth out the step change in monthly simulated flows (USBR, 2008, pp. 9-14, 9-15), but this is not necessarily adequate to simulate the fluctuations of flows within the month. The use of the monthly time step certainly could have a significant influence on such performance measures as OMR flows, particularly when such flows are recommended in RPAs for triggering export curtailments. USFWS and NMFS should provide a comparison of daily versus monthly average simulations of DSM2 for a historical period to ascertain the reliability of using monthly CalSim output as input to DSM2.

The incompatibility of temporal resolutions is particularly important given that flows in the delta are strongly influenced by tides. The flows at such locations as Old River and Middle River are characterized by two flood-ebb cycles per day, with positive and negative values of much larger magnitude than the average net flow at these locations (Gartrell, 2010). In view of the fact that OMR flows have sub-hourly hydrodynamic components, averaging over a longer period such as 5 to 14 days to define the thresholds in the implementation of the RPAs could produce unnecessary changes in water exports. The use of monthly average flows produced by CalSim-II could further add to the concerns regarding the recommended thresholds of OMR flows. In view of these modeling uncertainties, further clarification as to how the modeled OMR flows were used for jeopardy determination and hence for the development and implementation of RPAs is needed.

2. Inconsistent use of baselines.

Both biological opinions use historical data along with modeling results of the CALSIM-II scenarios. Study 7.0, which represents the existing condition, is expected to be closest to historical conditions. However, important differences between the two (historical and existing conditions) could exist due to differences in demands and more importantly due to deviations in operations. Because of the simplifying assumptions used in CalSim-II historical simulations, the FWS BO opted to use actual historical data to develop their baseline (FWS, 2008, p. 206) and continued to compare historical data with the modeling results

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of the numerous scenarios described above (see, for example, Figures E-3 through E-19).

The results suggest that often, actual data are very different in magnitude in comparison to Study 7.0 and furthermore, most scenarios (Studies 7, 7.1, 8, and study series 9) are clumped together with relatively small differences between them in relation to the magnitude of differences with the historical data. In view of these differences, the validation of Study 7.0 and consequently others, becomes even more important for the purpose of RPA development.

The use of historical data to make inferences is very typical and appropriate in the biological opinions. However, since the evaluation of project actions and the development of RPAs are based on the evaluation of modeling scenarios, which appear to greatly differ from historical data, a comparison of the two sets of data (historical and simulated) may incur errors in interpretation. The committee recommends that the biological opinions provide a better justification for the reasonableness of the baseline scenario, Study 7.0, as well as the comparison of scenario results with historical data.

3. *Challenges in calibrating and validating any of the models to historical observations and operations.*

It is a standard practice to ensure the appropriate use of models through the processes of calibration and testing (ASTM, 2004; NRC 2008). Validation of CalSim-II is described in Appendix U of the OCAP BA (USBR, 2008), which provides a comparison of Study 7.0 (existing condition) with the recent historical data. A review of those results shows that there are significant deviations of the historical data from the simulated storages and exports that may be of the same magnitude as the differences between the scenarios being evaluated. Thus, while the tool itself performs well, some questions remain regarding the gross nature of generalized rules used in CalSim-II to operate CVP and SWP systems, relative to actual variability of dynamic operations (USBR, 2008, pages 9-4). In their peer review of the CalSim-II model, Close et al. (2003) suggested that "Given present and anticipated uses of CalSim-II, the model should be calibrated, tested, and documented for "absolute" or non-comparative uses." It is not clear if the agencies that developed the model have responded to this suggestion in a comprehensive manner. As emphasized above, a clear presentation of the realism of Study 7.0 with respect to recent operations or observations would help avoid the criticism as to the results of Study 7.0 as well as other derivatives of it (Studies 7.1, 8.0 and series 9).

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The OCAP BA (USBR, 2008) provides sufficient information on the calibration and testing of temperature models, and the time steps vary among models, although all used the monthly output of CalSim-II in predictions. Thus, they appear to be adequate for predicting temperature variation and making comparisons at the monthly time scale. Information on the calibration of DSM2 and PTM is provided in part by DWR, which has been posted online (*http://modeling.water.ca.gov/delta/studies/validation2000/*) results of the calibration of this 1-D, hydrodynamic model of the delta. Based on the information provided, it appears to adequately mimic the historical data at a daily time-scale. However, the DSM2 simulations should demonstrate that the range of negative OMR flows used for calibration covers the high negative flows simulated by CalSim-II for future scenarios. There has been an attempt to test PTM (Wilbur, 2001), but clearly this tool needs further improvements. Wilbur (2001) reports that the existing velocity profiles used in PTM consistently over-predict the field observations (i.e., the predicted velocities exceed the observed velocities).

In addition, with the potential for changes in the historical patterns of climate and hydrology, calibrating models with historical data alone may be less meaningful for projection of future operations. Thus, in addition to providing support for model improvement and adaptive management, a more robust monitoring program will also support calibration and testing of models with more relevant representation of the current and future system. For example, drought-induced low flows of the past several years provide opportunities to calibrate and test models under infrequent but foreseeable conditions. Realistic modeling of the system that incorporates what actually happens in an operational setting with climate outlook will be important in the future.

The biological models such as USBR's mortality model and SALMOD are essentially uncalibrated for the system, and further concerns about these models were addressed in previous sections.

4. Challenges of the Tiered Modeling Approach.

Temperature, OMR flows, and X2 performance measures are particularly challenged by the tiered modeling approach, with limitations related to data availability and inconsistency in model resolution (spatial and temporal) and complexity (USBR, 2008, pp. 9-31). However, the use of models may still be beneficial in planning and triggering adaptive management needs. For example, for NMFS implementation of Action II.2 (Lower American River Temperature Management), forecasts will be used to simulate operations and compliance with thermal criteria for specific life stages in months when salmon would be present

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(NMFS, 2009, p. 614). However, if the USBR determines that it cannot meet the temperature requirement, and can demonstrate this through modeling of allocations and delivery schedules, consultation with the NMFS will occur. In this example, modeling results are used to evaluate the feasibility of meeting criteria, rather than trying to derive direct loss estimates. The RPA then leads to a process for adaptive management of the temperature operations based on updates to the hydrologic information. Thus, despite the particularly challenging example of managing temperature, the use of models appears to have allowed for flexibility.

However, no qualitative or quantitative analysis of the magnitude of errors across these model linkages and the resulting uncertainties are presented. While not required for the justification of RPAs, failing to consider error propagation across the models makes it difficult to evaluate the reliability of meeting the RPAs and their ability to provide the intended benefits.

5. *Lack of an integrative analysis of RPAs*

Numerous RPA actions proposed in both biological opinions cover new projects as well as operational changes. However, the information provided to the committee did not include a comprehensive analysis of all RPA actions, either individually or, more important, jointly, with respect to their ability to reduce the risks to the fish or to estimate system-wide water requirements. Clearly, the agencies lacked properly linked operations/hydrodynamic/biological models at the appropriate scales for RPA development. The agencies should be complimented for using historical data as well as best available science when modeling was not adequate. However, the proposed RPAs could incur significant water supply costs, and there should be an attempt to provide an integrative analysis of the RPAs with quantitative tools. The committee also acknowledges the challenges associated with estimating water requirements for some RPAs, particularly those based on adaptive management strategies, but explicit and transparent consideration of water requirements and biological benefits of specific actions and of subsets of actions would provide the basis for a smoother implementation of the RPAs.

The committee recommends that the agencies consider investigating the use of CalSim-II and other quantitative tools (e.g., PTM, life-cycle models) to simulate appropriate RPA actions of both biological opinions. These linked models would allow an integrated evaluation of the biological benefits and water requirements of individual actions and suites of actions, and the identification of potential species conflicts among the RPAs. Although not required by the ESA,

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such an integrative analysis would be helpful to all concerned to evaluate the degree to which the RPAs are likely to produce biological benefits and to quantify the water requirements to those who might be affected by the future actions of the two biological opinions. In addition to further model development, efforts to improve documentation of model use would be beneficial. Documentation should include a record of the decisions, assumptions, and limitations of the models (e.g., NRC, 2008).

Thus, we find that, while used appropriately in this analysis, the PTM and biological models for both salmon and smelt should be further developed, evaluated, and documented**.** The models show promise for being quantitative tools that would allow for examination of alternative ideas about key relationships underlying the RPAs. In addition, complete life-cycle models capable of being linked to these other models should be developed. Although developing, testing, and evaluating such models would require a significant investment, the committee judges that the investment would be worthwhile in the long term.

CONCLUSION

Modeling is useful for understanding the system as well as predicting future performance. As long as modelers understand and accurately convey the uncertainties of models, they can provide valuable information for making decisions. The committee reviewed the models the agencies used to determine to what degree they used the models in developing the RPAs. The biological opinions have used results of a variety of operations, hydrodynamic, and biological models currently available to them for RPA development. However, the agencies have not developed a comprehensive modeling strategy that includes the development of new models (e.g., life-cycle and movement models that link behavior and hydrology); such models may have provided important additional information for the development of RPAs. Nonetheless, the agencies should be complimented for combining the available modeling results with historical observations and peer-reviewed literature. The committee also compliments the agencies for the extensive discussion and presentation of the rationale for the particular types of actions proposed in the RPAs.

The committee concluded that as far as they went, despite flaws, the individual models were scientifically justified, but that they needed improvements and that they did not go far enough toward an integrated analysis of the RPAs. The committee has raised several important issues related to the modeling process used, including the model scale and management information; the adequacy of models, particularly the particle-tracking model and the lack of life-cycle

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models; incompatibilities in both temporal and spatial scales among the models and between model output and the scale of the RPA actions; the use of baselines; inadequate calibration and testing of modeling tools (in some cases); and inadequate model documentation. A more-thorough, integrative evaluation of RPA actions with respect to their likelihood of reducing adverse effects on the listed fishes and their likely economic consequences, coupled with clear documentation would improve the credibility and perhaps the acceptance of the RPAs. Thus the committee concluded that improving the models by making them more realistic and by better matching the scale of their outputs to the scale of the actions, and by extending the modeling to be more comprehensive and to include features such as fish life cycles would improve the agencies' abilities to assess risks to the fishes, to fine-tune various actions, and to predict the effects of the actions. Three-dimensional models are more expensive and time-consuming than simpler models, but they can contribute valuable understanding if used appropriately (e.g., Gross et al., 1999; Gross et al., 2009).

In addition, the committee concludes that opportunities exist for developing a framework to improve the credibility, accountability, and utility of models used in implementing the RPAs. The framework will be particularly important for some of the more-complex actions, such as those involving Shasta and San Joaquin storage and flows, which rely heavily on model predictions. The committee plans to address such issues, including the framework mentioned above, in more detail in its second report.

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5

Other Stressors

INTRODUCTION

Declines in the listed species must be considered in the context of the many changes that are occurring in the "baseline" factors in the region. While the CVP and SWP pumps kill fish, no scientific study has demonstrated that pumping in the south delta is the most important or the only factor accounting for the delta-smelt population decline. Therefore, the multiple other stressors that are affecting fish in the delta environment as well as in the other environments they occupy during their lives must be considered, as well as their comparative importance with respect to the effects of export pumping. These factors and their impacts, only some of which originate within the delta itself, will be described in greater detail in the committee's second report. Some are described here to highlight their potential importance and to underscore that a holistic approach to managing the ecology of imperiled fishes in the delta will be required if species declines are to be reversed. The factors described here are not meant to be exhaustive, but are intended to demonstrate that the effects of these factors are numerous and, in some cases, not only potentially very important but also under-characterized. Moreover, while individual relationships with these stress factors are generally weakly understood, the cumulative or interactive effects of these factors with each other and with water exports are virtually unknown and unexplored (Sommer et al., 2007).

CONTAMINANTS

It has long been recognized that contaminants are present in the delta, have had impacts on the fishes, and may be increasing (Davis et al., 2003; Edmunds et al., 1999; Linville et al., 2002). Contamination of runoff from agricultural use of pesticides has been documented and has been shown to affect invertebrates and other prey, as well as on some life stages of fish (e.g., Giddings, 2000; Kuivila and Foe, 1995; Weston et al., 2004). Kuivila and Moon (2004) found

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that larval and juvenile delta smelt coincide with elevated levels of pesticides in the spring. Pyrethroid insecticide use has increased in recent years. Such insecticides have been found in higher concentrations in runoff, and may be toxic to macroinvertebrates in the sediment (Weston et al., 2004, 2005); it is toxic to the amphipod *Hyalella azteca*, which is found in the delta (Weston and Lydy, 2010). The use of pyrethroids increased substantially in the recent years during which the decline of pelagic organisms in the delta became a serious concern as compared to earlier decades (Oros and Werner, 2005). Among other identified contaminants that may also have effects are selenium and mercury. Histopathological studies have shown a range of effects, from little to no effect (Foott et al., 2006) to significant evidence of impairment depending on species, timing, and contaminant biomarker.

ALTERED NUTRIENT LOADS

Nutrients have received recent attention as a potential stress factor for phytoplankton, zooplankton, and fish populations for several reasons. First, research by Wilkerson et al. (2006) and Dugdale et al. (2007) found that phytoplankton (diatom) growth in mesocosm experiments did not occur under *in situ* ammonium levels, and only increased when ammonium levels were reduced. They interpreted this finding to mean that diatom growth was suppressed under ambient ammonium levels, and only after ammonium concentrations began to be drawn down did diatoms begin to use nitrate, an alternate nitrogen form, and then proliferate.

With respect to nutrient loading effects, declines in phosphate loading may be related to declines in chlorophyll-*a* throughout the Sacramento-San Joaquin delta (Van Niewenhuyse, 2007). While these results show that chlorophyll-*a* in the water column declined coincident with the decline in phosphate in 1996, phosphate levels, both inorganic and organic, are not at extremely low concentrations in the water. Nevertheless, the effects of the rapid and substantial change in the ratio of inorganic nitrogen to inorganic phosphate in the system have yet to be adequately explored.

CHANGES IN FOOD AVAILABILITY AND QUALITY

Significant changes in the food web may have affected food abundance and food quality available to delta smelt. From changes in zooplankton to declines in chlorophyll to increases in submerged aquatic vegetation, these changes have

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enormous effects on the amount and quality of food potentially available for various fish species (e.g., Bouley and Kimmerer, 2006; Muller-Solger et al., 2006). The benthic community was significantly changed after the overbite clam, *Corbula amurense*, became dominant in the late 1980s; such changes have effects on food availability that may cascade through the food web to affect the abundance of delta smelt.

In addition to changes in food availability, other changes in the food web have had potentially large impacts on smelt. Since 1999, blooms of the cyanobacterium *Microcystis* have increased and are especially common in the central delta when water temperatures exceed 20°C (Lehman et al., 2005). Although delta smelt may not be in the central delta during the period of maximum *Microcystis* abundance, during dry years the spread of *Microcystis* extends well into the western delta so that the zone of influence may be greater than previously thought (Lehman et al., 2008). Most recently it has been demonstrated that the *Microcystis* toxin, microcystin, not only is present in water and in zooplankton, but histopathological studies have shown liver tissue impacts on striped bass and silversides (Lehman et al., 2010).

INTRODUCED FISHES

The delta is a substantially altered ecosystem, and that applies to the fish species present as well. Some environmental changes likely enhance the spread of nonnative species (for example warm, irregularly flowing water around dams or diversions can favor warm-water species) (FWS, 2008, p. 147), as can the presence of riprap to support banks (Michny and Hampton, 1984). Thus, the spread of nonnative species may be, at least in part, an effect of other ecosystem changes. Once nonnative species become established, they further alter the ecosystem. Some species, such as American shad (*Alosa sapidissima*) and striped bass (*Morone saxatilis*), native to the Atlantic and Gulf coasts of North America, have been present in the delta region since the late 19th century (Lampman, 1946; Moyle, 2002). Striped bass (along with the native Sacramento pikeminnow, *Ptychocheilus grandis*) have been implicated as predators on juvenile Chinook salmon, especially when they congregate below the Red Bluff Diversion Dam (Tucker et al., 2003) and other structures; at the Suisun Marsh Salinity Control Gates they were the dominant predator on juvenile Chinook salmon (Edwards et al., 1996; Tillman et al., 1996). Other introductions are more recent, and some might be more threatening to native species. For example, the silverside, *Menidia beryllina*, is becoming more widespread in the delta and

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likely preys on juvenile delta smelt (Moyle, 2002) or competes for similar copepod prey (Bennett and Moyle, 1996). Largemouth bass (*Micropterus salmoides*) and many other members of its family (Centrarchidae), along with various species of catfish (family Siluridae), native to the Mississippi and Atlantic drainages, also are increasing, while the lone member of the centrarchid family that was native to the region, the Sacramento perch (*Archoplites interruptus*), no longer occurs in the delta (Moyle, 2002). All the above species include fish in their diets to a greater or lesser degree, including various life stages of delta smelt at times. In addition, other species, such as common carp (*Cyprinus carpio*) and threadfin shad (*Dorosoma petenense*), are not significant piscivores, but likely compete with delta smelt for food or otherwise affect their environment. Finally, the wakasagi (*Hypomesus nipponensis*), an introduced Japanese smelt very similar to the delta smelt, is becoming increasingly widespread in the delta. It interbreeds and competes with the delta smelt and might prey on it, and its presence in the delta complicates the assessment of delta smelt populations and salvage because it is so similar to the delta smelt that it is not easy to distinguish between the two species (Moyle, 2002). Delta smelt have co-existed with many of these alien fishes for more than 100 years before the recent declines, and so the decline of smelt cannot be attributed entirely to their presence, but some species have increased recently and their effects on smelt and salmonids—including on the potential for smelt populations to recover—have not been well studied.

IMPEDIMENTS TO PASSAGE, CHANGES IN OCEAN CONDITIONS, FISHING, AND HATCHERIES

Clark (1929) estimated that 80 percent of the original spawning habitat available to Chinook salmon in California's Central Valley had been made unavailable by blockages, mainly dams, by 1928. A similar loss of habitat has occurred for Central Valley steelhead as well (Lindley et al., 2006). Dams, diversion points, gates, and screens also affect green sturgeon. Ocean conditions vary, and in general they fluctuate between periods of relatively high productivity for salmon and lower productivity (Hare et al., 1999; Mantua and Hare, 2002). Lindley et al. (2009) concluded that ocean conditions have recently been poor for salmon, although there has been a long-term, steady deterioration in freshwater and estuarine environments as well. Sport and commercial fishing for salmon, sturgeon, and steelhead has been tightly regulated both at sea and in freshwater, and in 2008, there was a complete closure of the commercial and recreational fishery for Chinook salmon (NMFS, 2009, p. 145). However, Chi-

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nook salmon make very long oceanic migrations and their bycatch in other fisheries cannot be totally eliminated (NRC, 2005). Hatchery operations have been controversial, but it is almost impossible to operate hatcheries without adverse genetic and even ecological effects on salmon (NRC, 2004b; NMFS, 2009, p. 143) or steelhead (NMFS, 2009, p. 143).

DISEASES

Histopathological studies have revealed a range of diseases of potential concern in the delta. For example, parasites have been found in threadfin shad gills, but not at a high enough infection rate to be of alarm, but evidence from endrocrine disruption analyses shows some degree of intersex delta smelt males, having immature oocytes in the testes (Anderson et al., 2003). Other investigators have found myxosporean infections in yellowfin goby in Suisun Marsh (Baxa et al., In Progress). These and other measures suggest that parasitic infections, viral infections, or other infections are affecting fish, and that interactions with other stressors, such as contaminants, may be having increasing effects on fish.

CLIMATE CHANGE

Climate change could have severe negative consequences for the listed fishes. There are at least three reasons why this is of concern. First, the recent meteorological trend has runoff from the Sierra Nevada shifting from spring to winter as more precipitation falls as rain rather than snow, and as snowmelt occurs earlier and faster because of warming, increasing the likelihood and frequency of winter floods and altered hydrographs, and thus changes in the salinity of delta water (Knowles and Cayan, 2002, 2004; Roos, 1987, 1991). Alteration of precipitation type and timing of runoff may affect patterns in reproduction of the smelt and migration of salmon and sturgeon (Moyle, 2002). Additionally, effects of sea-level rise will increase salinity intrusion further upstream, again impacting fish distributions that rely on salinity gradients to define habitat; their habitat will be reduced. Lastly, as climate warms, so too does the water. This will impact fish distributions in several ways. Temperature is a cue for many biological processes, so many stages of the life cycle are likely to be affected. Moreover, warmer water will mean proportionately more days in which the temperature is in the lethal range, ~25°C (Swanson et al., 2000). The effects of these climate consequences are less suitable habitat for delta smelt in future

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years as well as threats to the migration of anadromous species like salmon and sturgeon.

CONCLUSION

Based on the evidence summarized above, the committee agreed that the adverse effects of all the other stressors on the listed fishes are potentially large. Time did not permit full exploration of this issue in this intense first phase of the committee's study. The committee will explore this issue more thoroughly in its second report.

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6

Assessment of the RPAs

INTRODUCTION

The RPAs include many specific actions that fall into several categories for each species. The RPA in the FWS biological opinion for delta smelt focuses on limiting OMR negative flows in winter to protect migrating adults (Actions 1 and 2) and to protect larval smelt (Action 3) from entrainment at the export pumps. It also aims to protect estuarine habitat for smelt during the fall by managing the position of X2 (Action 4). Action 5 is to protect larval and juvenile smelt from entrainments by refraining from installing the Head of Old River Barrier (HORB) depending on conditions; if the HORB is installed, then the Temporary Barrier Project's gates would remain open. Finally, Action 6 calls for restoration and construction of 8,000 acres of intertidal and tidal habitat.

The RPA in the NMFS biological opinion for Chinook salmon, Central Valley steelhead, and green sturgeon is divided into far too many specific actions (72) to summarize here, but the biological opinion describes 10 major effects of the RPA on the listed species. They include management of storage and releases to manage temperature in the Sacramento River for steelhead and salmon; maintaining flows and temperatures in Clear Creek for spring-run Chinook salmon; opening gates at the Red Bluff Diversion Dam (RBDD) at critical times to promote passage for salmon and sturgeon; improving rearing habitat for salmon in the lower Sacramento River and in the northern delta; closure of the gates of the Delta Cross Channel (DCC) at critical times to keep juvenile salmon and steelhead out of the interior delta and instead allowing them to migrate out to sea; limiting OMR negative flows to avoid entrainment of juvenile salmon; increased flows in the San Joaquin River and curtailment of water exports to improve survival of San Joaquin steelhead smolts, along with an acoustic tagging program to evaluate the effectiveness of this action; flow and temperature management on the American River for steelhead; a year-round flow regime on the Stanislaus River to benefit steelhead; and the development of Hatchery Genetics Manage-

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ment Plans at the Nimbus (American River) and Trinity River hatcheries to benefit steelhead and fall-run Chinook salmon.

Rather than review every action and every detail, the committee comments on the broader concepts at issue and general categories of actions. Three important goals are to consider how well the RPAs are based on available scientific information; whether there are any potential RPAs not adopted that would have lesser impacts to other water uses as compared to those adopted in the biological opinions, and would provide equal or greater protection for the listed fishes; and whether there are provisions in the FWS and NMFS biological opinions to resolve potential incompatibilities between them. In addition we assess the integration of the RPAs within and across species and across all actions.

Addressing these goals requires explicitly recognizing the fundamental differences in the main conflicting arguments. There is concern, on one hand, that the increasing diversions of water from the delta over a period of many decades and the alteration of the seasonal flow regime have contributed to direct effects on populations of native species through mortality at the pumps, changes in habitat quality, and changes in water quality; and to indirect, long-term effects from alterations of food webs, biological communities, and delta-wide habitat changes. The RPAs propose that their collective effects will offset the impacts of the proposed operations of the SVP and the CWP by manipulating river flows and diversions, along with other actions. An alternative argument is that the effects of water diversions on the listed fishes are marginal. It is argued that the changes imposed by the RPAs would result, therefore, only in marginal benefits to the species, especially now that the delta environment and its biota have been altered (to a new ecological baseline) by multiple stressors. Those stressors obviously include water exports, but this argument suggests a smaller role for water exports in causing the fish declines and hence a smaller role for managing the exports to reduce or halt those declines. However, even with the copious amounts of data available, it is difficult to draw conclusions about what variable or variables are most important among the pervasive, irregular, multivariate changes in the system that have occurred over the past century.

The committee's charge was to provide a scientific evaluation, not a legal one, and that is what is presented below. Nothing in this report should be interpreted as a legal judgment as to whether the agencies have met their legal requirements under the ESA. The committee's report is intended to provide a scientific evaluation of agency actions, to help refine them, and to help the general attempt to better understand the dynamics of the delta ecosystem, including the listed fishes.

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DELTA SMELT

Actions Related to Limiting Flow Reversal on the Old and Middle Rivers (OMR)

The general purpose of this set of actions is to limit the size of the zone of influence around the water-diversion points at critical times. The actions would limit negative OMR flows (i.e., toward the pumps) by controlling water exports during crucial periods in winter (December through March) when delta smelt are expected to be in the central delta (FWS, 2008). The data supporting this approach show an increase in salvage of delta smelt as OMR flows become more negative. However, there are important disagreements about how to express salvage and the choice of the trigger point or threshold in negative flows above which diversions should be limited.

An important issue is whether and how salvage numbers should be normalized to account for delta smelt population size. An increase in salvage could be due to an increase in the number of smelt at risk for entrainment, an increase in negative flows that bring smelt within range of the pumps, or both. Thus, an increase in salvage could reflect a recovery of the smelt population or it could reflect increasingly adverse flows toward the pumps for the remaining smelt population. The biological opinion (FWS, 2008) recognizes this relationship, and that is why salvage is used to calculate the percentage of the population entrained, rather than absolute numbers (FWS, 2008, Figures E-4 and E-5). However, the historical distribution of smelt on which the relationship with OMR flows was established no longer exists. Delta smelt are now sparsely distributed in the central and southern delta (*www.dfg.ca.gov/delta/data*), and pump salvage also has been extremely low, less than four percent of the 50-year average index. Since 2005, a significant portion of the remaining smelt population, 42 percent (Sommer et al., 2009), is in the Cache Slough complex to the north and is therefore largely isolated from the central delta. These changes in the distribution of delta smelt increase the uncertainty surrounding current estimates of the population and its likely response to alterations in delta hydraulics, and until the numbers of smelt rise closer towards the pre-2005 levels, they do not provide a reliable index for incorporation into models for the effects of pumping on smelt salvage.

Different authors have taken different statistical approaches to analyzing the data to interpret the relationship between OMR flows and effects on smelt, and thus chose different thresholds at which OMR flows should be limited. The choice of the limit to negative flows in the RPA gives the benefit of the doubt to the species. But there are important uncertainties in the choice. The different

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trigger points suggested by the different analyses have important implications for water users. The committee concludes that until better monitoring data and comprehensive life-cycle and fish-movement models are available, it is scientifically reasonable to conclude that high negative OMR flows in winter probably adversely affect smelt. We note as well that actions 1 and 2 of the FWS RPA are adaptive in that they depend for their implementation on a trigger related to measured turbidity and measured salvage numbers; they also may be suspended during three-day average flows of 90,000 cfs or greater in the Sacramento River at Rio Vista and 10,000 cfs or greater in the San Joaquin River at Vernalis. However, the portion of the existing smelt population in the Cache Slough complex appears not to move downstream towards the brackish areas (Sommer et al., 2009) and thus they should be largely insulated from the effects of the OMR flows and actions 1 and 2.

The biological benefits and the water requirements of this action are likely to be sensitive to the precise values of trigger and threshold values. There clearly is a relationship between OMR flows and salvage rates, but the available data do not permit a confident identification of the threshold values to use in the action, and they do not permit a confident assessment of the benefits to the population of the action. As a result, the implementation of this action needs to be accompanied by careful monitoring, adaptive management, and additional analyses.

Some monitoring and reporting is required in RPA component 5 (monitoring and reporting). However, more should be required, recognizing limits to the agencies' and operators' human and fiscal resources. Given the uncertainties in any choice of a trigger point, a carefully designed study that directly addresses measures of the performance (effectiveness) of the action is essential. This could include monitoring of variables like salvage at the pumps and numbers of delta smelt adults and larvae at the south ends of OMR channels during pumping actions, but it should also include other variables that might affect both salvage and populations. History shows that salvage and delta smelt indices have been insufficient for such an analysis alone, partly because the populations are small and partly because of the uncertainties in the salvage numbers (e.g., to what degree do they accurately reflect mortality, and to what degree are they affected by sampling error?). This deficiency in the data needs to be remedied. But other "proximate" measures such as monitoring of flows over the tidal cycle between and during the pumping limitations could help to understand the driving mechanism for the predicted entrainment mortality associated with pumping. Measuring mean daily discharges also is not sufficient. Temperature, salinity, turbidity, and possibly other environmental factors should also be monitored at appropriate scales as this action is implemented, to determine the availability of suitable

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A Scientific Assessment of Alternatives for Reducing Water Management Effects on Threatened and Endangered Fishes in California's Bay Delta

habitat in the south delta during periods of reduced pumping. Information also is needed on how fish movement is affected by the immediate water-quality and hydraulic environment they experience. Because the effectiveness of the pumping needs to be expressed in terms of the population, the influence of pumping needs to be identified in more life-stage and area specific measures, In particular, the relevance of the Cache Slough complex needs to be resolved in assessing the effectiveness of pumping restrictions. In addition, because uncertainty is high regarding several aspects of this action, it would be helpful to include an accounting of the water requirements. Ongoing evaluation of performance measures could ultimately reduce the water requirements of actions and increase the benefits to the species. Addressing the effectiveness of the proposed actions on a long-term basis could also support consensus conclusions about the effectiveness of specific actions and increase public trust. To the degree that such studies could be jointly planned and conducted by the agencies and other interested parties, transparency and public trust would be enhanced.

X2 Management for Delta Smelt

Although the mean position of X2, the isohaline (contour line of equal salinity) of total salinity 2, is a measure of the location of a single salinity characteristic, it is used in this system to indicate the position and nature of the salinity gradient between the Sacramento River and San Francisco Bay. The position of X2 is measured in kilometers from the Golden Gate Bridge. In the RPA, it has been used by the agencies as a measure of the amount of smelt habitat—influenced by salinity as well as temperature and turbidity, which are also driven by the river-estuary interaction—and thus to approximate the seasonal extent and shifting of that habitat within the ecosystem. By this reasoning, the position of X2 affects the size of delta smelt habitat (Feyrer et al., 2007; Kimmerer, 2008a).

The RPA's action 4 (FWS, 2008, page 369) proposes to maintain X2 in the fall of wet years at 74 km east of the Golden Gate Bridge and in above-normal years at 81 km east. (The action was restricted to wetter years in response to consultation with the NMFS, which expressed concern that in drier years, this action could adversely affect salmon and steelhead [memorandum from FWS and NMFS to this committee on coordination, January 15, 2010].) The action is to be achieved primarily by releases from reservoirs. The objective of the component is to manage X2 to increase the quality and quantity of habitat for delta smelt growth and rearing.

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The relationship between the position of X2 and habitat area for delta smelt, as defined by smelt presence, turbidity, temperature, and salinity (Nobriga et al, 2008; Feyrer et al., in review), is critical in designing this action. A habitat-area index was derived from the probability of occurrence estimates for delta smelt (fall mid-water trawl survey, FMT) when individuals are recruiting to the adult population. Presence/absence data were used because populations are so small that quantitative estimates of populations probably are unreliable. The authors show a broad relationship between the FMT index and salinity and turbidity, supporting the choice of these variables as habitat indicators. The statistical relationship is complex. When the area of highly suitable habitat as defined by the indicators is low, either high or low FMT indices can occur. In other words, delta smelt can be successful even when habitat is restricted. More important, however, is that the lowest abundances all occurred when the habitat-area index was less than 6,000 ha. This could mean that reduced habitat area is a necessary condition for the worst population collapses, but it is not the only cause of the collapse. Thus, the relationship between the habitat and FMT indexes is not strong or simple. Above a threshold on the x-axis it allows a response on the y-axis (allows very low FMT indices).

The controversy about the action arises from the poor and sometimes confounding relationship between indirect measures of delta smelt populations (indices) and X2. The weak statistical relationship between the location of X2 and the size of smelt populations makes the justification for this action difficult to understand. In addition, although the position of X2 is correlated with the distribution of salinity and turbidity regimes (Feyrer et al., 2007), the relationship of that distribution and smelt abundance indices is unclear. The X2 action is conceptually sound in that to the degree that habitat for smelt limits their abundance, the provision of more or better habitat would be helpful. However, the examination of uncertainty in the derivation of the details of this action lacks rigor. The action is based on a series of linked statistical analyses (e.g., the relationship of presence/absence data to environmental variables, the relationship of environmental variables to habitat, the relationship of habitat to X2, the relationship of X2 to smelt abundance), with each step being uncertain. The relationships are correlative with substantial variance being left unexplained at each step. The action also may have high water requirements and may adversely affect salmon and steelhead under some conditions (memorandum from FWS and NMFS, January 15, 2010). As a result, how specific X2 targets were chosen and their likely beneficial effects need further clarification.

The X2 action for delta smelt includes a requirement for an adaptive management process that includes evaluation of other possible means of achieving the RPA's goal and it requires the establishment and peer review of performance

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measures and performance evaluation. It also requires "additional studies addressing elements of the habitat conceptual model" to be formulated as soon as possible and to be implemented promptly. Finally, it requires the FWS to "conduct a comprehensive review of the outcomes of the Action and the effectiveness of the adaptive management program ten years from the signing of the biological opinion, or sooner if circumstances warrant." This review is to include an independent peer review; the overall aim is to decide whether the action should be continued, modified, or terminated. It is critical that these requirements be implemented in light of the uncertainty about the biological effectiveness of the action and its high water requirements.

Tidal Habitat Action

The proposed RPA calls for the creation or restoration of 8,000 acres of intertidal and associated subtidal habitat in the delta and in Suisun Marsh. A separate planning effort also is under way for Suisun Marsh. The justification provided in the biological opinion is that the original amount of approximately 350,000 acres of tidal wetland has been reduced to less than 10,000 acres today, that the near-complete loss of tidal wetlands threatens delta smelt by reducing productivity at the base of the food web, and that delta smelt appear to benefit from the intertidal and subtidal habitat in Liberty Island, which includes tidal wetlands. This action has been less controversial than the others because it does not directly affect other water users.

However, although the concept of increasing and improving habitat to help offset other risks to smelt is conceptually sound, the scientific justification provided in the biological opinion is weak, because the relationship between tidal habitat and food availability for smelt is poorly understood, and it is inadequate to support the details of the implementation of this action. The opinion notes the importance of high-quality food sources to delta smelt and the association of these food resources with tidal habitats (including wetlands), and it references recent monitoring data from Liberty Island showing that such freshwater tidal habitats can be a source of high-quality phytoplankton that contribute to the pelagic food web downstream (p. 380). However, the specifics of which attributes of tidal habitat are essential to providing these food sources are not addressed.

In addition, the California Department of Fish and Game has raised questions about the details of this action (Wilcox, 2010). They include questions about the relative benefits of vegetated tidal marsh as opposed to open water; the extent to which invasive clams may divert new primary production; the amount of suitable productivity exported from restoration areas; the potential effect of

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the restored habitat on predation; the importance of productivity from vegetated tidal marsh directly or indirectly to the smelt; and the degree to which other fish species might use the habitat, possibly to the detriment of the smelt In briefings to the panel, the importance of ongoing studies in resolving these issues was identified. Identifying the characteristics of the "intertidal and associated subtidal habitat" that the action is expected to produce is needed to ensure that expectations of the outcomes, in terms of both habitat type and species benefits, are clear to all. The relative roles of areas of emergent vegetation, unvegetated intertidal and shallow, highly turbid subtidal habitat must be identified for the action to be effectively implemented.

The committee recommends that this action be implemented in phases, with the first phase to include the development of an implementation and adaptive management plan (similar to the approach used for the floodplain habitat action in the NMFS biological opinion), but also to explicitly consider the sustainability of the resulting habitats, especially those dependent on emergent vegetation, in the face of expected sea-level rise. In addition, there should be consideration of the types and amounts of tidal habitats necessary to produce the expected outcomes and how they can be achieved and sustained in the long term. More justification for the extent of the restoration is needed. The committee supports the monitoring program referred to in Action 6, and appropriate adaptive management triggers and actions.

SALMONIDS AND STURGEON

The NMFS RPA for salmon, steelhead, and green sturgeon is a broad complex of diverse actions spanning three habitat realms: tributary watersheds, the mainstem Sacramento and San Joaquin Rivers, and the delta. On balance, the actions are primarily crafted to improve life-stage-specific survival rates for salmon and steelhead, with the recognition that the benefits also will accrue to sturgeon. The committee agrees with this approach. The conceptual bases of the strategies underpinning many of the individual actions are generally well-founded, although the extent to which the intended responses are likely to be realized is not always clear. Given the absence of a clear, quantitative framework for analyzing the effects of individual and collective actions, it is difficult to make definitive statements regarding the merits of such a complex RPA. Indeed, absent such an analysis, the controversial aspects of some of the RPA actions could detract from the merits of the rest of the RPA.

The assortment of actions among the three habitat realms (watersheds, mainstem rivers, and delta) is designed to improve survival and to enhance con-

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nectivity throughout this system. This approach is consistent with the contemporary scientific consensus on improving ecosystem functioning as a means to improve productivity of anadromous and other migratory species (e.g., NRC 1996, 2004a, 2004b; Williams 2005). Watershed actions would be pointless if mainstem passage conditions connecting the tributaries to, and through, the delta were not made satisfactory.

Watershed and Mainstem River Actions

Watershed-level actions that are implemented in the tributaries are organized and formulated to meet the needs of specific listed populations in that system. The actions target limiting factors specific to those locales and populations. In general, the rationale for conducting the actions appears to be well-founded. However, it is difficult to ascertain to what extent, or even whether, the collective actions will appreciably reduce the risk to the fishes within the watershed or throughout the entire river system. We suggest that inclusion of some type of quantitative analysis using a tool like Ecosystem Diagnosis and Treatment (EDT) model during the planning process may have provided an even stronger justification for the set of actions selected (*http://jonesandstokes.com/*). We understand there is a recent application of EDT in the lower San Joaquin River, by Jones & Stokes, thus providing a precedent for its use in California's Central Valley. EDT is presented here as an example of a quantitative modeling approach that integrates the effects of various actions to produce relative changes in productivity and abundance. The committee emphasizes the need for a quantitative assessment framework, and does not necessarily specifically advocate the use of EDT.

The RPA also prescribes actions to improve mainstem passage conditions, most notably at the Red Bluff Diversion Dam (RBDD). The objective is to provide unobstructed upstream passage at the RBDD, to ensure more efficient access of adult salmonids to restored watersheds, and access for adult sturgeon to spawning grounds. Without such actions connectivity could not be fully realized. Furthermore, the passage improvement at the diversion dam, in combination with increased water delivery from storage reservoirs, is expected to improve smolt survival during downstream migration. This component is well justified scientifically, although the absence of a system-wide salmon survival model limits our ability to evaluate the extent to which this action contributes to improved survival for the populations in question.

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Smolt Survival Near and Through the Delta

The net survival of salmonid smolts though the mainstem rivers and the delta under different water-management operations is of keen interest. Several RPA actions are intended to improve survival of the juveniles as they migrate seaward. Some of these actions have significant water requirements, and so they are controversial. The common goal of these actions is improve smolt survival by retaining a high proportion of the migrating smolt population in the mainstem Sacramento and San Joaquin Rivers. This involves two general approaches: block entrances to the interior delta, or manipulate currents in major channels to reduce the transport of smolt towards the pump facilities and possible entrainment or locations where they may be lost to predation, starvation, or disease. Here we focus on three pivotal actions: the closure of the Delta Cross Channel, the manipulation of OMR flows, and water-management actions in the lower San Joaquin River.

Delta Cross Channel (DCC)

As smolts migrate seaward from the upper Sacramento River they encounter the DCC near Walnut Grove. The DCC can at times draw large volumes of water from the Sacramento River, and some of the smolts follow that current toward the interior delta, where salmon mortality is high.

The objective of this action is to physically block the entrance of the DCC at strategic times during the smolt migration, thereby preventing access to the interior delta. This is a long-standing action that appears to be scientifically justified. However, Burau et al. (2007) estimated that when the DCC gates are open, approximately 45 percent of the Sacramento River flow measured at Freeport is redirected into the delta interior through the DCC and Georgiana Slough. The salmon action (Action Suite IV.1), which under certain triggers requires prolonged closure of the DCC gates from October 1 through June 15, must also consider the effects on delta smelt. The Smelt Working Group (notes from June 4, 2007 meeting) concluded that there could be a small beneficial effect on delta smelt from having the DCC gates open from late May until mid-June.

Although this action does not appear to constitute an important conflict between the needs of smelt and salmon, it illustrates the potential for conflict among the two opinions and the need for closer integration of the actions within the delta that have consequences for more than one of the listed species. This is an example where a systematic analysis of the implications for both species of actions would seem to be a scientific requirement.

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Managing OMR Flows for Salmonids

This RPA action (IV.2.3, Old and Middle River Flow Management) also seeks to limit smolt excursion into part of the delta associated with high smolt mortality, but it does so by manipulating current direction and intensity within the Old and Middle River (OMR) drainages. The objective is to reduce current velocity toward the SWP and CVP facilities, thereby exposing fewer smolts to pump entrainment and being drawn into other unfavorable environments.

To accomplish the objective, the action calls for, reducing exports from January 1 through June 15, as necessary, to limit negative OMR flows to -2,500 to -5,000 cfs, depending on the presence of salmonids. The reverse flow will be managed within this range to reduce flows toward the pumps during periods of increased salmonid presence. The flow range was established through correlations of OMR flow and salmon entrainment indices at the pumps, and from entrainment proportions derived using the particle-tracking model (PTM). While the flow management strategy is conceptually sound, the threshold levels needed to protect fish is not definitively established. The response of loss at the pumps to OMR flow (e.g. figure 6-65 from NMFS, 2009) does not suggest a significant change in the vicinity of the flow triggers, but it does suggest that the loss rate increases exponentially above the triggers. The PTM suggests a gradual linear response in the vicinity of the trigger. However, no analysis was presented for the entrainment rate above the trigger (Figure 6-68 from NMFS, 2009), and it is not clear whether the salvage *rates* as well as salvage numbers were modeled. Therefore, the committee is unable to evaluate the validity of the exponential increase in loss rate above the trigger. Uncertainty in the effect of the flow triggers needs to be reduced, and more flexible triggers that might require less water should be evaluated.

The committee concludes that the strategy of limiting net tidal flows toward the pump facilities is sound, but the support for the specific flows targets is less certain. In the near-term telemetry-based smolt migration and survival studies (e.g, Perry and Skalski, 2008) should be used to improve our understanding of smolt responses to OMR flow levels. Reliance on salvage indices or the PTM results alone is not sufficient.

Additionally, there is little direct evidence to support the position that this action alone will benefit the San Joaquin salmon, unless it is combined with an increase in San Joaquin River flows. Furthermore, we understand this and other flow management actions are coordinated with the delta smelt actions. But we found no quantitative analysis that integrates across the actions to systematically evaluate their aggregate effects on both salmonids and smelt. Understanding

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those interactions will benefit from the development and use of multiple single-species models, including movement models.

Managing Exports and Flows in the San Joaquin River

The objective of this action (IV.2.1) is to reduce the vulnerability of emigrating Central Valley steelhead within the lower San Joaquin River to entrainment into the channels of the south delta and at the pumps by increasing the inflow-to-export ratio. It seeks to enhance the likelihood of salmonids' successfully exiting the delta at Chipps Island by creating more suitable hydraulic conditions in the mainstem of the San Joaquin River for emigrating fish, including greater net downstream flows.

The action has two components: reducing exports, and augmenting San Joaquin River flows at Vernalis. The rationale that increasing San Joaquin inflows to the delta will benefit smolt survival through this region of the delta is based on data from coded-wire tags on smolts. This statistical evidence provides only a coarse assessment of the action, but it indicates that increasing San Joaquin River flows can explain observed increases in escapement. Historical data indicate that high San Joaquin River flows in the spring result in higher survival of outmigrating Chinook salmon smolts and greater adult returns 2.5 years later (Kjelson et al., 1981; Kjelson and Brandes, 1989), and that when the ratio between spring flows and exports increase, Chinook salmon production increases (CDFG, 2005; SJRGA, 2007). In its biological opinion, NMFS therefore concludes that San Joaquin River Basin and Calaveras River steelhead would likewise benefit under higher spring flows in the San Joaquin River in much the same way as fall-run Chinook do. NMFS recognizes this assumption is critical, and thus the biological opinion calls for implementation of a six-year smolt-survival study (acoustic tags) (Action IV.2.2), using hatchery steelhead and fall Chinook.

The controversy lies in the effectiveness of the component of this action that reduces water exports from the delta. The effectiveness of reducing exports to improve steelhead smolt survival is less certain, in part because within the VAMP (Vernalis Adaptive Management Plan) increased flows and reduced exports are combined, and in part because steelhead smolts are larger and stronger swimmers than Chinook salmon smolts. Furthermore, it is not clear in the biological opinion how managing exports for this purpose would be integrated with export management for other actions. The choice of a 4:1 ratio of net flows to exports appears to be the result of coordinated discussions among the interested parties. Given the weak influence of exports in all survival relationships (New-

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man, 2008), continued negotiation offers opportunities to reduce water use in this specific action without great risk to steelhead. Further analysis of VAMP data also offers an opportunity to help clarify the issue.

The committee concludes that the rationale for increasing San Joaquin River flows has a stronger foundation than the prescribed action of concurrently managing inflows and exports. We further conclude that the implementation of the six-year steelhead smolt survival study (action IV.2.2) could provide useful insight as to the actual effectiveness of the proposed flow management actions as a long-term solution.

Increase Passage through Yolo Bypass

This action would reduce migratory delays and loss of adult and juvenile salmon and green sturgeon at structures in the Yolo Bypass. For sturgeon there is substantial evidence that improved upstream passage at Yolo will be beneficial. For salmon, the purpose is to route salmon away from the interior delta and through a habitat that is favorable for growth. This action is scientifically justified and prudent, but its implications for the routing of flows through the system as a whole were not transparently evaluated. For example, moving water through the Yolo Bypass results in less water coming through the Sacramento River. Were the effects of less flow in the Sacramento River considered in the design of the action? Similarly, how were the possible negative consequences of increased flooding of the Yolo Bypass on mercury cycling considered? This exemplifies a general tendency throughout the discussion of the actions to focus on the biologically beneficial aspects but to not fully present how any conflicting consequences or potential for such consequences were considered.

Floodplain Habitat

The floodplain habitat actions (Actions I.6.1-4) involve increasing the inundation of private and public lands within the Sacramento River basin to increase the amount and quality of rearing habitat for juvenile salmon. This action suite appears scientifically justified on the basis of a number of studies (e.g., Moyle et al., 2007; Sommer et al., 2001; Whitener and Kennedy, 1999). Given the strong basis, the committee recommends early implementation of these actions providing the implications for releases and routing of flows on other actions, and any potential negative consequences, e.g., mobilization of mercury, are adequately considered. In addition, the committee suggests detailed studies of the outcome

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of these actions to provide important data for improved life cycle models for these species.

INTEGRATION OF RPAs

The RPAs lack a quantitative analytical framework that ties them together within species, between smelt and salmonid species, and across the watershed. This type of systematic, formalized analysis is necessary to provide an objective determination of the net effect of the actions on the listed species and on water users.

An additional overall, systematic, coordinated analysis of the effect of all actions taken together and a process for implementing the optimized, combined set of actions would help to establish the credibility of the effort overall. Instances of coordination certainly exist. For example, the analysis done by NMFS for the Action IV.2.1 (Appendix 5), is an example of coordination, where the water needs for the 4-to-1 flow-to-export ratio for steelhead were determined and used to refine the action. But coordination is not integration. The lack of a systematic, well framed overall analysis is a serious deficiency. The interagency effort to transparently reach consensus on implications of the combined RPAs for their effects on all the species and on water quality and quantity within the delta and on water operations and deliveries should use scientific principles and methods in a collaborative and integrative manner. Full documentation of decisions is an essential part of such an effort, as is inclusion of the environmental water needs of specific actions and for the entire RPA.

It is clear that integrative tools that, for example, combine the effect over life stages into a population-level response would greatly help the development and evaluation of the combined actions. This was acknowledged by the FWS and NMFS, as well by many of the other presenters during the two days of public session of the committee meeting. There has been significant investment in operations and hydrodynamic models for the system, which have been invaluable for understanding and managing the system. An investment in ecological models that complement the operations and hydrodynamics models is sorely needed. This issue has been raised repeatedly in peer reviews, but still has not been incorporated in the NMFS and FWS analyses. Without a quantitative integration tool, the expected effects of individual actions on the listed species will remain a matter of judgment based on the interpretation of many disparate studies. The NMFS and FWS had to therefore determine the cumulative effects of the multiple actions in each RPA in a qualitative manner. This leads to arguments and disputes that are extremely difficult to resolve and that can undermine

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the credibility of the biological opinions. Commitment to a long-term effort to develop a quantitative tool (or tools) should be part of the RPA, with the explicit goal of formalizing and focusing the sources of disagreement and allowing for the clear testing of alternative arguments.

Transparent consideration of the implications of water requirements also would seem well advised because some of the actions have significant water requirements. DWR and NMFS used CalSim-II and Calite to simulate a collection of actions to determine water needs associated with the NMFS RPA, and concluded that they would amount to 5-7 percent of total water allocations (NMFS, 2009). (Because the actions involving negative OMR flows were similar in timing and magnitude in both the NMFS and the FWS RPAs, all OMR flow management was included in this estimate.) Those, and complementary efforts, should be extended to as many of the actions in combination as feasible, recognizing that the adaptive nature of many aspects of the RPAs, along with variations in environmental conditions and in water demands, limit the degree of certainty associated with such estimates. Credible documentation of the water needed to implement each action and the combined actions, would enable an even clearer and more logical formulation of how the suite of actions might be coordinated to simultaneously benefit the species and ensure water efficiency.

OTHER POSSIBLE RPAs

The committee's charge included the task that the committee should identify, if possible, additional potential RPAs that would provide the potential to provide equal or greater protection to the fishes than the current RPAs while costing less in terms of water availability for other uses. The committee considered RPAs that had been considered and rejected by the agencies or that were recommended to the committee for its consideration (Hamilton, 2010). They included using bubble-curtain technology instead of hard barriers to direct migration of salmon and steelhead smolts, use of weirs to protect wild steelhead from interbreeding and competition, use of weirs to reduce spring-run Chinook from inbreeding and competition with fall-run Chinook, habitat restoration and food-web enhancement, restoration of a more-natural hydrograph, reducing mortality caused by nonnative predators, reducing contaminants, reducing other sources of 'take," implementation of actions to reduce adverse effects of hatcheries, and ferrying San Joaquin River steelhead smolts through the delta.

Some of these are already included to some degree in the RPAs (e.g., reduction of adverse hatchery effects, habitat restoration), and some might not be within the agencies' authorities as RPA actions under the ESA (e.g., contami-

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nant reduction and reduction of other sources of "take"). The committee did not attempt to evaluate whether these suggestions represent good actions to help reduce risks to the listed species in a general attempt at restoration, as that will be addressed in the committee's second report. The committee concludes that none of the above suggested alternative RPAs has received sufficient documentation or evaluation to be confident at present that any of them would have the potential to provide equal or greater protection for the listed species while requiring less disruption of delta water diversions.

Several long-term actions described above have the potential to increase protections for the species while requiring the use of less water for that purpose, because they will result in a better understanding of the system. That better understanding should allow for a better matching of water for species needs, thus potentially reducing the amount of water used in less-effective actions. However, no short-term measure was identified that would provide equal protection to the fishes while reducing restrictions on water diversions.

RESOLVING INCOMPATIBILITIES BETWEEN THE RPAs

The committee noted in its discussion of the Delta Cross Channel action for salmon that it has a small potential for conflict with the requirements for smelt, although the action itself includes a consideration of the effects on smelt. In addition, the agencies have coordinated, and in some cases changed, their actions to avoid or reduce such conflicts, including actions concerning the installation of a "non-physical" barrier at the Head of Old River and the possibility of constructing a barrier across Georgiana Slough (NMFS and FWS, 2010). However, as the committee has noted elsewhere, coordination is not integration, and while it commends the agencies for working together to avoid incompatibilities between the RPAs, it concludes that this coordination is not sufficient to achieve the best results or full evaluation of incompatibilities. To achieve those goals requires an integrated analysis, because without such an analysis it is difficult or impossible to properly evaluate potential conflicts among RPA actions. More important, such an analysis would help to produce more-effective actions. The lack of an integrated analysis also prevented the committee from a fuller evaluation of potential incompatibilities between the RPAs.

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EXPECTATIONS AND PROXIMATE MEASURES

The committee heard several times at the public sessions that the RPA actions for delta smelt are not working as there has been no response in the standard annual abundance indices during the last three years when action-related restrictions have been imposed. Such comments are appropriate, but only if realistic expectations are used to judge effectiveness. In this case, it is unrealistic to expect immediate and proportional responses to actions in annual indices of delta smelt, especially within the first few years of implementation. There are several reasons for this. First, fish abundances are influenced by many factors not affected by the actions. This is true in all estuarine and marine systems, and is simply inherent in fish population dynamics. For example, in the case of the species here, three drought years coincided with the implementation of the actions. Other factors have also varied that would further mask any response in the annual indices.

Second, delta smelt populations are very small. The ability of the annual indices to show changes in response to actions is compromised due to the inherent lack of precision in sampling and constructing indices of abundance when populations are very small. Unlike salmon and steelhead, the adults of which can be counted with great precision as they migrate upstream, delta smelt are more difficult to count as well as being rare. While this is frustrating, little change in the annual indices over a few years neither invalidates the utility of the actions nor do they demonstrate that the actions are effective. Finally, there were no prior quantified estimates of response to calibrate expectations. Expectations would be better established if the RPA proposals more explicitly quantified the nature and the expected timescale of responses in the target species, and detailed exactly what would be done to assess the validity of those predictions.

RPA RECOMMENDATIONS

The committee concluded that the uncertainties and disagreements surrounding some of the RPA actions could be reduced by some additional activities. In general, the committee recommends that, within the limits the agencies face with respect to human and financial resources, a more-integrated approach to analyzing adverse effects of water operations and potential actions to reduce those effects would be helpful. The approach would include a broader examination of the life cycles of each fish species and where possible, integrating analyses across species. Although there is much general evidence that the profound reduction and altered timing of the delta water supply has been part of the reason

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for the degradation of these species' habitats, the marginal benefits of beginning to reverse the damage will be difficult to recognize for some time and there is much uncertainty about how to design attempts at the reversal. At this time, the best that can be done is to design a strategy of pumping limitations that uses the best available monitoring data and the best methods of statistical analysis to design an exploratory approach that could include enhanced field measurements to manage the pumping limitations adaptively while minimizing impacts on water users. Such an approach would include a more explicit and transparent consideration of water requirements, despite the variability in environmental conditions and water demand; and population models to evaluate the combined effects of the individual actions.

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Appendixes

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Appendix A

Committee on Sustainable Water and Environmental Management in the California Bay-Delta

STATEMENT OF TASK

At the request of Congress and the Departments of the Interior and Commerce, a committee of independent experts will be formed to review the scientific basis of actions that have been and could be taken to simultaneously achieve both an environmentally sustainable Bay-Delta and a reliable water supply. In order to balance the need to inform near-term decisions with the need for an integrated view of water and environmental management challenges over the longer-term, the committee will undertake two main projects over a term of two years resulting in two reports.

First, by approximately March 15, 2010, the committee will issue a report focusing on scientific questions, assumptions, and conclusions underlying water-management alternatives in the U.S. Fish and Wildlife Service's (FWS) Biological Opinion on Coordinated Operations of the Central Valley Project and State Water Project (Dec. 15, 2008) and the National Marine Fisheries Service's (NMFS) Biological Opinion on the Long-Term Central Valley Project and State Water Project Operations Criteria and Plan (June 4, 2009). This review will consider the following questions:

- Are there any "reasonable and prudent alternatives" (RPAs), including but not limited to alternatives considered but not adopted by FWS (e.g., potential entrainment index and the delta smelt behavioral model) and NMFS (e.g., bubble-curtain technology and engineering solutions to reduce diversion of emigrating juvenile salmonids to the interior and southern Delta instead of towards the sea), that, based on the best available scientific data and analysis, (1) would have lesser impacts to other

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A Scientific Assessment of Alternatives for Reducing Water Management Effects on Threatened and Endangered Fishes in California's Bay Delta

water uses as compared to those adopted in the biological opinions, and (2) would provide equal or greater protection for the relevant fish species and their designated critical habitat given the uncertainties involved?

- Are there provisions in the FWS and NMFS biological opinions to resolve potential incompatibilities between the opinions with regard to actions that would benefit one listed species while causing negative impacts on another, including, but not limited to, prescriptions that: (1) provide spring flows in the Delta in dry years primarily to meet water quality and outflow objectives pursuant to Water Board Decision-1641 and conserve upstream storage for summertime cold water pool management for anadromous fish species; and (2) provide fall flows during wet years in the Delta to benefit Delta smelt, while also conserving carryover storage to benefit next year's winter-run cohort of salmon in the event that the next year is dry?
- To the extent that time permits, the committee would consider the effects of other stressors (e.g., pesticides, ammonia discharges, invasive species) on federally listed and other at-risk species in the Bay-Delta. Details of this task are the first item discussed as part of the committee's second report, below, and to the degree that they cannot be addressed in the first report they will be addressed in the second.

Second, in approximately November 2011, the committee will issue a second report on how to most effectively incorporate science and adaptive management concepts into holistic programs for management and restoration of the Bay-Delta. This advice, to the extent possible, should be coordinated in a way that best informs the Bay-Delta Conservation Plan development process. The review will include tasks such as the following:

- Identify the factors that may be contributing to the decline of federally listed species, and as appropriate, other significant at-risk species in the Delta. To the extent practicable, rank the factors contributing to the decline of salmon, steelhead, delta smelt, and green sturgeon in order of their likely impact on the survival and recovery of the species, for the purpose of informing future conservation actions. This task would specifically seek to identify the effects of stressors other than those considered in the biological opinions and their RPAs (e.g., pesticides, ammonia discharges, invasive species) on federally listed and other at-risk species in the Delta, and their effects on baseline conditions. The com-

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mittee would consider the extent to which addressing stressors other than water exports might result in lesser restrictions on water supply. The committee's review should include existing scientific information, such as that in the NMFS Southwest Fisheries Science Center's paper on decline of Central Valley fall-run Chinook salmon, and products developed through the Pelagic Organism Decline studies (including the National Center for Ecosystem Analysis and Synthesis reviews and analyses that are presently under way).

- Identify future water-supply and delivery options that reflect proper consideration of climate change and compatibility with objectives of maintaining a sustainable Bay-Delta ecosystem. To the extent that water flows through the Delta system contribute to ecosystem structure and functioning, explore flow options that would contribute to sustaining and restoring desired, attainable ecosystem attributes, while providing for urban, industrial, and agricultural uses of tributary, mainstem, and Delta waters, including for drinking water.
- Identify gaps in available scientific information and uncertainties that constrain an ability to identify the factors described above. This part of the activity should take into account the Draft Central Valley Salmon and Steelhead recovery plans (NOAA 2009b), particularly the scientific basis for identification of threats to the species, proposed recovery standards, and the actions identified to achieve recovery.
- Advise, based on scientific information and experience elsewhere, what degree of restoration of the Delta system is likely to be attainable, given adequate resources. Identify metrics that can be used by resource managers to measure progress toward restoration goals.

The specific details of the tasks to be addressed in this second report will likely be refined after consultation among the departments of the Interior and Commerce, Congress, and the National Research Council, considering stakeholder input, and with the goal of building on, rather than duplicating, efforts already being adequately undertaken by others.

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Appendix B
Water Science and Technology Board

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CHARLES N. HAAS, Drexel University, Philadelphia, Pennsylvania
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JAMES M. HUGHES, Emory University, Atlanta, Georgia
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MICHAEL J. MCGUIRE, Michael J. McGuire, Inc., Santa Monica, California
G. TRACY MEHAN III, The Cadmus Group, Inc., Arlington, Virginia
DAVID H. MOREAU, University of North Carolina, Chapel Hill
DENNIS D. MURPHY, University of Nevada, Reno
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ANITA A. HALL, Senior Program Associate
MICHAEL J. STOEVER, Research Associate
STEPHEN T. RUSSELL, Senior Program Assistant

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Appendix C
Ocean Studies Board

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DEBRA HERNANDEZ, Southeast Coastal Ocean Observing Regional Association, Mt. Pleasant, South Carolina
ROBERT A. HOLMAN, Oregon State University, Corvallis
KIHO KIM, American University, Washington, D.C.
BARBARA A. KNUTH, Cornell University, Ithaca, New York
ROBERT A. LAWSON, Science Applications International Corporation, San Diego, California
GEORGE I. MATSUMOTO, Monterey Bay Aquarium Research Institute, Moss Landing, California
JAY S. PEARLMAN, The Boeing Company (ret.), Port Angeles, Washington
ANDREW A. ROSENBERG, Science & Knowledge Conservation International, Arlington, Virginia
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ROBERT J. SERAFIN, National Center for Atmospheric Research, Boulder, Colorado
ANNE M. TRÉHU, Oregon State University, Corvallis
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DAWN J. WRIGHT, Oregon State University, Corvallis
JAMES A. YODER, Woods Hole Oceanographic Institution, Massachusetts

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HEATHER CHIARELLO, Senior Program Assistant
JEREMY JUSTICE, Senior Program Assistant

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Appendix D
Speakers at Committee's Meeting
January 24-29, 2010
University of California, Davis

Ara Azhderian, San Luis and Delta Mendota Water Authority
Barbara Barrigan-Parilla, Restore the Delta
Brett Baker, Delta Resident
Letty Belin, U.S. Department of the Interior
Cheryl Bly-Chester, UC Berkeley
Dan Castleberry, U.S. Fish and Wildlife Service
Jim Costa, U.S. House of Representatives, California-District 20
DeeDee D'Adamo, Office of U.S. Representative Dennis Cardoza, California-District 18
Cliff Dahm, CALFED (Delta Science Program)
Stan Dean, Sacramento Regional County Sanitation District, Director of Policy
Rick Deriso, Inter-American Tropical Tuna Commission
Diana Engle, Larry Walker Associates
Fred Feyrer, Bureau of Reclamation
David Fullerton, Metropolitan Water District of Southern California
Greg Gartrell, Contra Costa Water District
Zeke Grader, Pacific Coast Federation of Fishermen's Association
Cay Goude, U.S. Fish and Wildlife Service
Scott Hamilton, Coalition for a Sustainable Delta
Ann Hayden, Environmental Defense Fund
Bruce Herbold, U.S. Environmental Protection Agency
John Herrick, South Delta Water Agency
Jerry Johns, California Department of Water Resources
Harold Johnson, Pacific Legal Institute
Linda Katehi, University of California, Davis
Jason Larroba, Tehama-Colusa Canal Authority
Tom Lindemuth, Delta Science Center, Big Break
Steve Lindley, National Marine Fisheries Service
Craig Manson, Council for Endangered Species Act Reliability

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BJ Miller, Consultant
Ron Milligan, Bureau of Reclamation
Jeffrey Mount, University of California, Davis
Peter B. Moyle, University of California, Davis
Steve Murawski, National Oceanic and Atmospheric Administration
Eligio Nava, Central Valley Hispanic Chamber
Dante John Nemellini, Central Delta Water Agency
Matt Nobriga, California Department of Fish and Game
Doug Obegi, Natural Resources Defense Council
Tim O'Laughlin, O'Laughlin & Paris
Bruce Oppenheim, National Marine Fisheries Service
Richard Pool, Salmon fishing industry
Maria Rea , National Marine Fisheries Service
Rhonda Reed, National Marine Fisheries Service
Mark Renz, Association of California Water Agencies
Spreck Rosekrans, Environmental Defense Fund
Melanie Rowland, NOAA-General Counsel
Patricia Schuffon, Pacific Advocate Program
Jeff Stuart, National Marine Fisheries Service
Nicky Suard, Delta Land and Business owners
Christina Swanson, The Bay Institute
Robert Thornton, Nossaman
Mike Urkov, Tehama-Colusa Canal Authority
Jay Wells, North American Power Sweeping Association
Carl Wilcox, California Department of Fish and Game
Susan William, Pt. Lobos Marine Preserve
Mary Winfree, PoE/USANG
Phil Wyman, Former Central Valley Senator/Assemblyman
Paula Yang, Hmong Sisterhood
Garwin Yip, National Marine Fisheries Service

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Appendix E
Biographical Sketches for Members of the Committee on Sustainable Water and Environmental Management in the California Bay-Delta

ROBERT J. HUGGETT, ***Chair***, is an independent consultant and professor emeritus and former chair of the Department of Environmental Sciences, Virginia Institute of Marine Sciences at the College of William and Mary, where he was on the faculty for over 20 years. He also served as Professor of Zoology and Vice President for Research and Graduate Studies at Michigan State University from 1997 to 2004. Dr. Huggett is an expert in aquatic biogeochemistry and ecosystem management whose research involved the fate and effects of hazardous substances in aquatic systems. From 1994 to 1997, he was the Assistant Administrator for Research and Development for the U.S. Environmental Protection Agency, where his responsibilities included planning and directing the agency's research program. During his time at the EPA, he served as Vice Chair of the Committee on Environment and Natural Resources and Chair of the Subcommittee on toxic substances and solid wastes, both of the White House Office of Science and Technology Policy. Dr. Huggett founded the EPA Star Competitive Research Grants program and the EPA Star Graduate Fellowship program. He has served on the National Research Council's (NRC) Board on Environmental Studies and Toxicology, the Water Science and Technology Board, and numerous study committees on wide ranging topics. Dr. Huggett earned an M.S. in Marine Chemistry from the Scripps Institution of Oceanography at the University of California at San Diego and completed his Ph.D. in Marine Science at the College of William and Mary.

JAMES J. ANDERSON is a research professor the School of Aquatic and Fisheries Sciences at the University of Washington, where he has been teaching since 1983, and Co-Director of Columbia Basin Research. Prior to joining the faculty at the University of Washington, he did research work at the University of Kyoto in Japan, the National Institute of Oceanography in Indonesia, and

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Institute of Oceanographic Sciences in Wormley, UK. Dr. Anderson's research focuses on models of ecological and biological processes from a mechanistic perspective, specifically: (1) migration of organisms, (2) decision processes, and (3) mortality processes. For three decades he has studied the effects of hydrosystems and water resource allocations on salmon and other fish species. He has developed computer models of the migration of juvenile and adult salmon through hydrosystems and heads the DART website, an internet database serving real-time environmental and fisheries data on the Columbia River. His other research interests include mathematical studies in ecosystems, biodemography, toxicology and animal behavior. He has served on a number of regional and national panels and has testified numerous times before Congress on the impacts of hydrosystems on fisheries resources. He received his B.S. and Ph.D. in oceanography from the University of Washington.

MICHAEL E. CAMPANA is Professor of Geosciences at Oregon State University, former Director of its Institute for Water and Watersheds, and Emeritus Professor of Earth and Planetary Sciences at the University of New Mexico. Prior to joining OSU in 2006 he held the Albert J. and Mary Jane Black Chair of Hydrogeology and directed the Water Resources Program at the University of New Mexico and was a research hydrologist at the Desert Research Institute and taught in the University of Nevada-Reno's Hydrologic Sciences Program. He has supervised 70 graduate students. His research and interests include hydrophilanthropy, water resources management and policy, communications, transboundary water resources, hydrogeology, and environmental fluid mechanics, and he has published on a variety of topics. Dr. Campana was a Fulbright Scholar to Belize and a Visiting Scientist at Research Institute for Groundwater (Egypt) and the IAEA in Vienna. Central America and the South Caucasus are the current foci of his international work. He has served on six NRC-NAS committees. Dr. Campana is founder, president, and treasurer of the Ann Campana Judge Foundation (www.acjfoundation.org), a 501(c)(3) charitable foundation that funds and undertakes projects related to water, sanitation, and hygiene (WASH) in Central America. He operates the WaterWired blog and Twitter. He earned a BS in geology from the College of William and Mary and MS and PhD degrees in hydrology from the University of Arizona.

THOMAS DUNNE is a professor in the Donald Bren School of Environmental Science and Management at the University of California at Santa Barbara. He is a hydrologist and a geomorphologist, with research interests that include alluvial processes; field and theoretical studies of drainage basin and hill-slope evolution; sediment transport and floodplain sedimentation; debris flows and sedi-

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ment budgets of drainage basins. He served as a member of the WSTB Committee on Water Resources Research and Committee on Opportunities in the Hydrologic Sciences and was elected to the National Academy of Sciences in 1988. He has acted as a scientific advisor to the United Nations, the governments of Brazil, Taiwan, Kenya, Spain, the Philippines, Washington, Oregon, several U.S. federal agencies, and The Environmental Defense Fund. He is a recipient of the American Geophysical Union Horton Award. Dr. Dunne holds a B.A. from Cambridge University and a Ph.D. in geography from the Johns Hopkins University.

ALBERT E. GIORGI is president and senior fisheries scientist at BioAnalysts, Inc in Redmond, WA. He has been conducting research on Pacific Northwest salmonid resources since 1982. Prior to 1982, he was a research scientist with NOAA in Seattle, WA. He specializes in fish passage migratory behavior, juvenile salmon survival studies, biological effects of hydroelectric facilities and operation. His research includes the use of radio telemetry, acoustic tags, and PIT-tag technologies. In addition to his research, he acts as a technical analyst and advisor to public agencies and private parties. He regularly teams with structural and hydraulic engineers in the design and evaluation of fishways and fish bypass systems. He served on the NRC Committee on Water Resources Management, Instream Flows, and Salmon Survival in the Columbia River. He received his B.A. and M.A. in biology from Humboldt State University and his Ph.D. in fisheries from the University of Washington.

PATRICIA M. GLIBERT is a professor at the University of Maryland Center for Environmental Science, Horn Point Laboratory, where she has been on the faculty since 1986. Prior to UMD-HPL, she was a postdoctoral scholar and an assistant scientist at the Woods Hole Oceanographic Institution. Her research areas are in transformations and fate of inorganic and organic nitrogen in marine and estuarine systems; ecology of phytoplankton in coastal and oceanic environments; stable isotope techniques; eutrophication and its effects; growth and physiology of marine cyanobacteria and harmful algal bloom species; "top-down" control of nitrogen cycling; primary productivity and its regulation by environmental factors; and impacts of harmful algae on oysters. Her current projects are in the Chesapeake and coastal bays of Maryland, Florida Bay, and the Arabian Sea. She received her B.S. in biology from Skidmore College; M.S. in earth science from the University of New Hampshire; and her Ph.D. in organismal and evolutionary biology from Harvard University.

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CHRISTINE A. KLEIN is the Chesterfield Smith Professor of Law at the University of Florida Levin College of Law, where she has been teaching since 2003. She offers courses on natural resources law, environmental law, water law, and property. Previously, she was a member of the faculty of Michigan State University College of Law, where she served as Environmental Law Program Director. From 1989 to 1993, she was an assistant attorney general in the Office of Colorado Attorney General, Natural Resources Section, where she specialized in water rights litigation. She has published widely on a variety of water law and natural resources law topics. She holds a B.A. from Middlebury College, Vermont; a J.D. from the University of Colorado School of Law; and an LL.M. from Columbia University School of Law, New York.

SAMUEL N. LUOMA is a a research professor at the John Muir Institute of the Environment, University of California, Davis and an emeritus Senior Research Hydrologist in the Water Resources Division of the U.S. Geological Survey, where he worked for 34 years. He also holds an appointment as a Scientific Associate at The Natural History Museum, London. Dr. Luoma's research centers on processes the control the fate, bioavailability and effects of contaminants, particularly in the San Francisco Bay-Delta. He served as the first lead on the CALFED Bay-delta program and is the Editor-in-Chief of San Francisco Estuary & Watershed Science. He has helped refine approaches to determine the toxicity of marine and estuarine sediments and developed models that are used in development of water quality standards. His most recent research interests are in environmental implications of nanotechnology and better connecting water science to water policy. He has served multiple times on the EPA's Science Advisory Board Subcommittee on Sediment Quality Criteria and on other NRC committees. Dr. Luoma received his B.S. and M.S. in Zoology from Montana State University, Bozeman, and his Ph.D. in Marine Biology from the University of Hawaii, Honolulu.

MICHAEL J. MCGUIRE is president and founder of Michael J. McGuire, Inc., in Santa Monica, California. He has provided consulting services over the past 18 years to public water utilities and industries in the areas of Safe Drinking Water Act compliance, source water quality protection and water treatment optimization. Prior to his consulting assignments, he was director of water quality and assistant general manager of the Metropolitan Water District of Southern California. His research interests include control of trace contaminants in drinking water; compliance with the Safe Drinking Water Act and all related regulations; occurrence, chemistry, and control of disinfection by-products; and identification and control of tastes and odors in water supplies. He is currently a

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member of the Water Science and Technology Board of the National Research Council and was selected as a member of the National Academy of Engineering in 2009. Dr. McGuire received his B.S. in civil engineering from the University of Pennsylvania and M.S. and Ph.D. in environmental engineering from Drexel University in Philadelphia.

THOMAS MILLER is professor of fisheries at the Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, where he has been teaching since 1994. Prior to UMCES-CBL, he was a postdoctoral fellow at McGill University, Montreal, Canada, and research specialist with the Center for Great Lakes Studies, University of Wisconsin, Milwaukee. His research focuses on population dynamics of aquatic animals, particularly in understanding recruitment, feeding and bio-physical interactions and early life history of fish and crustaceans. He has been involved in the development of a Chesapeake Bay fishery ecosystem plan, which includes detailed background information on fisheries, foodwebs, habitats and monitoring required to develop multispecies stock assessments. Most recently, he has developed an interest in the sublethal effects of contamination on Chesapeake Bay living resources using population dynamic approaches. He received his B.Sc. (hons) in human and environmental biology from the University of York, UK; his M.S. in ecology and Ph.D. in zoology and oceanography from North Carolina State University.

JAYANTHA OBEYSEKERA directs the Hydrologic & Environmental Systems Modeling Department at the South Florida Water Management District, where he is a lead member of a modeling team dealing with development and applications of computer simulation models for Kissimmee River restoration and the restoration of the Everglades Ecosystem. Prior to joining the South Florida Water Management District, he taught courses in hydrology and water resources at Colorado State University, Fort Collins; George Washington University, Washington, D.C.; and at Florida Atlantic University, Boca Raton, Florida. Dr. Obeysekera has published numerous research articles in refereed journals in the field of water resources. Dr. Obeysekera has over 20 years of experience practicing water resources engineering with an emphasis on both stochastic and deterministic modeling. He has taught short courses on modeling in the Dominican Republic, Colombia, Spain, Sri Lanka, and the U.S. He was a member of the Surface Runoff Committee of the American Geophysical Union and is currently serving as a member of a Federal Task Group on Hydrologic Modeling. He served as member of NRC's Committee on Further Studies of Endangered and Threatened Fishes in the Klamath River. Dr. Obeysekera has a B.S. degree in civil engineering from University of Sri Lanka; M.E. in hydrology from Univer-

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sity of Roorkee, India; and Ph.D. in civil engineering with specialization in water resources from Colorado State University.

MAX J. PFEFFER is International Professor of Development Sociology and Chair of the Department at Cornell University. His teaching concentrates on environmental sociology and sociological theory. His research spans several areas including farm labor, rural labor markets, international migration, land use, and environmental planning. The empirical work covers a variety of rural and urban communities, including rural/urban fringe areas. Research sites include rural New York and Central America. He has been awarded competitive grants from the National Institutes of Health, the National Science Foundation, the U.S. Environmental Protection Agency, the U.S. Department of Agriculture's National Research Initiative and its Fund for Rural America, and the Social Science Research Council. Dr. Pfeffer has published a wide range of scholarly articles and has written or co-edited four books. He recently published (with John Schelhas) *Saving Forests, Protecting People? Environmental Conservation in Central America.* He also previously served as the Associate Director of both the Cornell University Agricultural Experiment Station and the Cornell University Center for the Environment. Dr. Pfeffer has served on other NRC committees studying aspects of watershed management. He received his Ph.D. degree in sociology from the University of Wisconsin, Madison.

DENISE J. REED is a University Research Professor at the University of New Orleans and is currently Interim Director of the Ponchartrain Institute for Environmental sciences. Her research interests include coastal marsh response to sea-level rise and how this is affected by human activities. She has worked on coastal issues on the Atlantic, Pacific, and Gulf coasts of the United States, as well as other parts of the world, and has published the results in numerous papers and reports. She is involved in ecosystem restoration planning both in Louisiana and in California. Dr. Reed has served on numerous boards and panels concerning the effects of human alterations on coastal environments and the role of science in guiding ecosystem restoration, including the Chief of Engineers Advisory Board, a number of NRC committees, and the Ecosystem Sciences and Management Working Group of the NOAA Science Advisory Board. She received her B.A. and Ph.D. degrees in geography from the University of Cambridge, United Kingdom.

KENNETH A. ROSE is E.L. Abraham Distinguished Professor in Louisiana Environmental Studies at the Department of Oceanography and Coastal Sciences, Louisiana State University in Baton Rouge. Prior to joining the faculty at

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LSU in 1998 he was a scientist at Oak Ridge National Laboratory from 1987 to 1998. He also consulted with Martin Marietta Environmental Systems from 1983 to 1987. His research interests include mathematical and simulation models to better understand and forecast the effects of natural and anthropogenic factors on aquatic populations, community food webs, and ecosystems; and use of models in resource management and risk assessment. He is a fellow of the American Association for the Advancement of Science and editor of the Canadian Journal of Fisheries and Aquatic Sciences, Marine and Coastal Fisheries, and San Francisco Estuary and Watershed Science. He received his B.S. from the State University of New York at Albany and his M.S. and Ph.D. in fisheries from the University of Washington.

DESIREE D. TULLOS is assistant professor in the Department of Biological and Ecological Engineering, Oregon State University, Corvallis. Dr. Tullos consulted with Blue Land Water Infrastructure and with Barge, Waggoner, Sumner, and Cannon before joining the faculty at Oregon State University. Her research areas include ecohydraulics, river morphology and restoration, bioassessment, and habitat and hydraulic modeling. She has done work on investigations of biological responses to restoration and engineered applications in riverine ecosystems; development and evaluation of targeted and appropriate bioindicators for the assessment of engineered designs in riverine systems; assessing effects of urban and agricultural activities and management practices on aquatic ecosystem stability in developing countries. She received her B.S. in civil engineering from the University of Tennessee, Knoxville, and her MC.E. in civil engineering and Ph.D. in biological engineering from North Carolina State University, Raleigh.

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Water and Power Policy Group

Hydrologic Modeling Results and Estimated Potential Hydropower Effects Due to the Implementation of the State Water Resources Control Board Delta Flow Criteria

December 2011

Prepared by:

DANIEL B. STEINER
CONSULTING ENGINEER

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Morn Worthington – Northern California Power Agency

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1.0 INTRODUCTION

At the direction of the Water and Power Policy Group, the HDR Team investigated the potential effects of implementing the SWRCB DFC. This product does not constitute the culmination of this project, but it does provide a marker from which further effort may proceed. To this end, we have identified hydropower effects caused by the alternative flow criteria on the CVP and SWP, as well as analyzed hydropower effects on San Joaquin River tributaries. It is our belief that a great percentage of the statewide hydropower effects can be identified by this level of analysis.

This document summarizes our analysis of potential effects the State Water Resources Control Board Delta Flow Criteria (SWRCB DFC) may have on CVP/SWP operations, San Joaquin River operations, and hydropower.

This document consists of the following sections:

- Definition of SWRCB DFC and those included in this analysis
- Summary of conclusions and modeling results
- Analytical approach
- Detailed modeling results

1.1 Background

To analyze the potential effects that the SWRCB DFC may have on hydropower, the following SWRCB DFC were analyzed:

- Delta Outflow Recommendation (75 percent of unimpaired flow from January through June).
- Sacramento River at Rio Vista (75 percent of unimpaired flow from November through June).
- San Joaquin River at Vernalis (60 percent of unimpaired flow from February through June).
- Old and Middle River (OMR) flow criteria (> than -1500 cfs in dry and critical years).

1.1.1 Delta Outflow Recommendation

The Delta Outflow Recommendation of 75 percent of unimpaired from January through June, and the unimpaired flow is used to determine flow requirements. Delta Smelt Fall X2 is included in the Existing (BO's) and as part of the SWRCB DFC. Data is provided in **Figure 1;** *Source: Table 20 Delta Outflow Summary Criteria, California Department of Water Resources Report, California Central Valley Unimpaired Flow Data, Fourth Edition, November 2006.*

Figure 1 – Delta Outflow Summary Criteria.

Table 20. Delta Outflow Summary Criteria

Delta Outflow Recommendations												
Category A												
Water Year												**Criteria**
O	N	D	J	F	M	A	M	J	J	A	S	
												1) Net Delta Outflow: 75 percent of 14-day average unimpaired flow
Category B												
Water Year												**Criteria**
O	N	D	J	F	M	A	M	J	J	A	S	
												2) Delta Smelt Fall X2 a. Wet years X2 less than 74 km (greater than approximately 12,400 cfs) b. Above normal years X2 less than 81 km (greater than approximately 7,100 cfs)
												3) 2006 Bay-Delta Plan Delta Outflow Objectives (critical, dry and below normal years)

Included in analysis

Included in Baseline

Basis for Criteria and Explanation

1) Promote increased abundance and improved productivity (positive population growth) for Longfin Smelt and other desirable estuarine species
2) Increase quantity and quality of habitat for Delta Smelt; Fall X2 requirement limited to above normal and wet years to reduce potential conflicts with cold water pool storage, while promoting variability with respect to fall flows and habitat conditions in above normal and wet water year types; expected to result in improved conditions for Delta Smelt, however, the statistical relationship between Fall X2 and abundance is not strong; note 2) above regarding need for improved understanding concerning the Fall X2 action also applies
3) Fish and wildlife beneficial use protection

Notes:

- These flow criteria do not consider any balancing of public trust resource protection with public interest needs for water.
- All flows are subject to appropriate ramping rates to avoid ramping impacts to public trust resources.
- These flow recommendations should be tempered by tributary specific flow needs and the need to manage cold-water resources for the protection of public trust resources.
- Criteria for percentages of unimpaired flows apply only up to a specified maximum cap; appropriate maximum flow caps still need to be determined based on public trust needs and to avoid flooding.
- Additional flows may be needed for the protection of public trust resources for periods of time for which no flow criteria are recommended or where 2006 Bay-Delta Plan flow objectives are recommended, but adequate information is not available at this time to recommend such flows.

1.1.2 Sacramento River

The Sacramento River requirement is modeled as 75 percent of unimpaired Sacramento River at Hood, plus an unimpaired Yolo Bypass flow into the Delta from November through June, rather than at Rio Vista. This model is more conservative (using less water) in comparison if it were modeled at Rio Vista.

The meeting 75 percent of unimpaired flow at Rio Vista requires the Sacramento River and the Yolo Bypass to be at 88 to 100 percent of the unimpaired flow, due to Cross Channel and the Georgiana Slough flow. The Rio Vista flow requires is included in the BO's as part of the SWRCB DFC. However, the Wilkins Slough and the Freeport flows of 13,000 to 17,000 cfs were not analyzed. Data is provided in **Figure 2;** *Source: Table 21 Sacramento River Inflow Summary Criteria, California Department of Water Resources Report, California Central Valley Unimpaired Flow Data, Fourth Edition, November 2006.*

Figure 2 – Sacramento River Inflow Summary Criteria

Table 21. Sacramento River Inflow Summary Criteria

Sacramento River		
Category A		
Water Year (O N D J F M A M J J A S)	Criteria	
	1) Rio Vista: 75 percent of 14-day average unimpaired flow	
Category B		
Water Year (O N D J F M A M J J A S)	Criteria	
	2) Rio Vista: 75 percent of 14-day average unimpaired flow to support same functions as #1 for other runs of Chinook salmon	Included in analysis
	3) Wilkins Slough: Provide pulse flows of 20,000 cfs for 7 days starting in November coinciding with storm events producing unimpaired flows at Wilkins Slough above 20,000 cfs until monitoring indicates that majority of smolts have moved downstream	Included in Baseline
	4) Freeport: Positive flows in Sacramento River downstream of confluence with Georgiana Slough while juvenile salmon are present (approximately 13,000 to 17,000 cfs)	
	5) Sacramento River at Rio Vista: 2006 Bay-Delta Plan flow objectives	

Basis for Criteria and Explanation, and Notes

1) Increases juvenile salmon outmigration survival for fall-run Chinook salmon
2) Promote juvenile salmon emigration for other runs of Chinook salmon
3) Increases juvenile salmon outmigration survival by reducing diversion into Georgiana Slough and the central Delta
4) Increases juvenile salmon outmigration survival
5) Fall adult Chinook salmon attraction flows

Notes:

- These flow criteria do not consider any balancing of public trust resource protection with public interest needs for water.
- All flows are subject to appropriate ramping rates to avoid ramping impacts to public trust resources.
- These flow recommendations should be tempered by tributary specific flow needs and the need to manage cold-water resources for the protection of public trust resources.
- Criteria for percentages of unimpaired flows apply only up to a specified maximum cap; appropriate maximum flow caps still need to be determined based on public trust needs and to avoid flooding.
- Additional flows may be needed for the protection of public trust resources for periods of time for which no flow criteria are recommended or where 2006 Bay-Delta Plan flow objectives are recommended, but adequate information is not available at this time to recommend such flows.

[1] Definition of storm, number of storms, and how to determine when the majority of juveniles have outmigrated needs to be determined.

1.1.3 San Joaquin River

The San Joaquin Rivera at Vernalis was analyzed at 60 percent of unimpaired flow from February through June. Data is provided in **Figure 3;** *Source: Table 22 San Joaquin River Inflow Summary Criteria, California Department of Water Resources Report, California Central Valley Unimpaired Flow Data, Fourth Edition, November 2006.*

Figure 3 – San Joaquin River Inflow Summary Criteria

Table 22. San Joaquin River Inflow Summary Criteria

San Joaquin River													
Category A													
Water Year													**Criteria**
O	N	D	J	F	M	A	M	J	J	A	S		
													1) Vernalis: 60 percent of 14-day average unimpaired flow
													2) Vernalis: 10 day minimum pulse of 3,600 cfs in late October (e.g., October 15 to 26)
Category B													
Water Year													**Criteria**
O	N	D	J	F	M	A	M	J	J	A	S		
													3) 2006 Bay-Delta Plan October pulse flow

Included in analysis

Included in Baseline

Basis for Criteria and Explanation, and Notes

1) Increase juvenile Chinook salmon outmigration survival and provide conditions that will generally produce positive population growth in most years and achieve the doubling goal in more than half of years
2) Minimum adult Chinook salmon attraction flows to decrease straying, increase DO, reduce temperatures, and improve olfactory homing fidelity
3) Adult Chinook salmon attraction flows

Notes:

- These flow criteria do not consider any balancing of public trust resource protection with public interest needs for water.
- All flows are subject to appropriate ramping rates to avoid ramping impacts to public trust resources.
- These flow recommendations should be tempered by tributary specific flow needs and the need to manage cold-water resources for the protection of public trust resources.
- Criteria for percentages of unimpaired flows apply only up to a specified maximum cap; appropriate maximum flow caps still need to be determined based on public trust needs and to avoid flooding.
- Additional flows may be needed for the protection of public trust resources for periods of time for which no flow criteria are recommended or where 2006 Bay-Delta Plan flow objectives are recommended, but adequate information is not available at this time to recommend such flows.

1.1.4 Old and Middle River, Inflow-Export Ratios, and Jersey Point

The Old and Middle River (OMR) did not analyze San Joaquin River flow to export ratio. The OMR included flows included in the BO's and the SWRCB DFC (**Figure 4**: *Source: Table 23: No. 4-6, Hydrodynamics Summary Criteria, California Department of Water Resources Report,*

California Central Valley Unimpaired Flow Data, Fourth Edition, November 2006). The Jersey Point criteria is not addressed in the data.

Figure 4 – Hydrodynamics Summary Criteria

Table 23. Hydrodynamics Summary Criteria

Hydrodynamics: Old and Middle River, Inflow-Export Ratios, and Jersey Point												
Category A												
Water Year												**Criteria**
O	N	D	J	F	M	A	M	J	J	A	S	
												1) San Joaquin River Flow to Export Ratio: Vernalis flows to exports greater than 0.33 during fall pulse flow (e.g., October 15 – 26); complementary action to San Joaquin River Inflow recommendation #2
Category B												
Water Year												**Criteria**
O	N	D	J	F	M	A	M	J	J	A	S	
												2) Old and Middle River Flows: greater than -1,500 cfs in Critical and Dry water years
												3) Old and Middle River Flows: greater than 0 or -1,500 cfs in Critical and Dry water years, when FMWT index for longfin smelt is less than 500, or greater than 500, respectively
												4) Old and Middle River Flows: greater than -5,000 cfs in all water year types
												5) Old and Middle River Flows: greater than -2,500 when salmon smolts are determined to be present in the Delta
												6) San Joaquin River Flow to Export Ratio: Vernalis flows to exports greater than 4.0 when juvenile San Joaquin River salmon are migrating in mainstem San Joaquin River
												7) Jersey Point: Positive flows when salmon present in the Delta
												8) 2006 Bay-Delta Plan Exports to Delta Inflows

Basis for Criteria and Explanation

1) Reduce straying and improve homing fidelity for San Joaquin basin adult salmon
2) Reduce entrainment of larval / juvenile delta smelt, longfin smelt, and provide benefits to other desirable species
3) Same as number 2), but if the previous FMWT index for longfin smelt is less than 500, then OMR must be greater than 0 (to reduce entrainment losses when abundance is low), or greater than -1,500 if the previous FMWT index for longfin smelt is greater than 500
4) Reduce entrainment of adult delta smelt, longfin smelt, and other species; less negative flows may be warranted during periods when significant portions of the adult smelt population migrate into the south or central Delta; thresholds for such flows need to be determined
5) Reduce risk of juvenile salmon entrainment and straying to central Delta at times when juveniles are present in the Delta; will also provide associated benefits for adult migration
6) Improve survival of San Joaquin River juvenile salmon emigrating down the San Joaquin River and improve subsequent escapement 2.5 years later
7) Increase survival of outmigrating smolts, decrease diversion of smolts into central Delta where survival is low, and provide attraction flows for adult returns
8) Protection of estuarine dependent species

(cont.)

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2.0 OVERVIEW

The analytical approach used for this effort was the latest publically available version of the CalSim II model. This version was used by the DWR to develop its 2009 State Water Program (SWP) Reliability Study, published by DWR on January 29, 2010.

The version was ideal for the application, because it was used to evaluate criteria submitted to the SWRCB during its Delta proceeding, and it has been used by members of the consultant team to evaluate the final criteria developed by the SWRCB.

The baseline CalSim II Study (BST_2005A01A_Existing_DRR_2Step) includes reasonable and prudent alternatives (RPAs) contained in the 2008 Fish and Wildlife Service Biological Opinion for the Coordinated Operations and the 2009 National Marine Fisheries Service Biological Opinion for OCAP.

The SWRCB DFC criteria's described above are input into the CalSim II Existing Conditions (BO's) model simulation to develop a model simulation with the SWRCB DFC. These model simulations are compared to derive changes to the water system, and then determine the hydropower impacts.

2.1 Summary of the State Water Resources Control Board Delta Flow Criteria Impacts

Table 1 – Summary of SWRCB DFC Impacts

Description	Impacts
Four of the SWRCB DFCs were analyzed, and assumptions made that imposed less onerous burden on water system.	▪ Effects to the water system were very severe, resulting in the inability to produce viable operations.
Increase in Delta Outflow	▪ There was approximately at 5 MAF of increased Delta outflow.
Significant and regular cuts	▪ Senior Water Rights holders (including pre-1914, Sacramento Settlement, and Exchange contractors, are cut regularly and significantly
Devastating decrease in project deliveries	▪ M&I South of Delta – 1.1 MAF = 2.5 Million households. ▪ Agriculture – 2 Million acres out of production (7000,000 + North, 1 Million + South).
Unable to meet biological opinions	▪ Impossible to meet salmon and smelt criteria. ▪ Cannot meet existing flow standards, including SWRCB D-1641.
Upstream storage	▪ Lower storage in all seasons. ▪ Fish habitat and cold water pool heavily impacted. ▪ Reduced hydropower capacity caused by loss in head.
State-wide impacts	▪ Impacts to groundwater storage. ▪ Reduced ability for conjunctive management. ▪ Impacts to Ephemeral streams and habitats.
Pacific Flyway Delivery	▪ Significant reduction in refuge delivery effective Pacific Flyway.

Description	Impacts
CVP/SWP Hydropower Generation	▪ A 30% average annual reduction in combined CVP/SWP generation. ▪ Change in timing (generation shifted to spring months when already surplus power in the system. ▪ Reduction in summer and fall months. ▪ Spring energy production is 50% greater with the SWRCB DFC than with the existing conditions. ▪ Summer energy production with the SWRCB DFC is about 50% less than with existing. ▪ Shift in timing of generation will produce economic cost. ▪ Summer generation value is 30% greater than on an MWh basis.
CVP/SWP Hydropower Generation Cost	▪ At 12,000 KWh/year/household the average annual generation reduction is equivalent to nearly 250,000 households each year.
CVP/SWP Load	▪ A decrease in Delta exports. ▪ A decrease in project use load, but will require additional energy for desalination of replacement water (greater than the project use load), savings by 2,000 GWh – at 12,000 KWh/year/household the average annual additional energy for desolation is equivalent to nearly 165,000 households per year. ▪ Replacement power costs will be 200 percent more costly than project power.
San Joaquin Tributary Hydropower Generation	▪ Don Pedro – Overall reduction in annual generation of 23% (135 GWH) ▪ Exchequer – Overall reduction in annual generation of 26% (90 GWH)
San Joaquin Tributary Hydropower Generation Cost	▪ At 12,000 KWh/year/household the average annual Don Pedro generation reduction is equivalent to over 11,000 households each year. ▪ At 12,000 KWh/year/household the average annual Exchequer generation reduction is equivalent to 7,500 households each year.

Figure 5 – Summary of Changes in Delta Boundary Flows – SWRCB DFC minus Existing (BO's). Average Annual Changes by 40-30-30 Water Year Type (MAF).

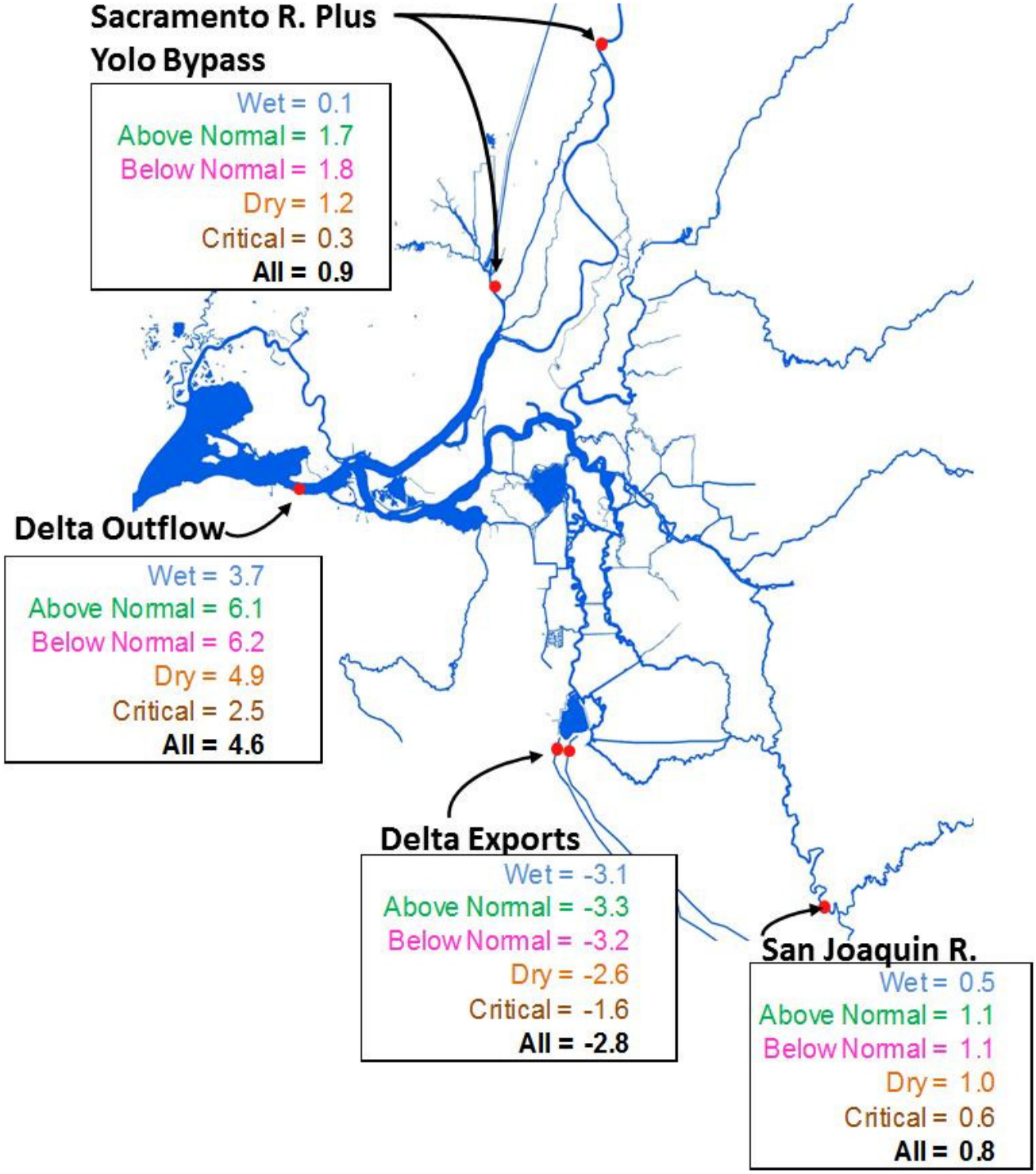


Figure 6 – Summary of Changes in Key River flows – SWRCB DFC minus Existing (BO's). Average Monthly Changes by 40-30-30 Water Year Type (cfs).

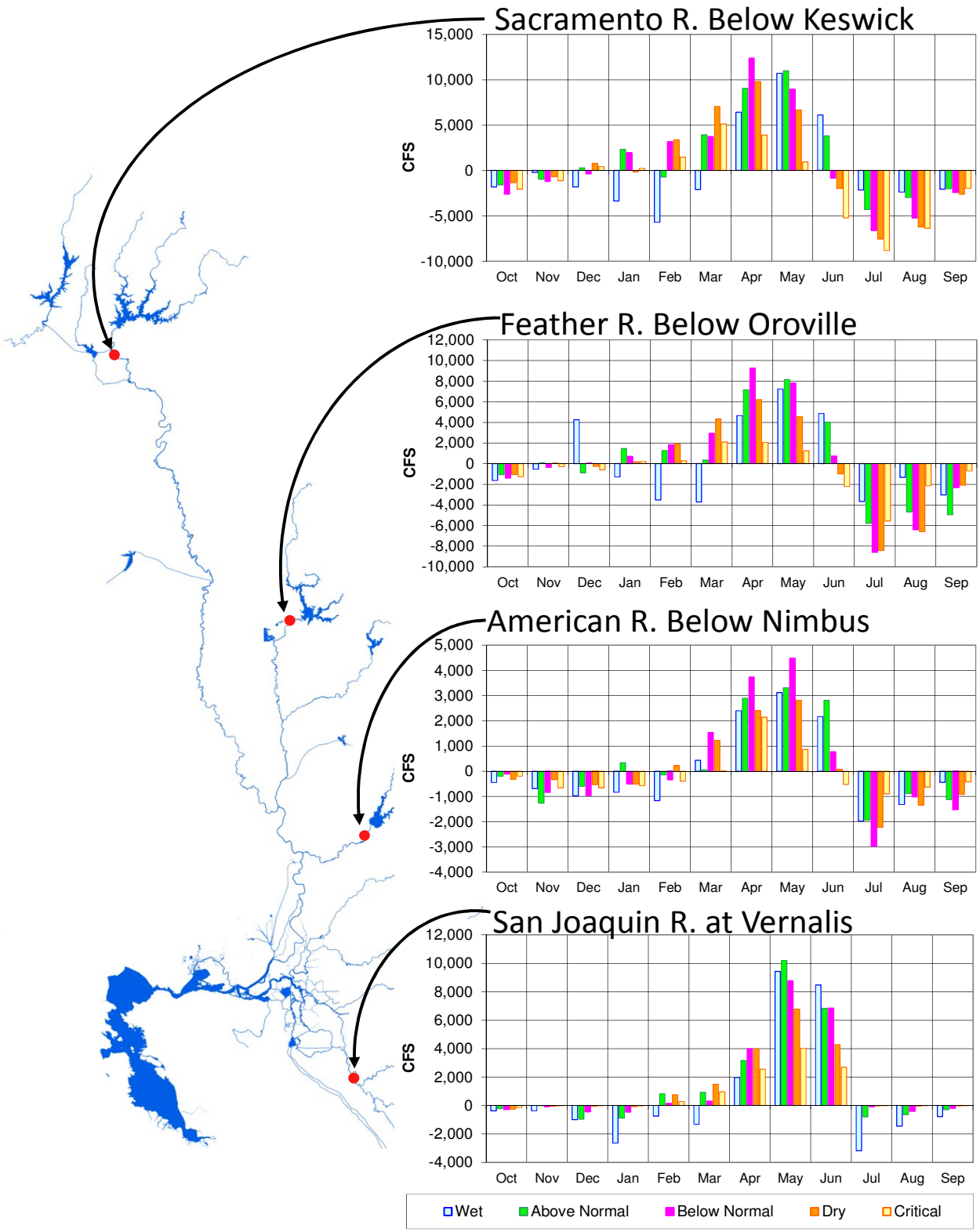


Figure 7 – Summary of Changes in Delta Boundary Flows – SWRCB DFC minus Existing (BO's). Average Monthly Changes by 40-30-30 Water Year Type (cfs).

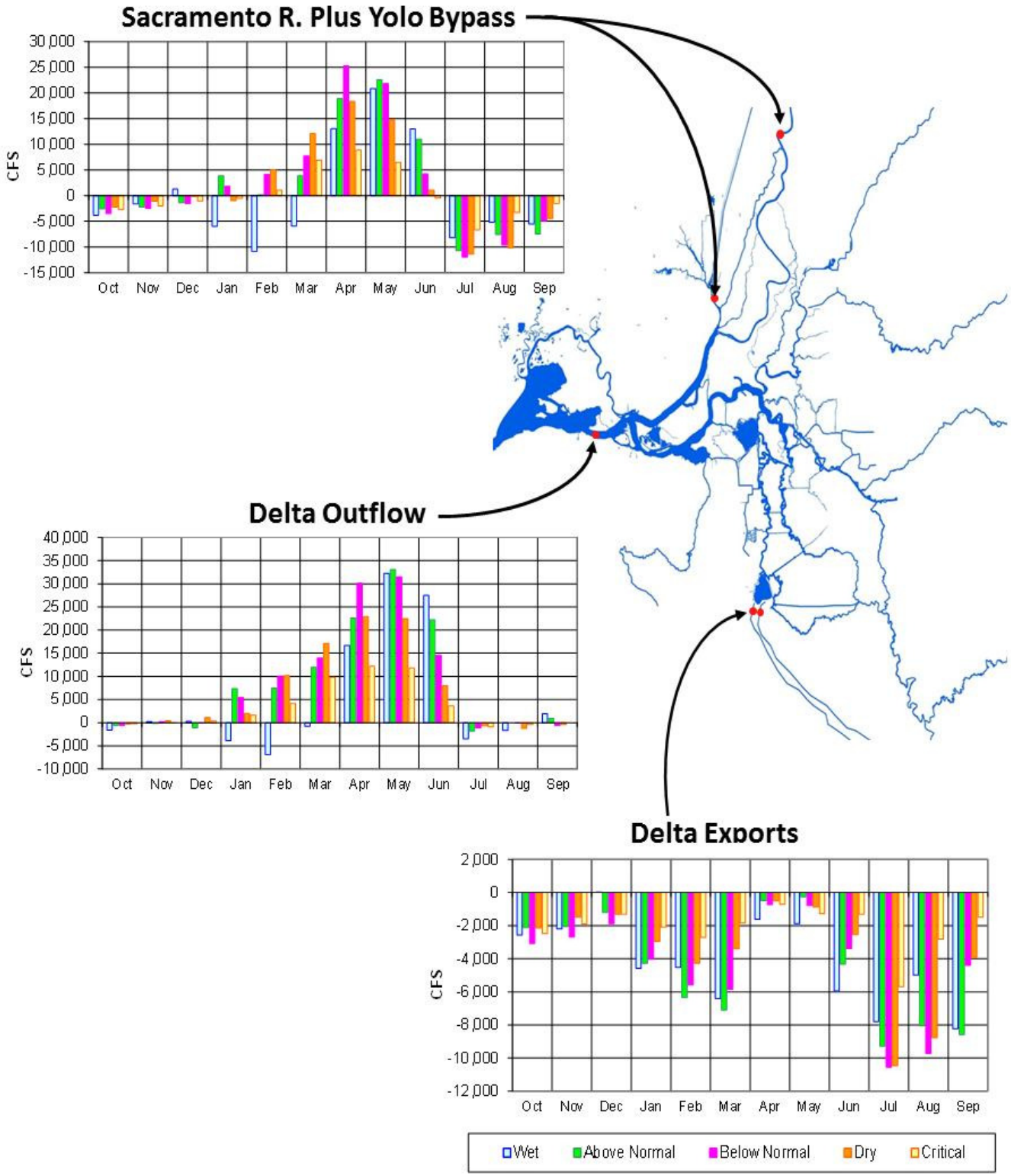
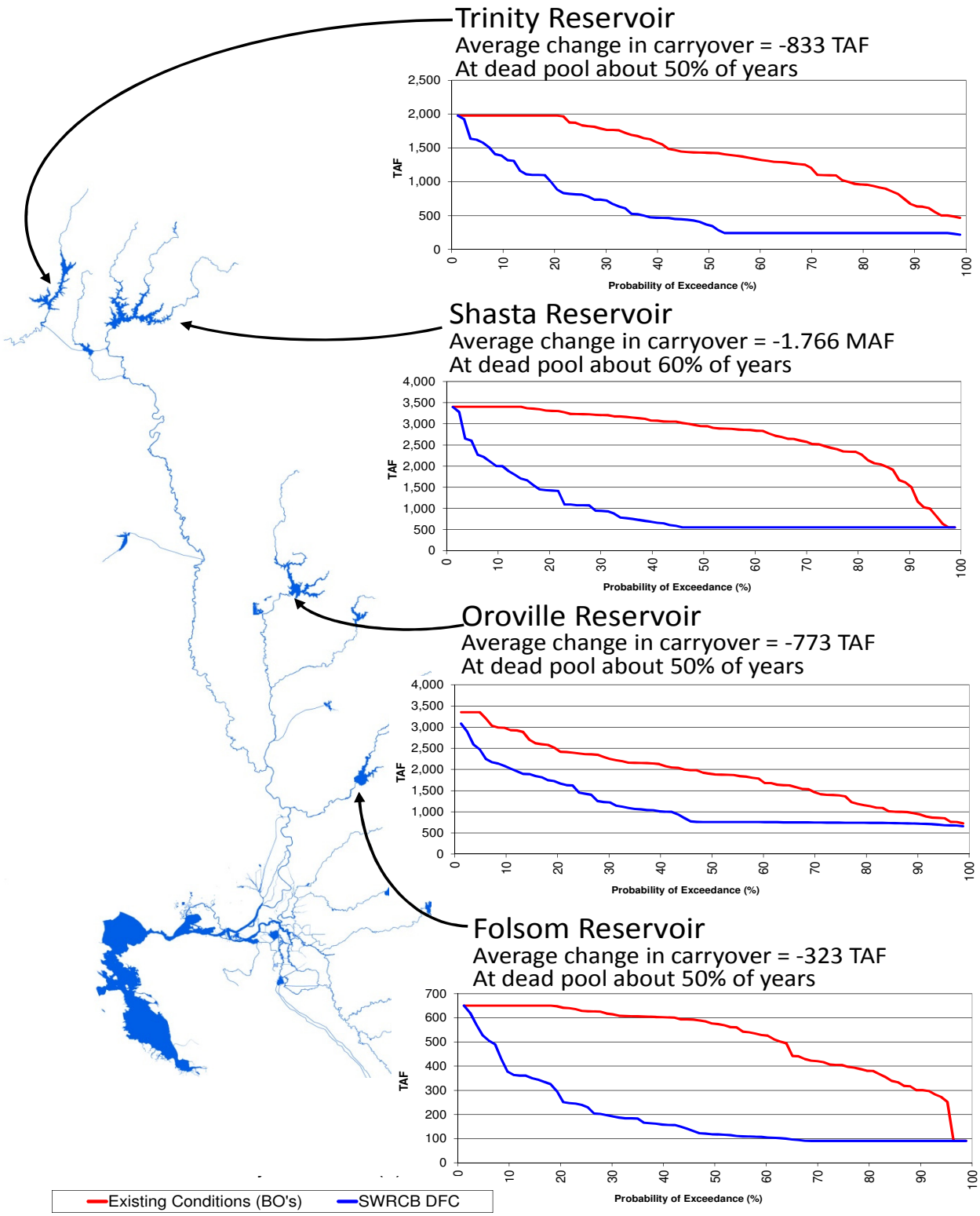


Figure 8 – Summary of Main CVP/SWP Reservoir Carryover – SWRCB DFC and Existing (BO's). End of September Storage (TAF).



3.0 ANALYTICAL APPROACH TO HYDROPOWER MODELING

The analytical approach used for this effort was to employ available hydropower models utilizing CalSim II model output from simulations described in Section 2.0. For the CVP hydropower analysis, Reclamation's LongTermGen spreadsheet was used. For the SWP hydropower analysis, DWR's SWPGen spreadsheet was used. Proprietary models for the San Joaquin River tributary hydropower analyses were employed by Daniel B. Steiner, Consulting Engineer, to obtain results for these watersheds.

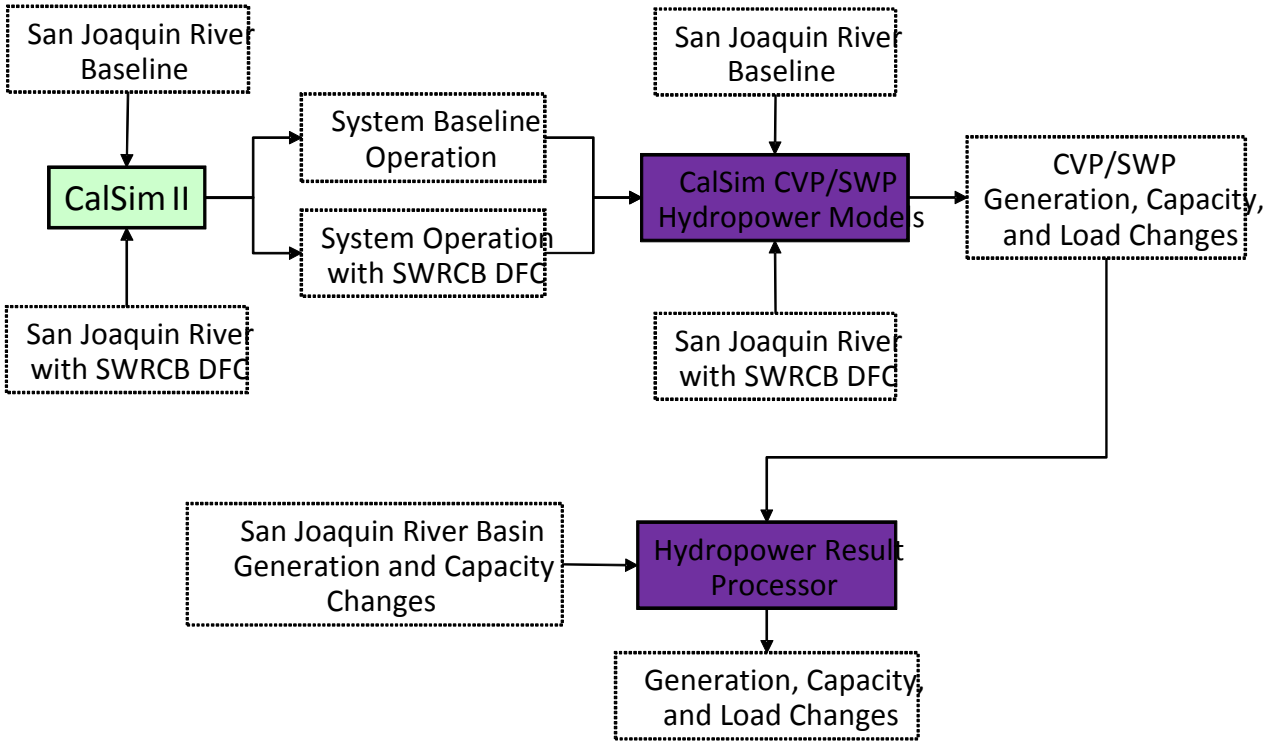
The analysis of the SWRCB DFC was performed using several different models to define both a baseline operations and an operation with the SWRCB DFC. Effects due to the SWRCB DFC are derived by comparing model simulations with and without the SWRCB DFC. The following flowchart illustrates the models used and information passing between models. Components of the flowchart are described in detail in this section.

3.1 CalSim II

CalSim II is a planning model designed to simulate the CVP and SWP water delivery systems while meeting various instream flow requirements, in-basin use obligations, and flood control criteria. The CalSim II model simulation used to support the State Water Project Delivery Reliability Report (SWP DRR) is the best available modeling tool and latest public release of the model. Appendix A of the SWP DRR describes the CalSim II modeling assumptions. For this analysis CalSim II was used to assess changes in CVP / SWP storage, river flows, water deliveries, and Delta conditions. The SWP DRR may be found at the following web location: http://baydeltaoffice.water.ca.gov/swpreliability/Reliability2010final101210.pdf

Besides its public availability, this version is ideal for the application because it has already been used to evaluate criteria submitted to the State Water Resources Control Board (SWRCB) during its Delta proceeding, and it has been used by members of the consultant team to evaluate the final criteria developed by the SWRCB. The baseline CalSim II study (BST_2005A01A_Existing_DRR_2Step) includes reasonable and prudent alternatives (RPAs) contained in the 2008 Fish and Wildlife Service Biological Opinion for the Coordinated Operations and the 2009 National Marine Fisheries Service Biological Opinion for OCAP.

Figure 9 – San Joaquin River Basin Analysis



3.2 CVP/SWP Hydropower Effects

The implementation of the SWRCB DFC creates considerable hydropower effects. These effects though sizeable on a monthly basis are likely to be even greater when brought into the world of real-time operations.

The analyses portrayed in this report are necessarily conducted on a monthly basis because of the limitations on data used for comparative input. These data are the result of CalSim II simulations of SWP/CVP conditions expected to occur in the future with and without the SWRCB DFC. Because CalSim II is constrained by its own input data which only exists on a monthly time step, so therefore is the hydropower analysis possible on a monthly basis.

Hydropower effects obtainable from the models include production; generation (MWH) and capacity (MW) at project power plants; and, energy use (MWH) and demand (MW) at project pumping plants. Not identifiable with these tools are the ancillary services: scheduling and dispatch, reactive power and voltage control, loss compensation, load following, system protection, and energy imbalance.

This report expresses results at Load Center, which is assumed to be at Tracy California. Values shown for load center include adjustments for station service at, and line losses from,

power plants as well as station service at and line losses to pumping plants. Reported energy values are averages over the month and capacity values are also head dependent monthly averages.

Given the limitations of a monthly time step, effects of the comparisons are largely identified by the temporal distribution of hydropower production and use along with the annual changes in these quantities.

3.3 San Joaquin River Tributary Hydropower Effects

Analysis of the San Joaquin River Basin was prepared for the San Joaquin River Group Authority by Daniel B. Steiner, Consulting Engineer, and the analysis is described in his February 15, 2011 paper titled: *"Power Operation Impact Analysis Associated with SWRCB Staff Vernalis Flow Requirements."* The purpose of this analysis was to describe the results of preliminary analyses that illustrate quantifiable potential power generation effects of alternative flow requirements applied to the major rim reservoir projects located on the Stanislaus, Tuolumne and Merced rivers. The analysis produced results that illustrate the magnitude of potential effects, in terms of monthly and annual energy production and the seasonal shifts of generation that could occur. These results are derived from models that have been used by the San Joaquin River Group Authority (SJRGA) and its members throughout recent watershed and basin planning efforts. Power generation is modeled as an incidental result of reservoir releases. Generation efficiency (kWh/AF) and capability (MW) curves, based on the reservoir elevation/storage parameter, applied to reservoir releases, provide month to month (or more frequent) generation values for each model's simulation period.

Similar to the discussion on CVP/SWP Hydropower Effects, San Joaquin River Hydropower effects are expressed in the same manner. Although different tools are incorporated into the analyses, the resultant comparisons are presented in the same manner as the CVP/SWP. Exceptions to the above are, however, that no adjustments are made to reflect quantities at the Tracy load center, nor are there any loads identified for these tributary projects.

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4.0 DETAILED ANALYTICAL RESULTS

Changes in the water system and hydropower are characterized by the following parameters:

- Changes in Delta outflow.
- Effectiveness of system to satisfy SWRCB flow requirements and SWRCB DFC.
- Sacramento River Basin flow to Delta.
- Effects on Delta Exports.
- Effects on Sacramento River Basin ground water.
- Effects on Shasta Lake and Upper Sacramento River.
- Effects on Trinity operations.
- Effects on Folsom Lake and the American River.
- Effects on Oroville and the Feather River.
- Effects on the San Joaquin River at Vernalis.
- Effects on San Luis Reservoir operations.
- Effects on CVP / SWP water deliveries.
- Effects on CVP / SWP hydropower generation.
- Effects on CVP / SWP energy load.

4.1 Change in Delta Outflow - SWRCB DFC Minus Existing (BO's)

- Large increases in January through June.
- Decreases in January and February in wet years as reservoirs refill.

Figure 10 – Changes in Delta Outflow – SWRCB DFC Minus Existing (BO's). Average by Year Type

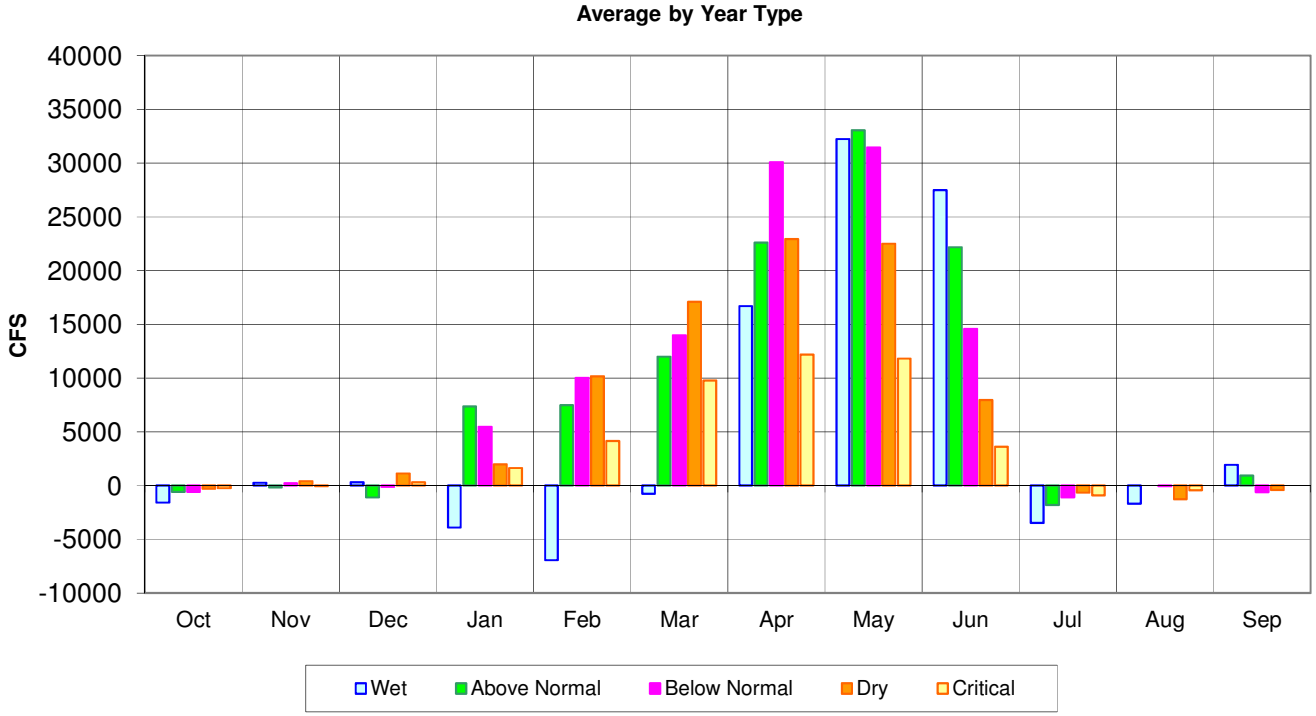


Figure 11 - Annual Change in Delta Outflow - SWRCB DFC minus Existing (BO's). Average increase of 4.6 MAF.

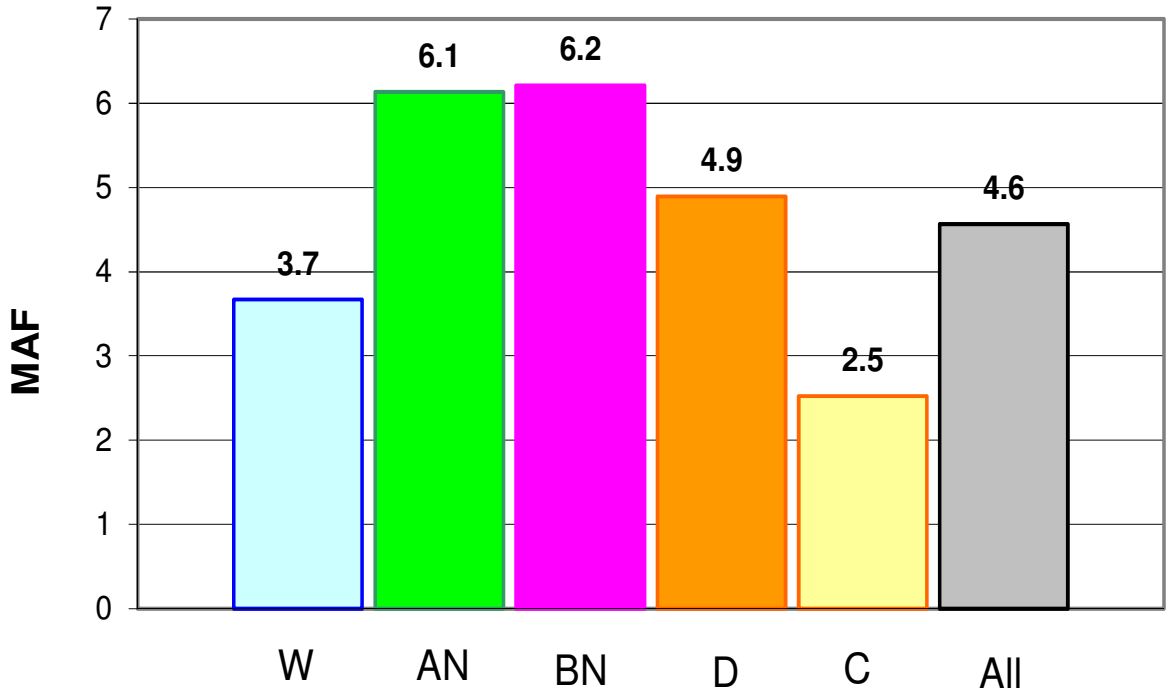
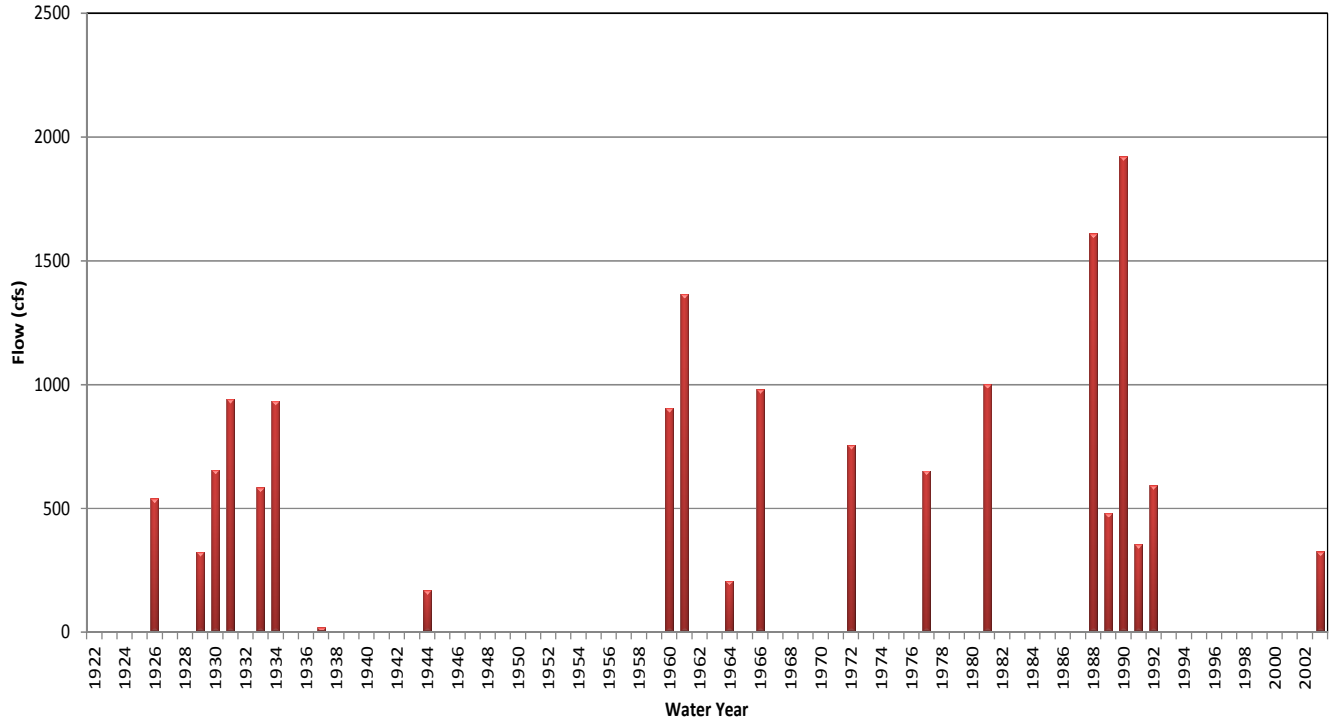
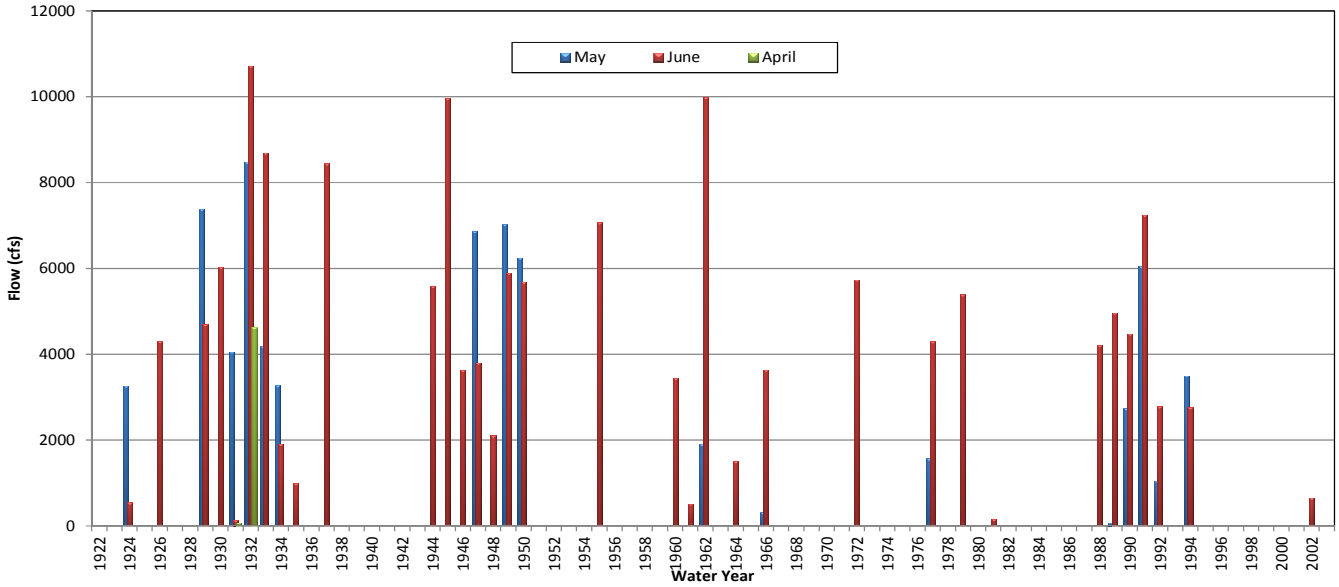


Figure 12 - Violations in D-1641 Delta Outflow Requirements in July in SWRCB DFC Scenario.



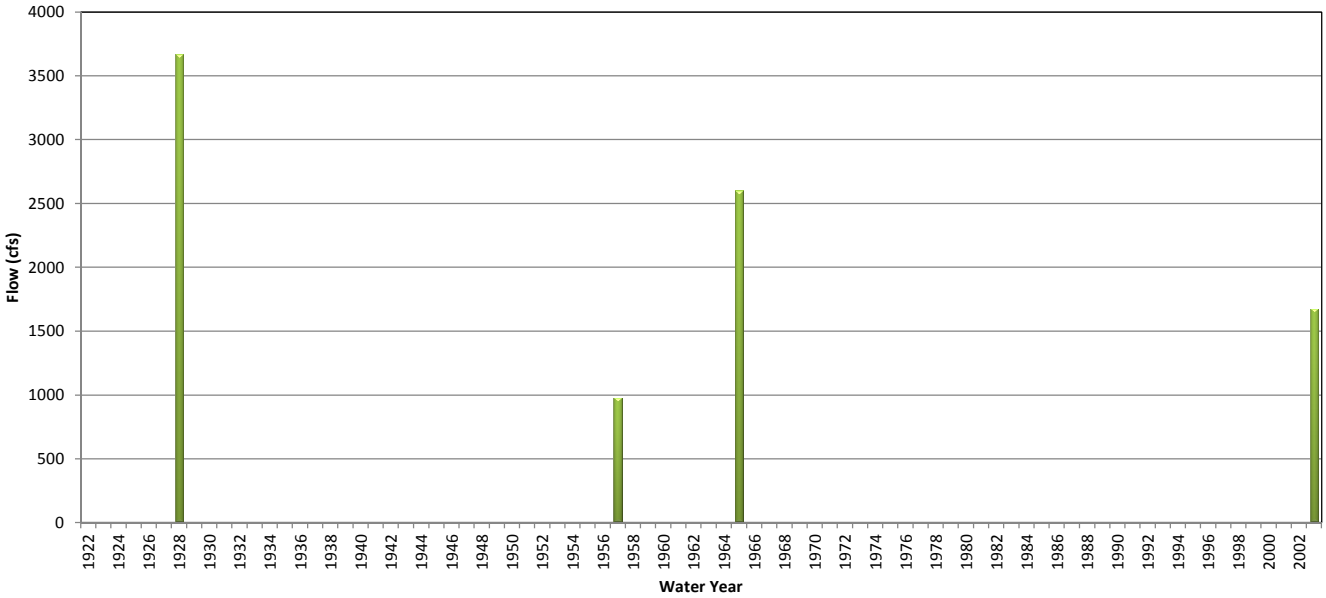
Increases flows in winter and spring cause upstream reservoirs to hit dead pool causing shortage in upstream diversions and inability to satisfy SWRCB D-1641 flow requirements.

Figure 13 - Shortage in Supply to Satisfy SWRCB DFC in April, May, and June.



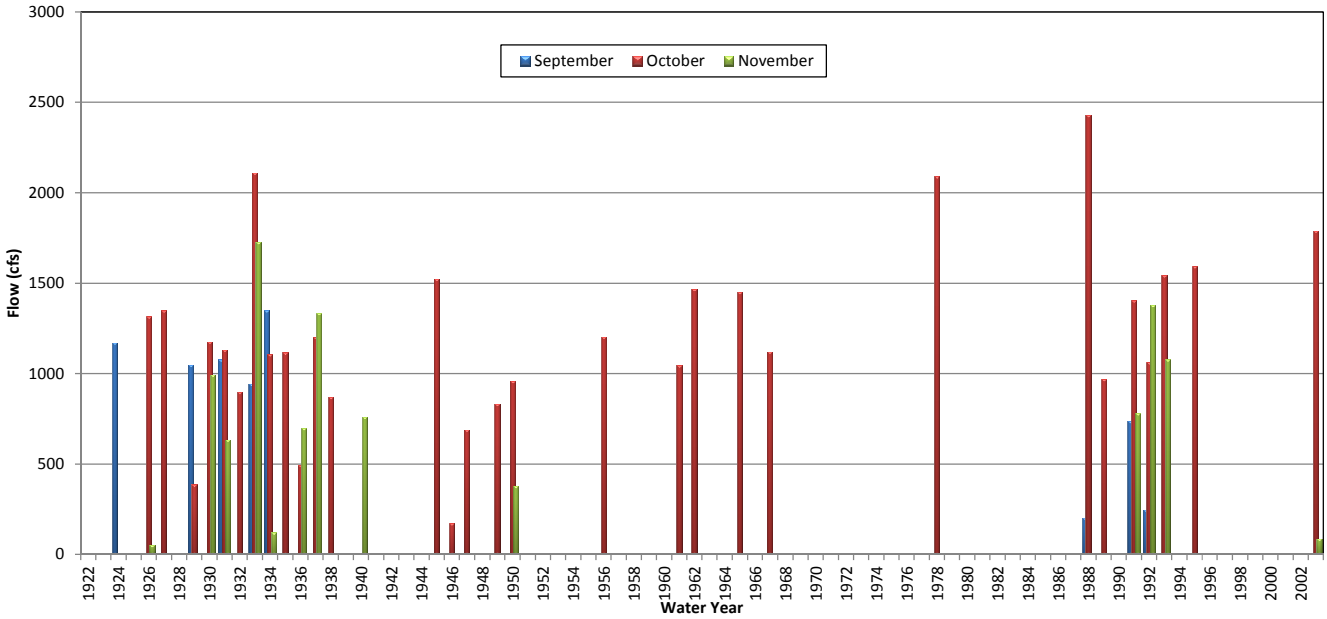
Satisfying the SWRCB DFC along with numerous existing flow requirements result in demands on the system in excess of its ability to satisfy existing requirements and the SWRCB DFC.

Figure 14 – Violation in Smelt Fall X2 RPA in September in SWRCB DFC Scenario



Satisfying the SWRCB DFC cause water shortages leading to inability to meet Fall X2 flows Smelt BO RPA's

Figure 15 – Violations in D-1641 Flow Requirement at Rio Vista in September, October, and November in SWRCB DFC Scenario



Satisfying the SWRCB DFC cause water shortages leading to inability to meet SWRCB D-1641 flow requirements in the Sacramento River during fall months

Figure 16 - Sacramento River Plus Yolo Bypass Inflow to Delta

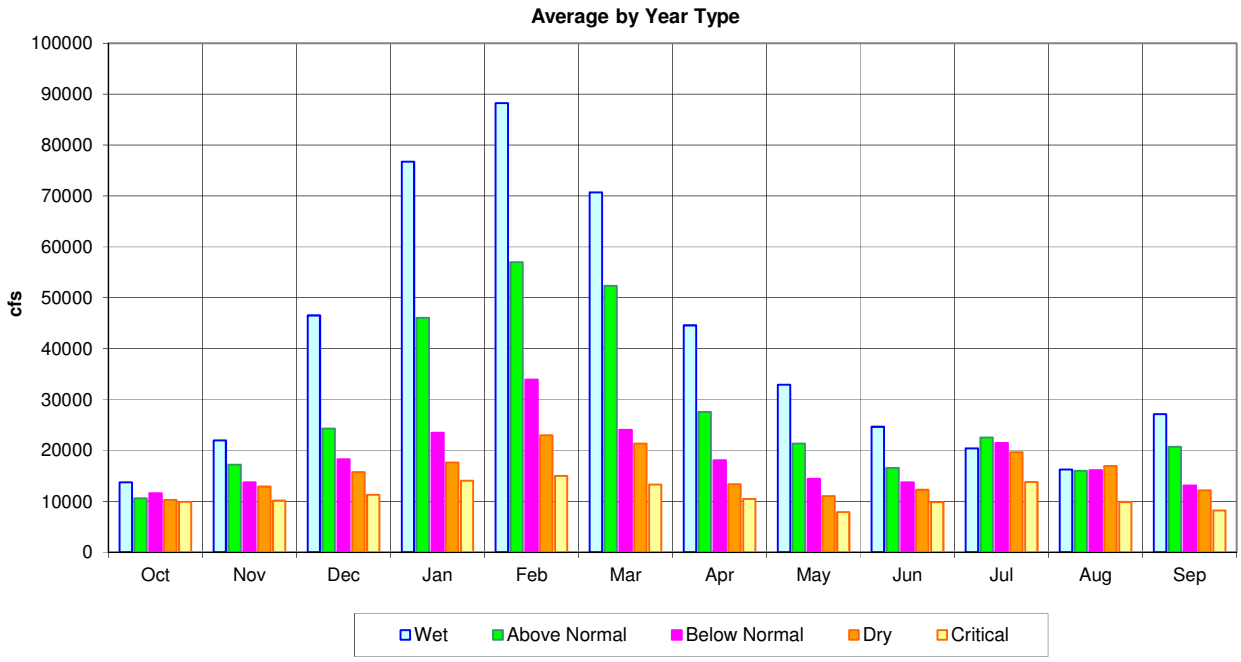
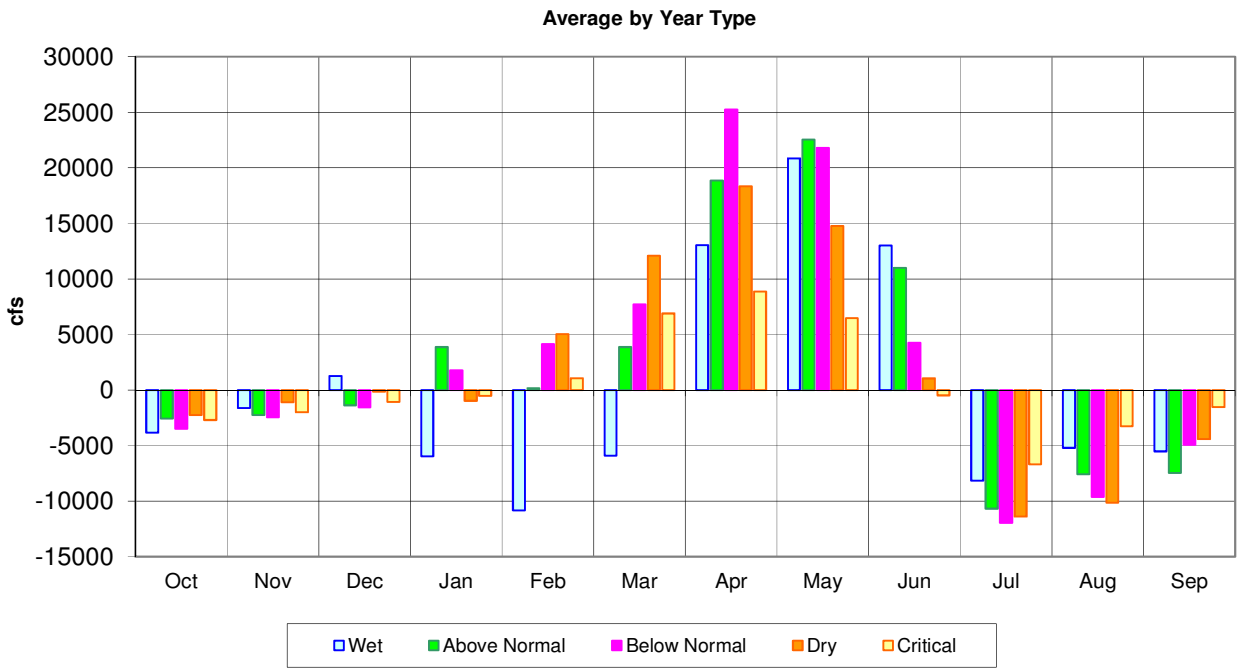
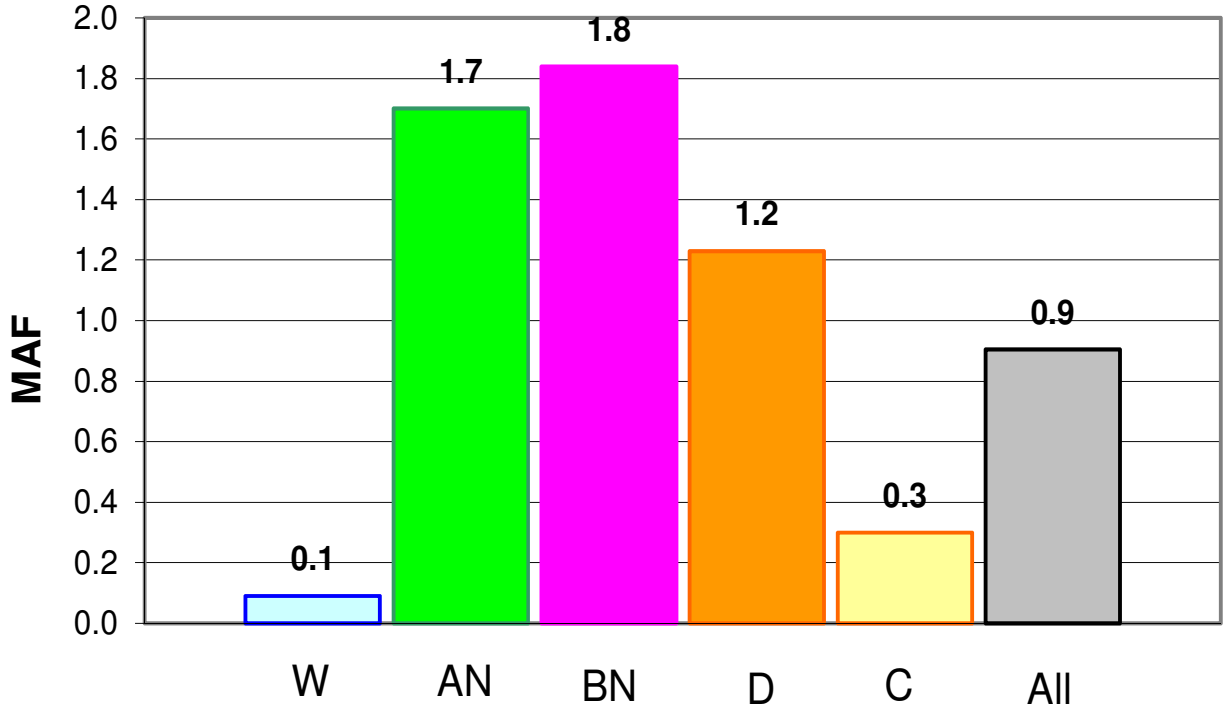


Figure 17 Change in Sacramento River plus Yolo Bypass Inflow to Delta - SWRCB DFC Minus Existing (BO's)



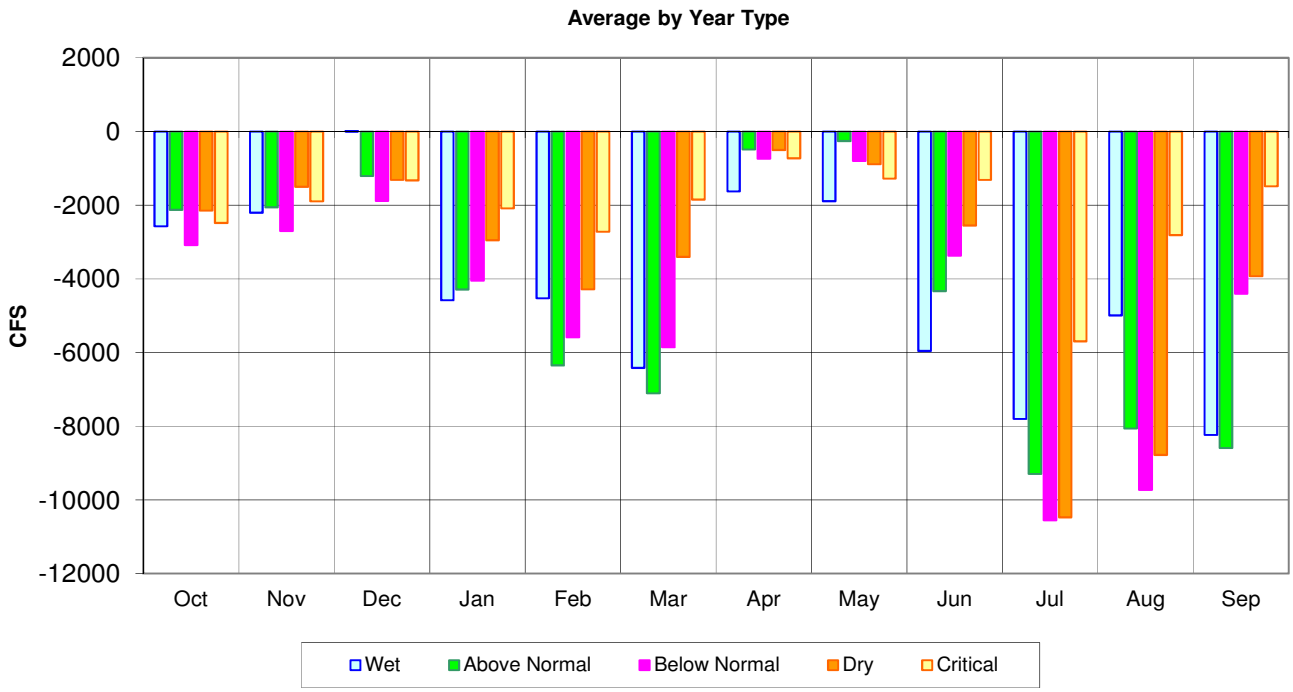
- Large increases in January through June.
- Decreases in January through March in wet years as reservoirs refill.
- Decreases in July through December, mostly due to low upstream reservoir storage but is also due to an assumption that reservoirs do not release additional water to support exports.

Figure 18 - Annual Change in Sacramento River Plus Yolo Bypass Inflow to Delta - SWRCB DFC minus Existing (BO's)



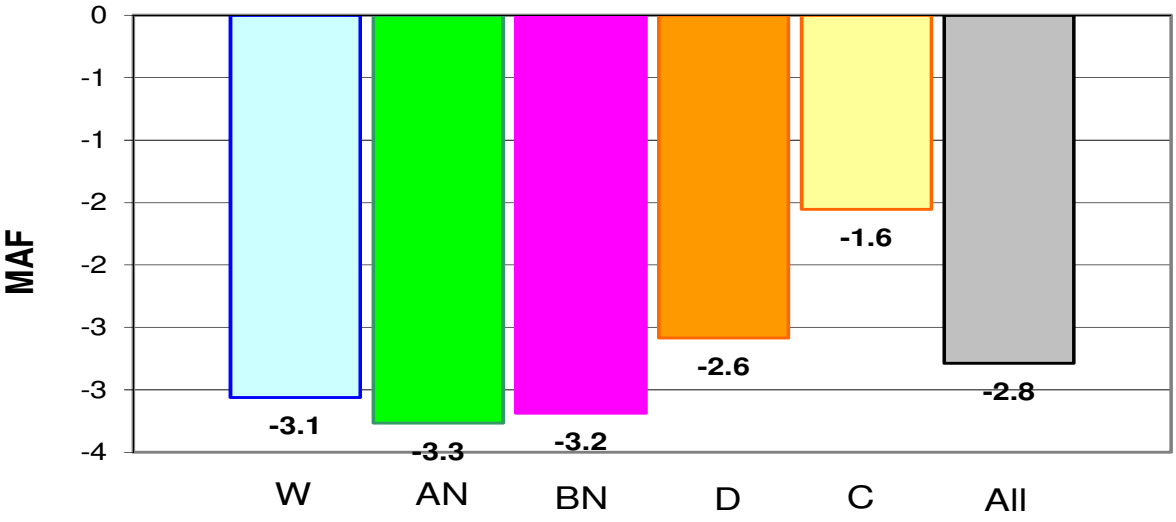
- Average annual increase of 900 TAF.
- Affected by increases in Trinity River import of about 170 TAF.
- Affected by increases in groundwater pumping of about 800 TAF.

Figure 19 - Monthly Change in Delta Exports - SWRCB DFC minus Existing (BO's)



- Delta exports are affected throughout each year and in all types of years.
- No Reservoir releases are made to support Delta export because of low upstream reservoir conditions.

Figure 20 - Annual Change in Delta Exports - SWRCB DFC minus Existing (BO's)



- Average annual Existing (BO's) level export = 4.93 MAF.
- Average annual export with SWRCB DFC = 2.14 MAF.
- Average annual change in export = 2.8 MAF.

4.2 Groundwater Pumping in Sacramento Valley

CalSim II is not designed to simulate CVP/SWP operations using criteria as onerous as the SWRCB DFC. Therefore, the model simulation produced using the SWRCB DFC overestimates changes in groundwater pumping. The level of increased pumping simulated in the model is not physically possible.

Although the model increases groundwater pumping to satisfy all demands, there would most likely be a reduction in crop acreage and refuge water supply, and any increase in groundwater pumping will likely result in lower groundwater tables, and increases in groundwater recharge (similar in magnitude to the increase in pumping). This increase in recharge would result in decreases in stream flow that would cause additional need for groundwater pumping, reservoir releases, and crop fallowing to satisfy the SWRCB DFC. It is also believed that decreases in groundwater levels would cause adverse impacts to ephemeral stream habitat, urban wells, and major surface water streams.

Figure 21 - Monthly Change in Groundwater Pumping in Sacramento Valley - SWRCB DFC minus Existing (BO's)

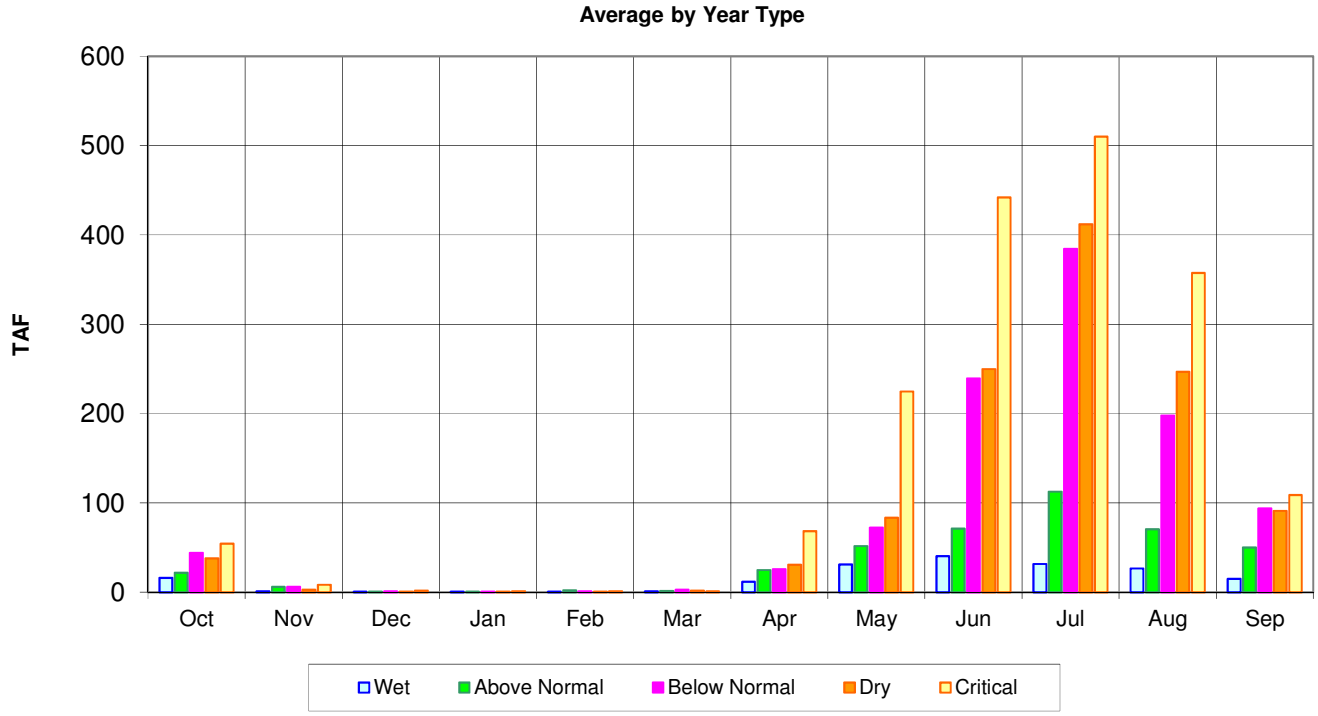
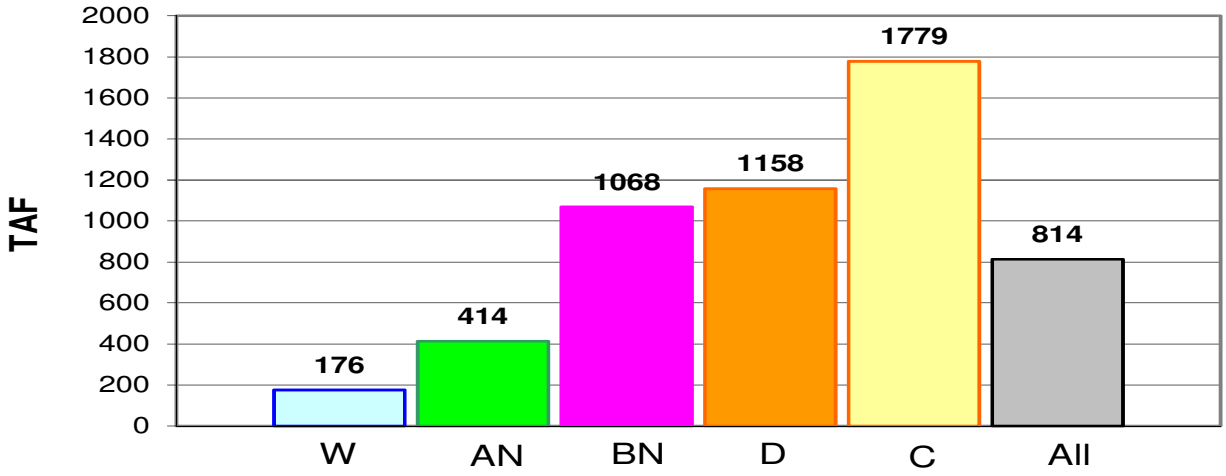


Figure 22 - Monthly Change in Groundwater Pumping in Sacramento Valley - SWRCB DFC minus Existing (BO's)



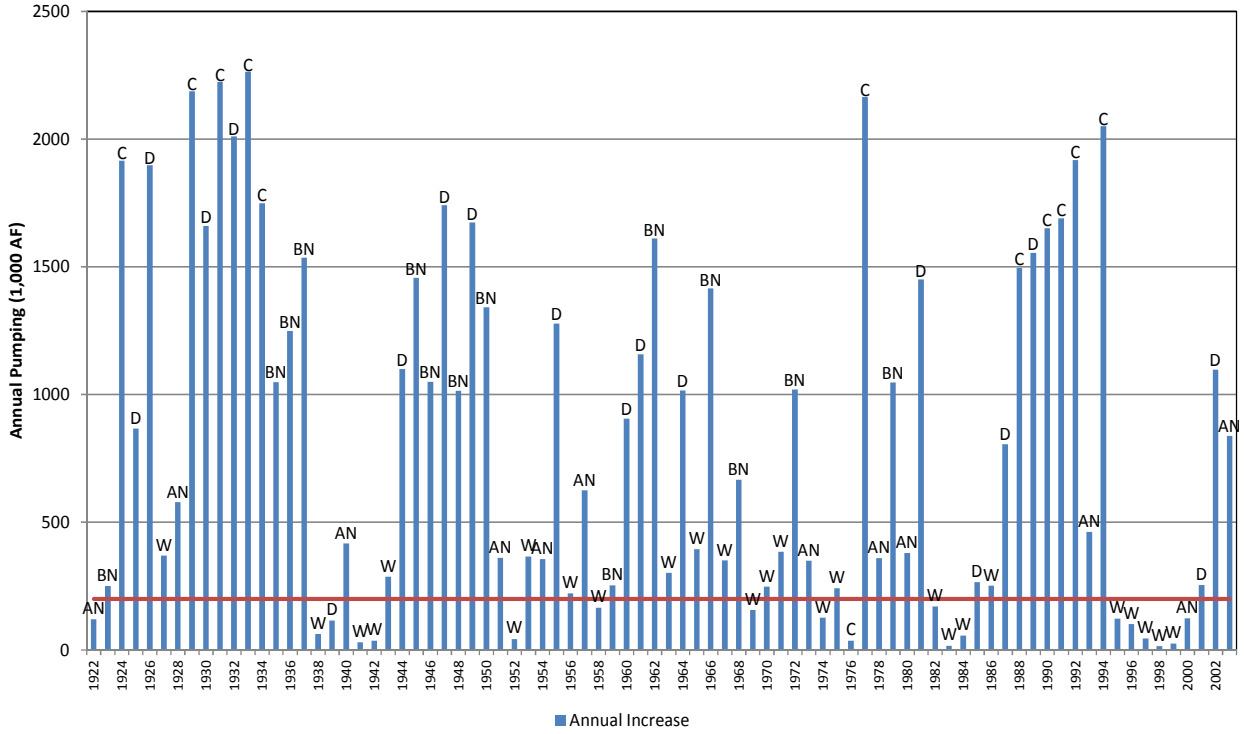
- Annual average existing (BO's) pumping according to CalSim II (very rough) = 2.385 MAF.
- Average annual pumping with SWRCB DFC = 3.198 MAF.
- Average annual change in groundwater pumping is 814 TAF.

There are a large number of factors affecting the interrelationship between groundwater levels and pumping, stream-groundwater interaction, deep percolation of applied water, percolation of precipitation, and natural recharge; making it difficult to speculate how much additional pumping, recharge, and fallowing would occur. Therefore, determining the appropriate equilibrium of these factors is difficult, if not impossible, under existing conditions, and is even more difficult under the SWRCB DFC.

Groundwater pumping is increased during dry and critical years, and is believed that increases in pumping could not be sustained. In the past during dry and critical years there have been groundwater substitution water transfers. A reasonable assumption is that some level of increased pumping may occur under SWRCB DFC conditions. For the purpose of this analysis, and due to the historical transfers and the proposed SWRCB Bay-Delta Hearing Phase 8 Settlement, it may be reasonable to assume that up to 200,000 AF of increased pumping may occur.

Annual limit of increased groundwater pumping is 200,000 AF indicated by the red line on the chart below. The amount of increased pumping used in the hydropower analysis is the minimum of 200,000 AF or the annual increase displayed **(Figure 23)**.

Figure 23 - Annual Change in Groundwater Pumping in Sacramento Valley - SWRCB DFC minus Existing (BO's)



Shasta storage would het dead pool in close to 60 percent of all years. Even in years when storage is above minimum it would be impossible to satisfy upper Sacramento River temperature objectives in almost every year. It may be possible to meet temperature objectives in less than 10 percent of years; however reductions in Keswick release from June through November will cause increased warming making it more difficult to meet objectives **(Figure 23).**

Figure 24 - End of September Shasta Storage

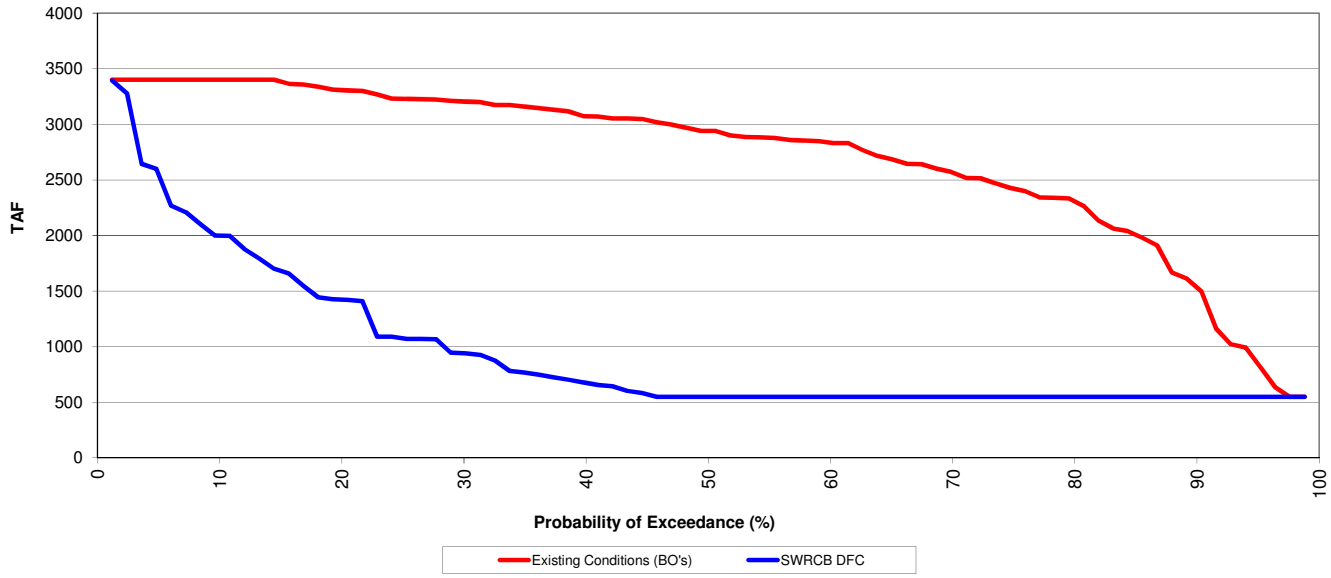


Figure 25 - Change in Keswick Release - SWRCB DFC minus Existing (BO's)

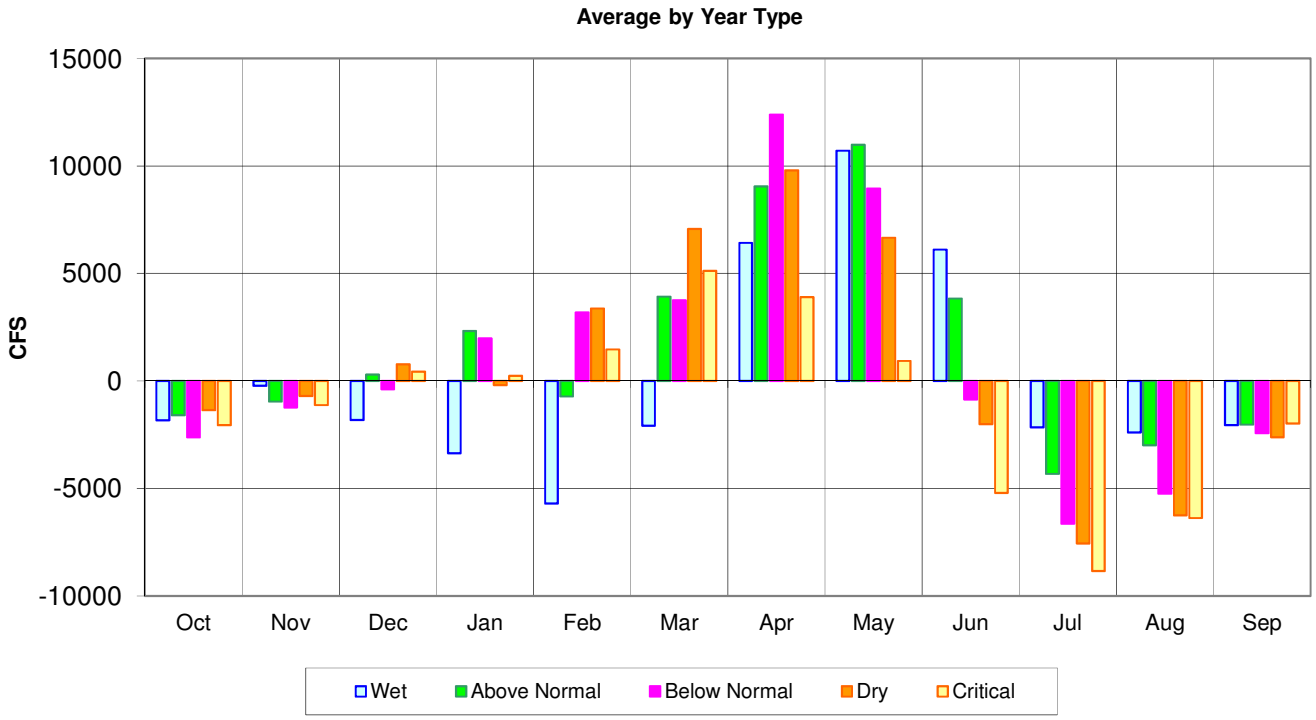


Figure 26 - Monthly Shasta Storage for Existing (BO's) and SWRCB DFC

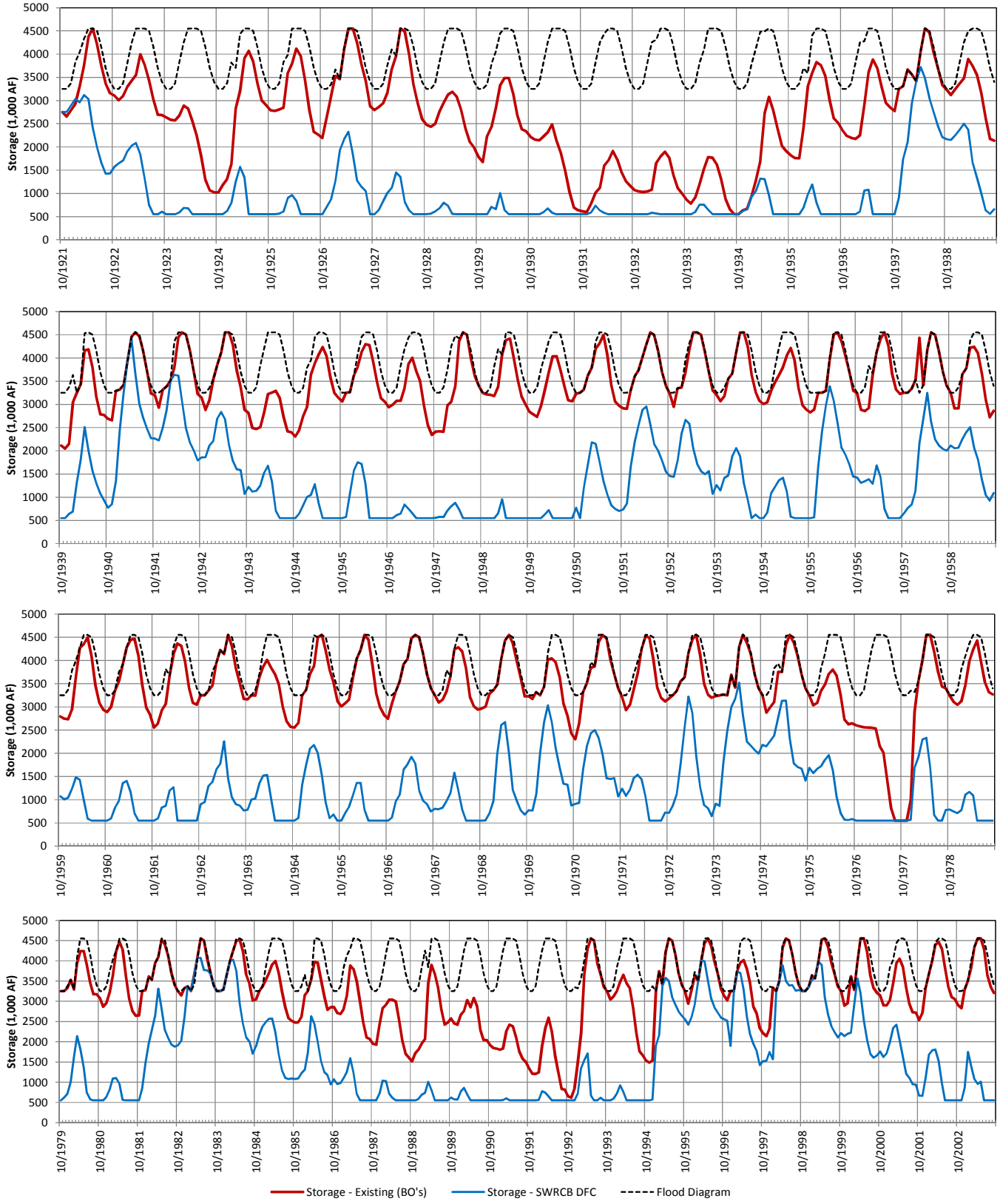
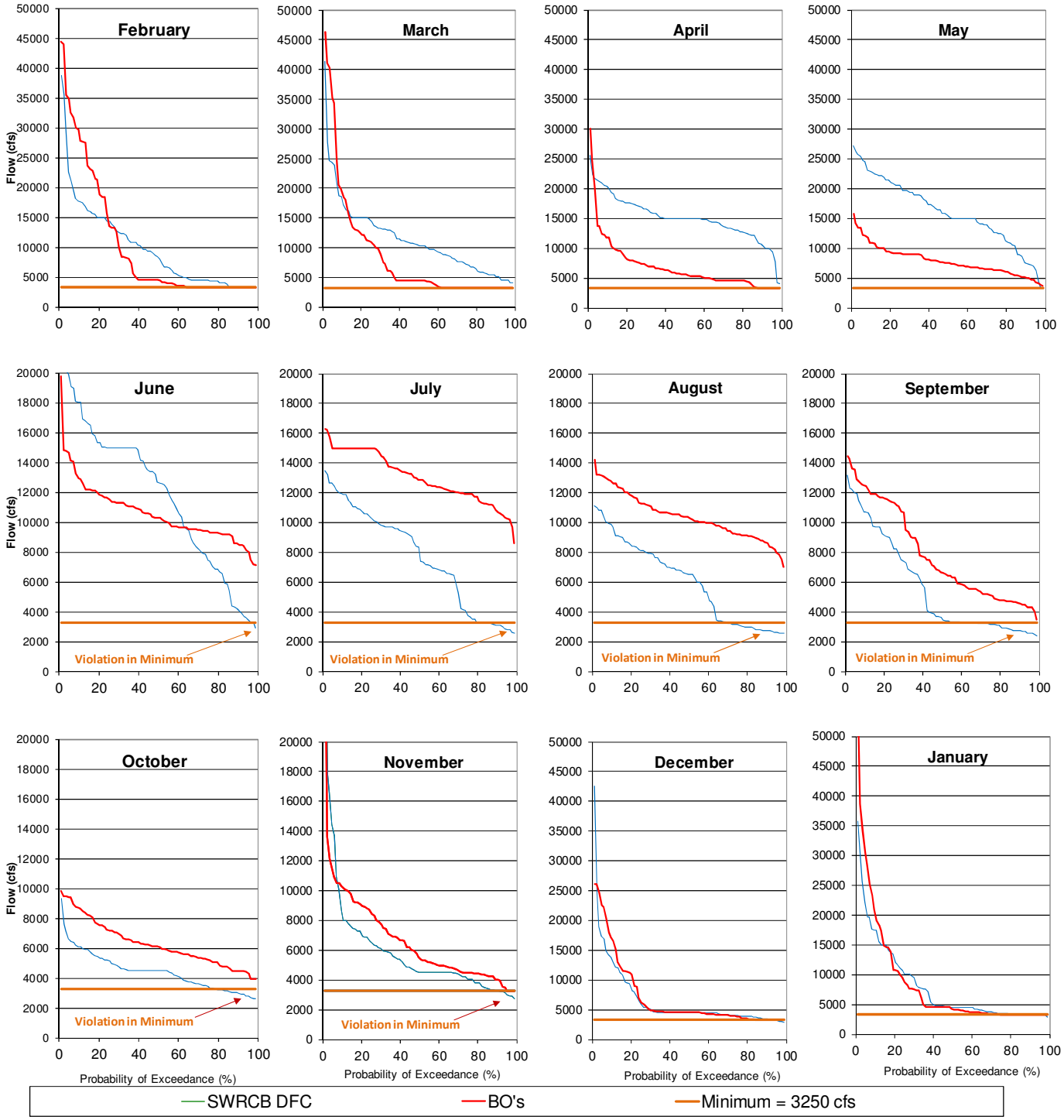
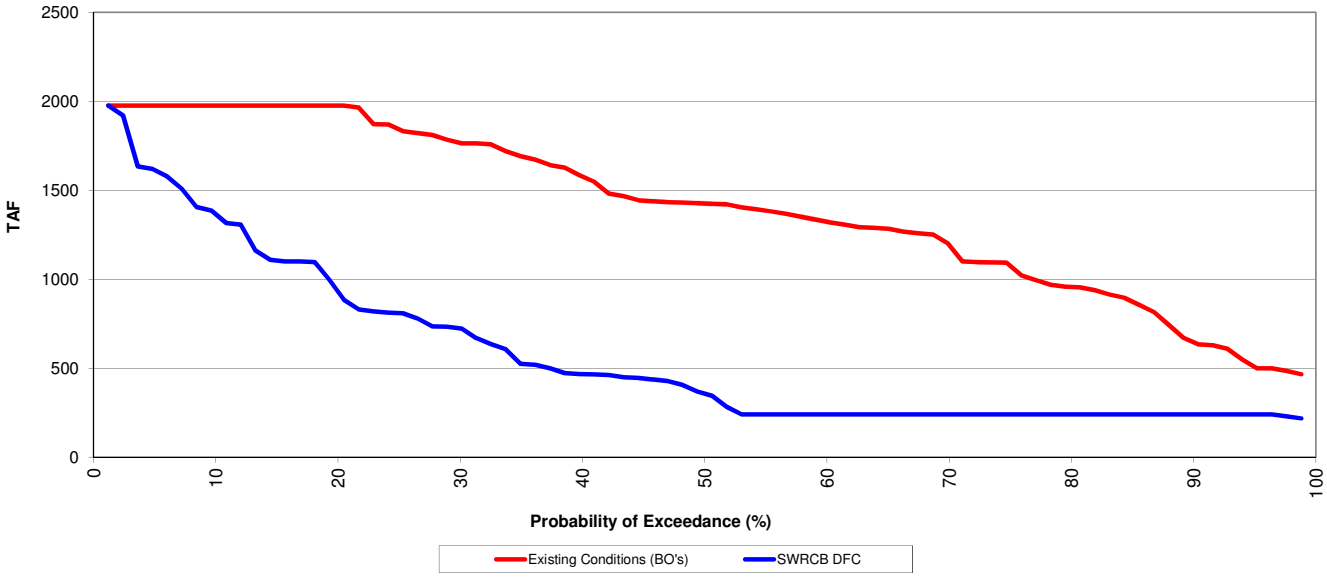


Figure 27 - Average Monthly Sacramento River Flow Below Keswick for Existing (BO's) and SWRCB DFC



There are often violation in the minimum flow requirement below Keswick, when this occurs both Shasta and Trinity Reservoirs are at dead storage (**Figure 28**).

Figure 28 - End of September Trinity Storage



The SWRCB DFC are very extreme and CalSim II was not designed to address these circumstances, therefore the logic that balances Trinity and Shasta Reservoir storage properly for existing (BO's) conditions may not be suitable when operating to satisfy the SWRCB flow criteria. Logic may need to be developed that isolates the Trinity operation from the Sacramento River Basin. Because Trinity River imports are increased in the SWRCB DFC model simulation there is likely an underestimate of hydropower impacts (**Figure 29**).

Figure 29 - Monthly Change in Trinity River Import - SWRCB DFC minus Existing (BO's)

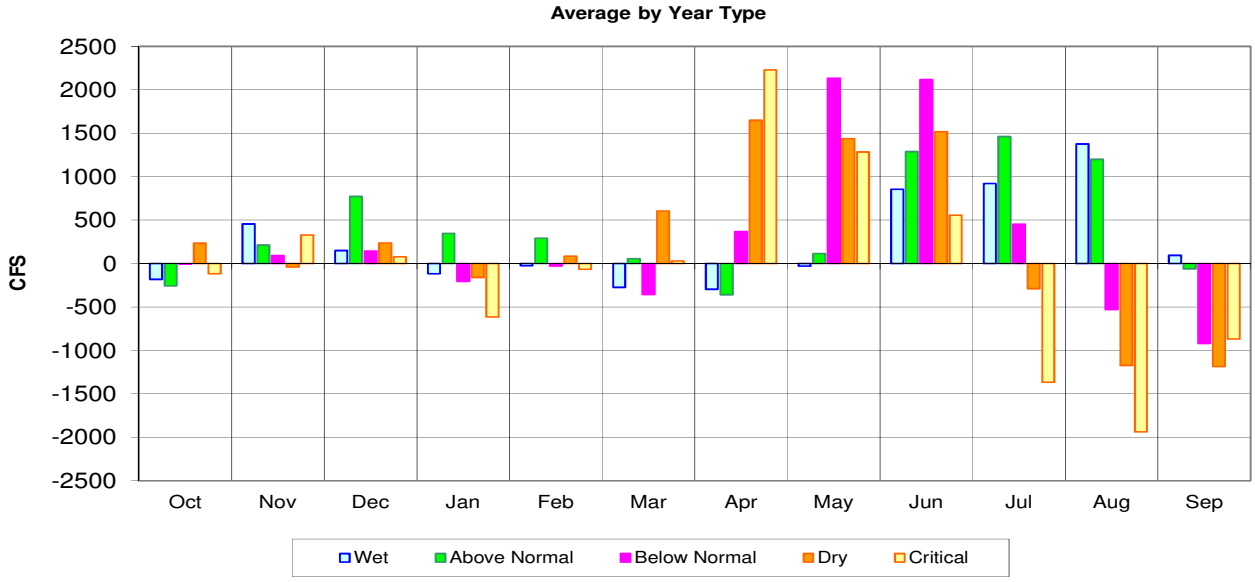


Figure 30 - Annual Change in Trinity River Import - SWRCB DFC minus Existing (BO's)

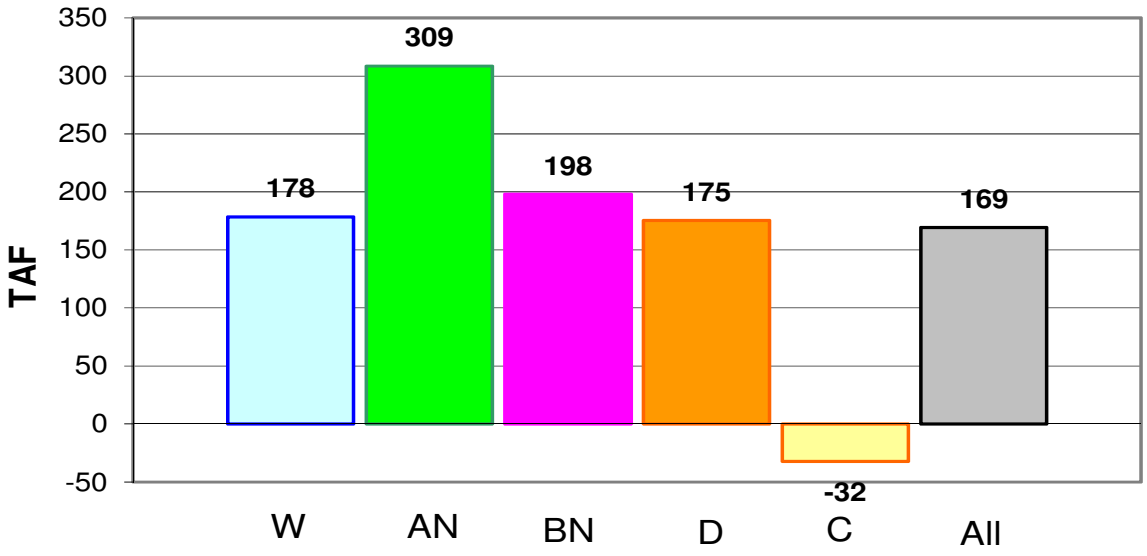
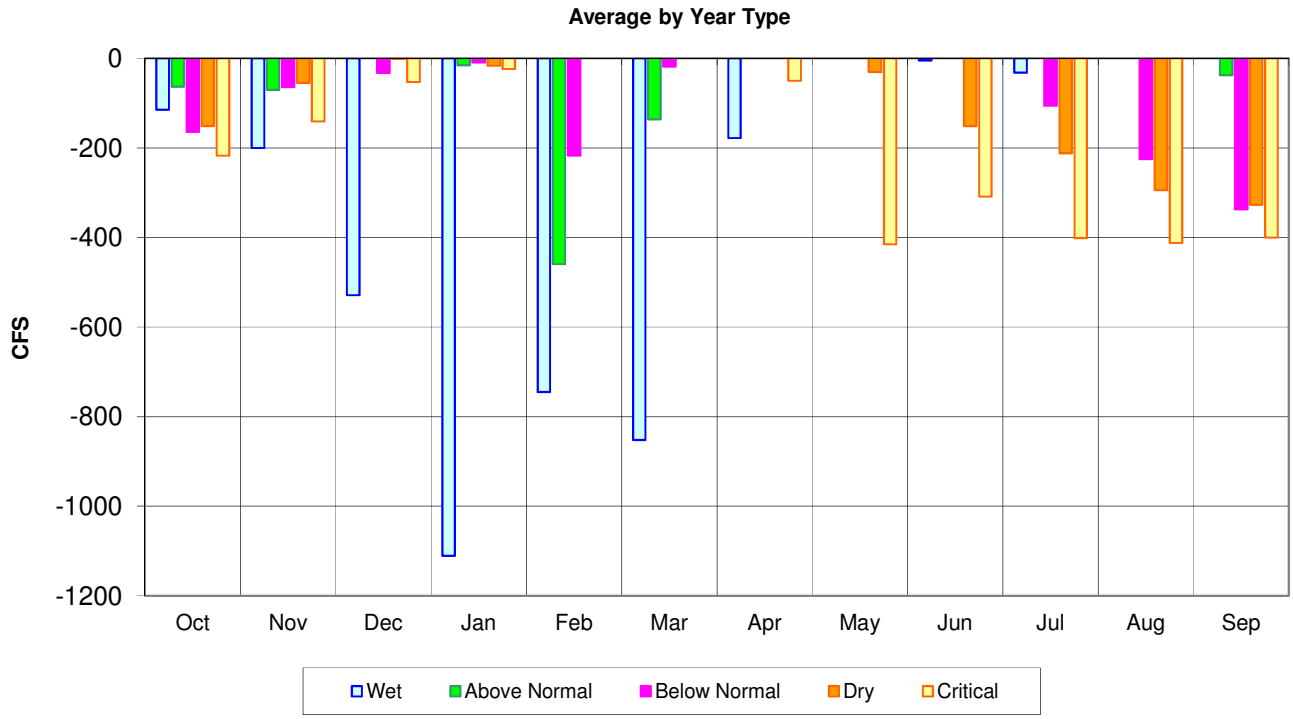


Figure 31 - Monthly Change in Trinity River Flow - SWRCB DFC minus Existing (BO's)



There is an average annual decrease of 129 TAF release to the Trinity River, this differs from the increase Trinity River import of 169 TAF because the end of simulation storage in Trinity is 1.5 MAF lower (**Figure 32**).

Figure 32 - Annual Change in Trinity River Flow - SWRCB DFC minus Existing (BO's)

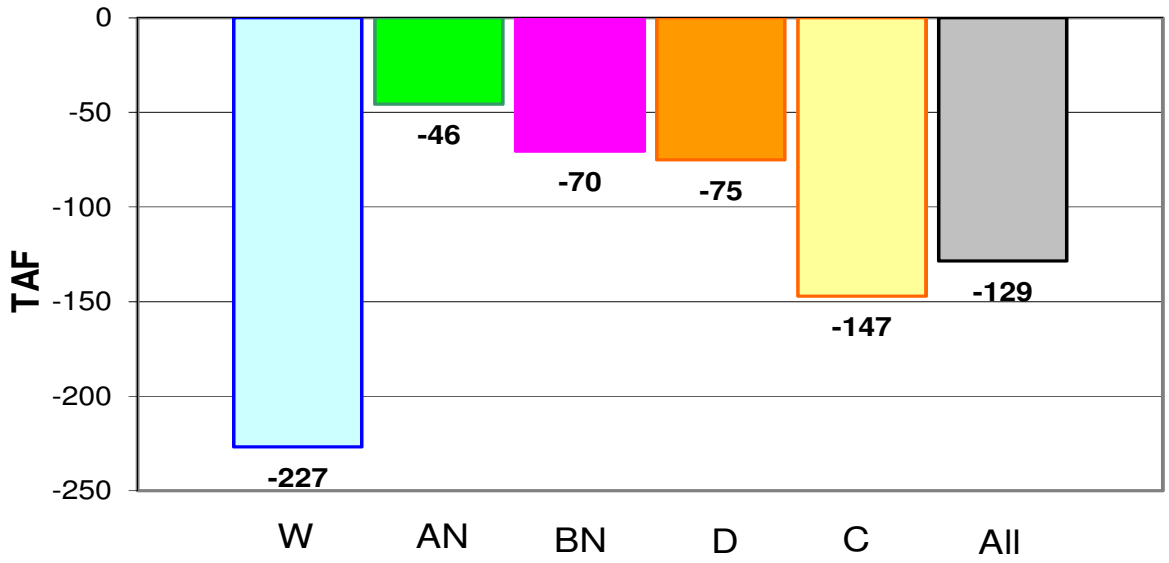
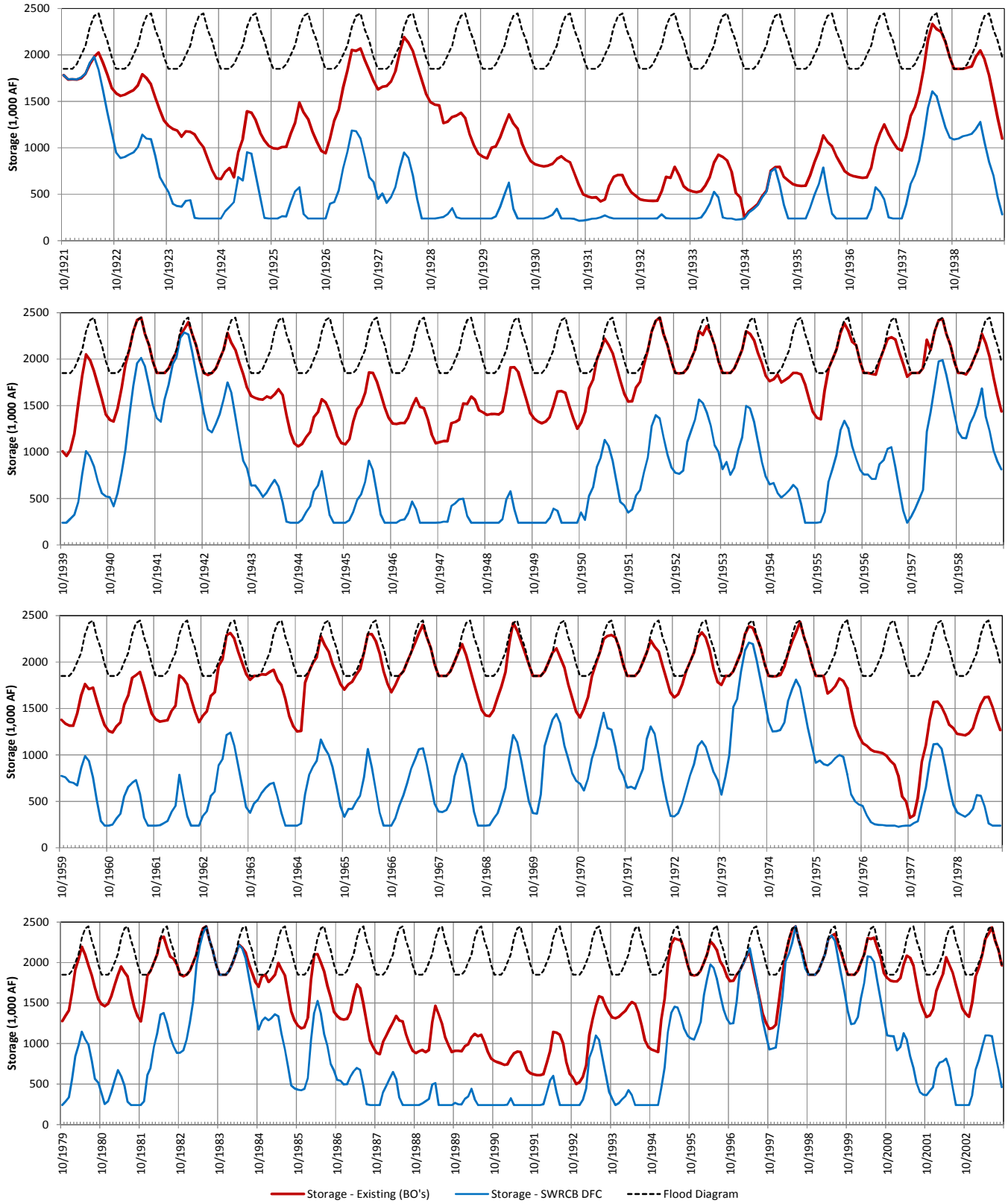


Figure 33 - Monthly Trinity Storage for Existing (BO's) and SWRCB DFC



Roughly 50 percent of the time Folsom would end the water year at dead storage (**Figure 34**).

Figure 34 - End of September Folsom Storage

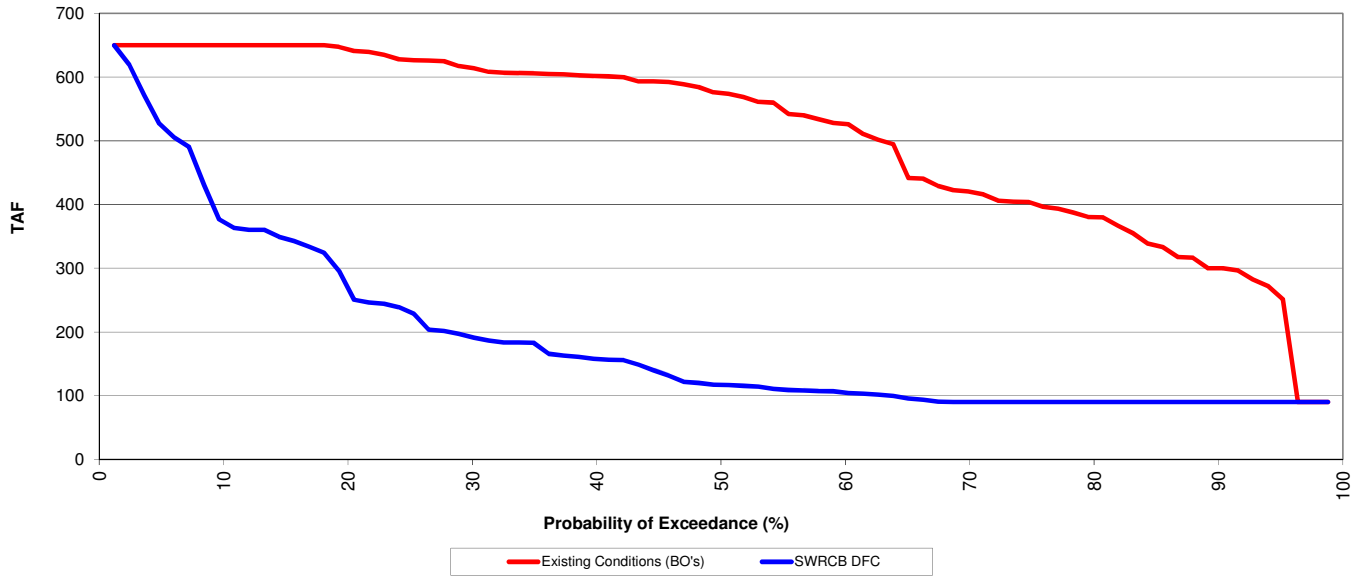


Figure 35 - Change in American River Flow below Nimbus - SWRCB DFC minus Existing (BO's)

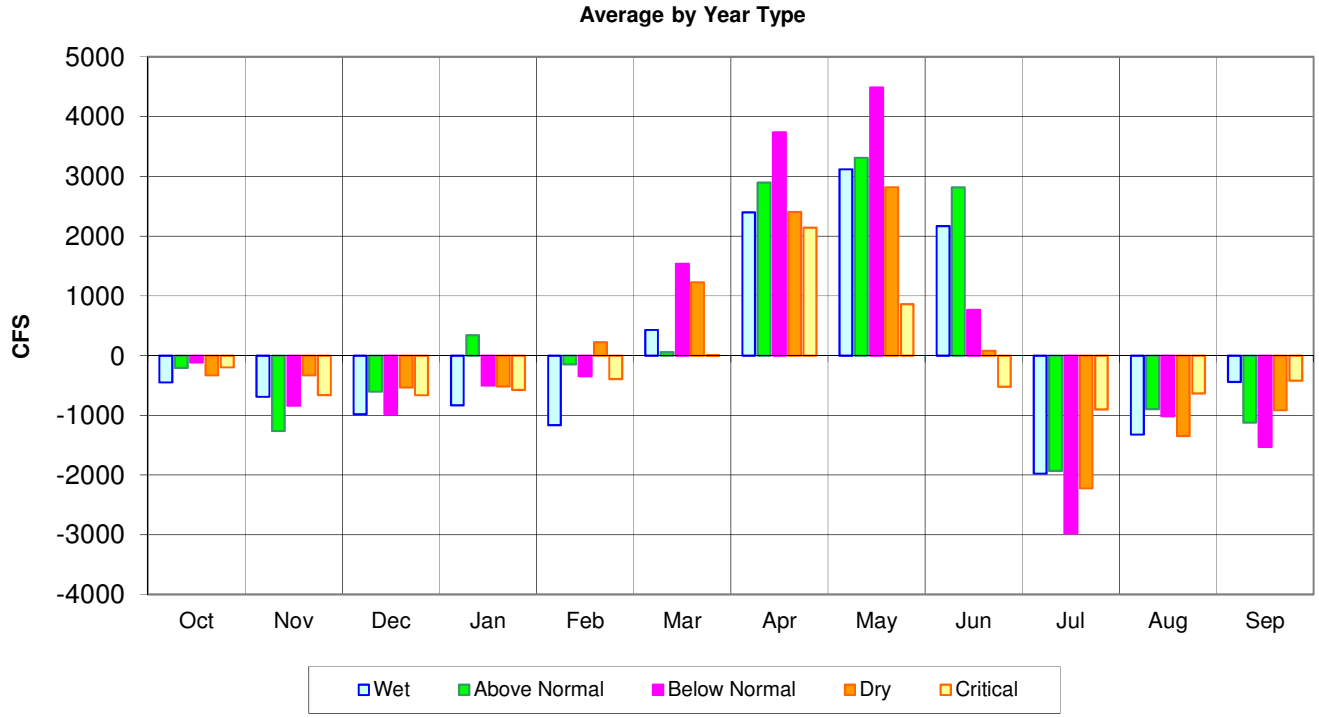


Figure 36 – Monthly Folsom Storage for Existing (BO's) and SWRCB DFC

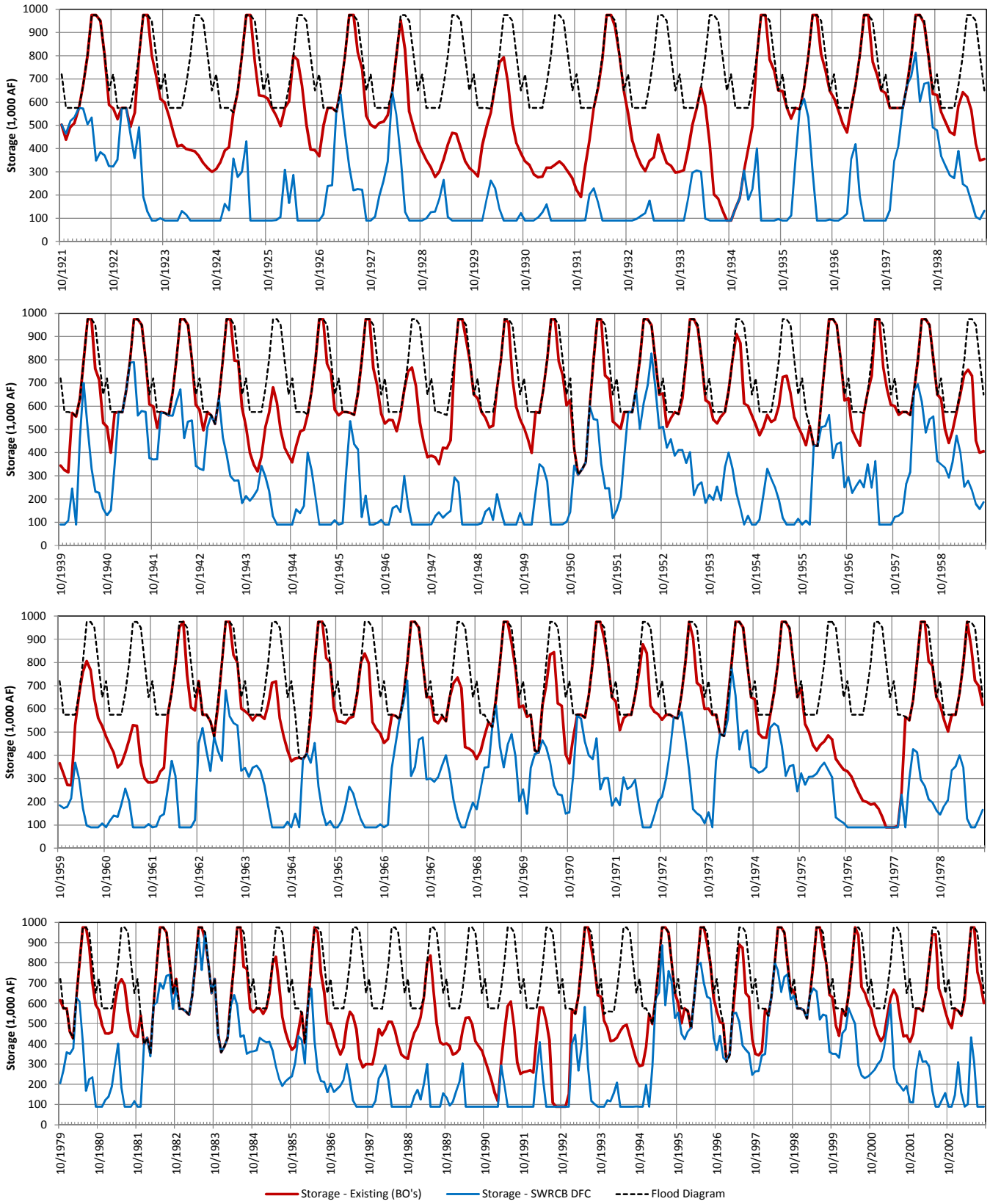


Figure 37 – Average Monthly American River Flow below Nimbus for Existing (BO's) and SWRCB DFC

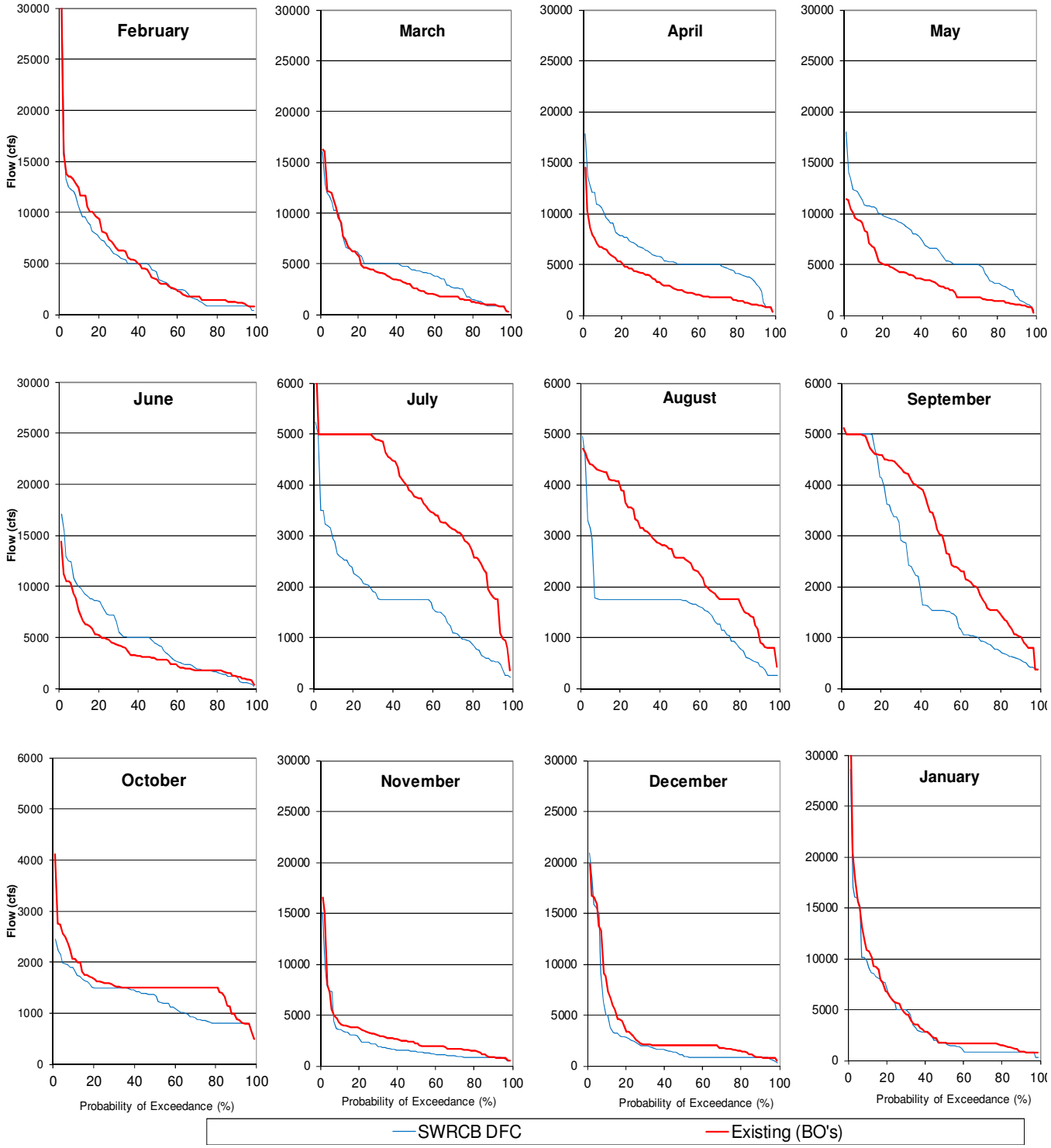


Figure 38 - End of September Oroville storage

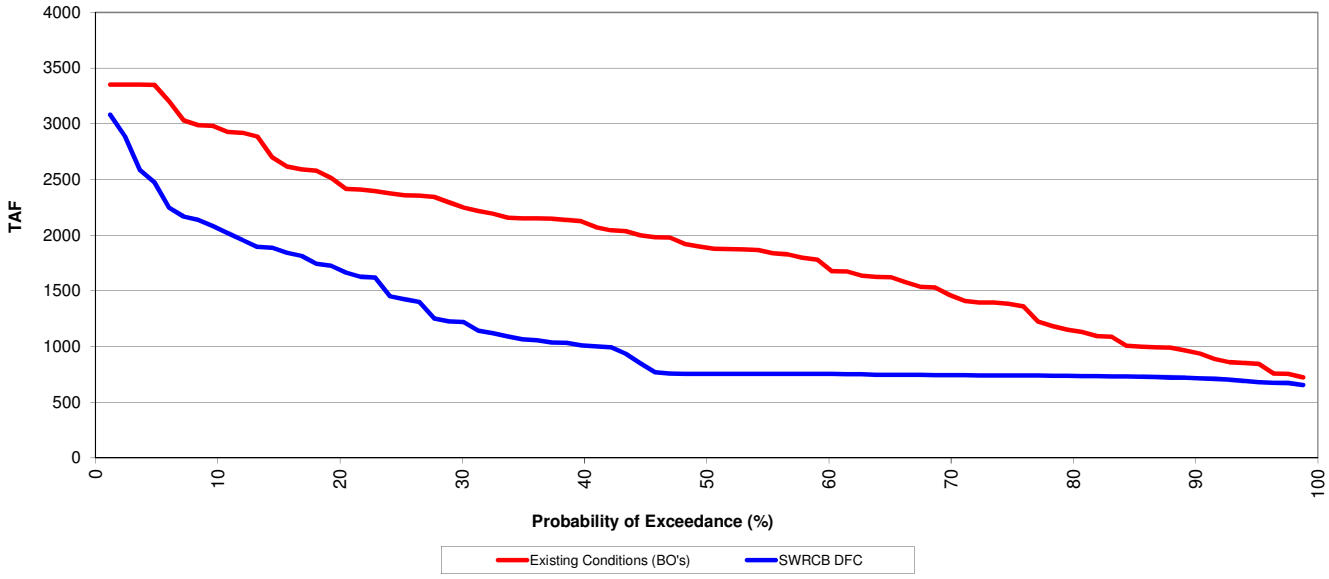


Figure 39 - Change in Feather River Flow below Thermalito - SWRCB DFC minus Existing (BO's)

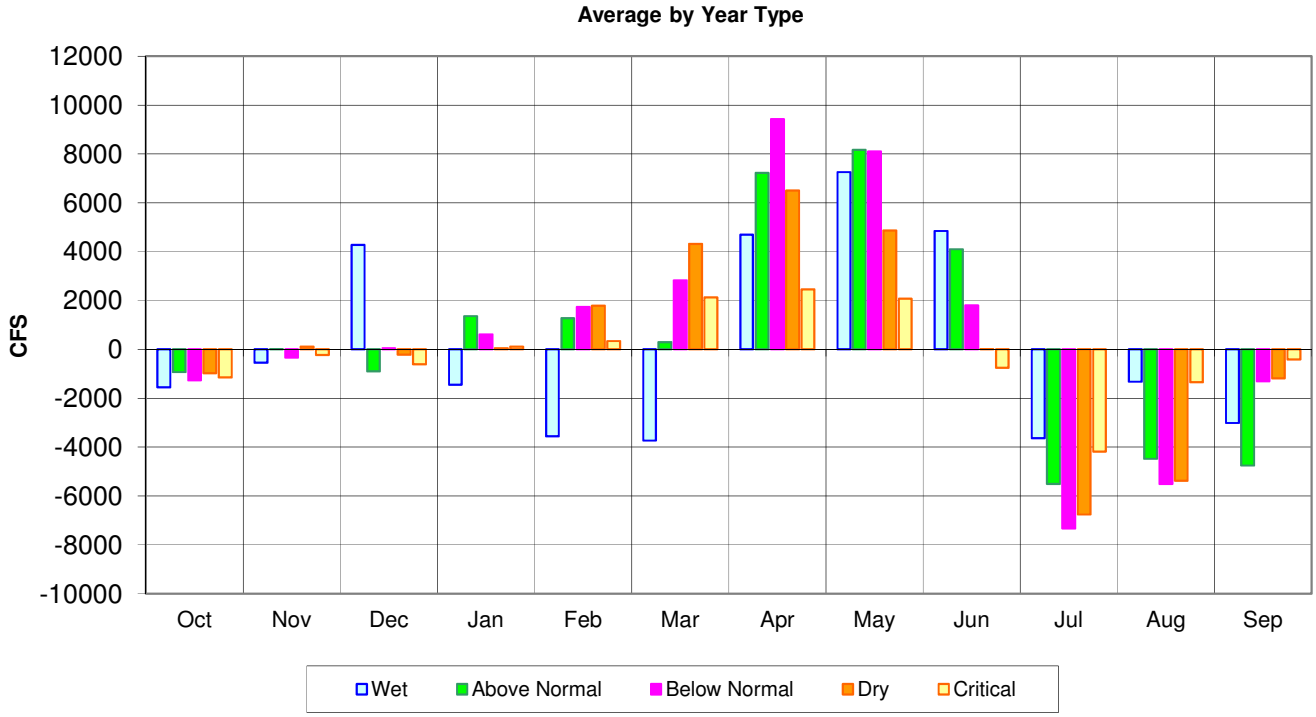


Figure 40 - Monthly Oroville Storage for Existing (BO's) and SWRCB DFC

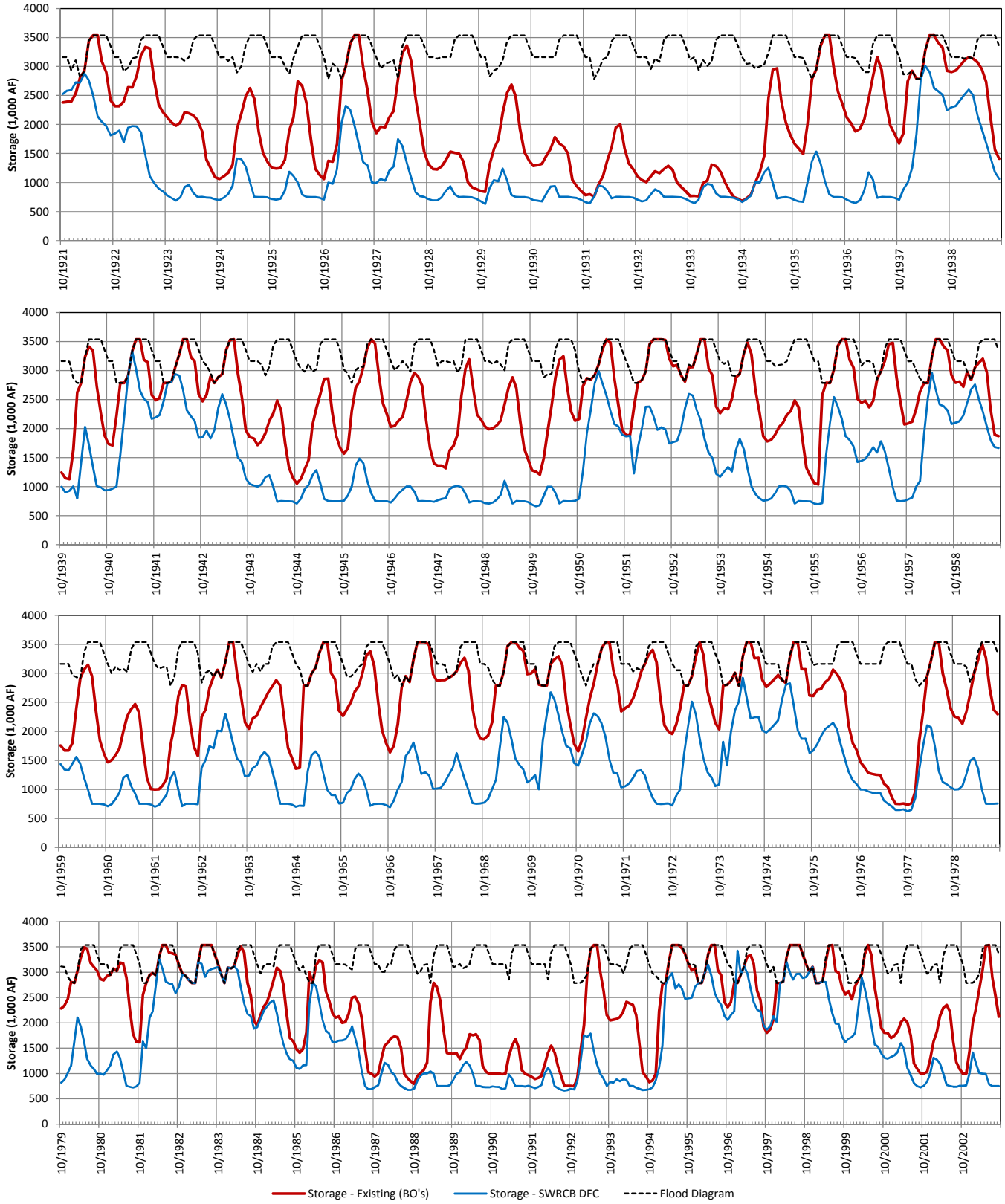


Figure 41 - Average Feather River Flow below Thermalito for Existing (BO's) and SWRCB DFC

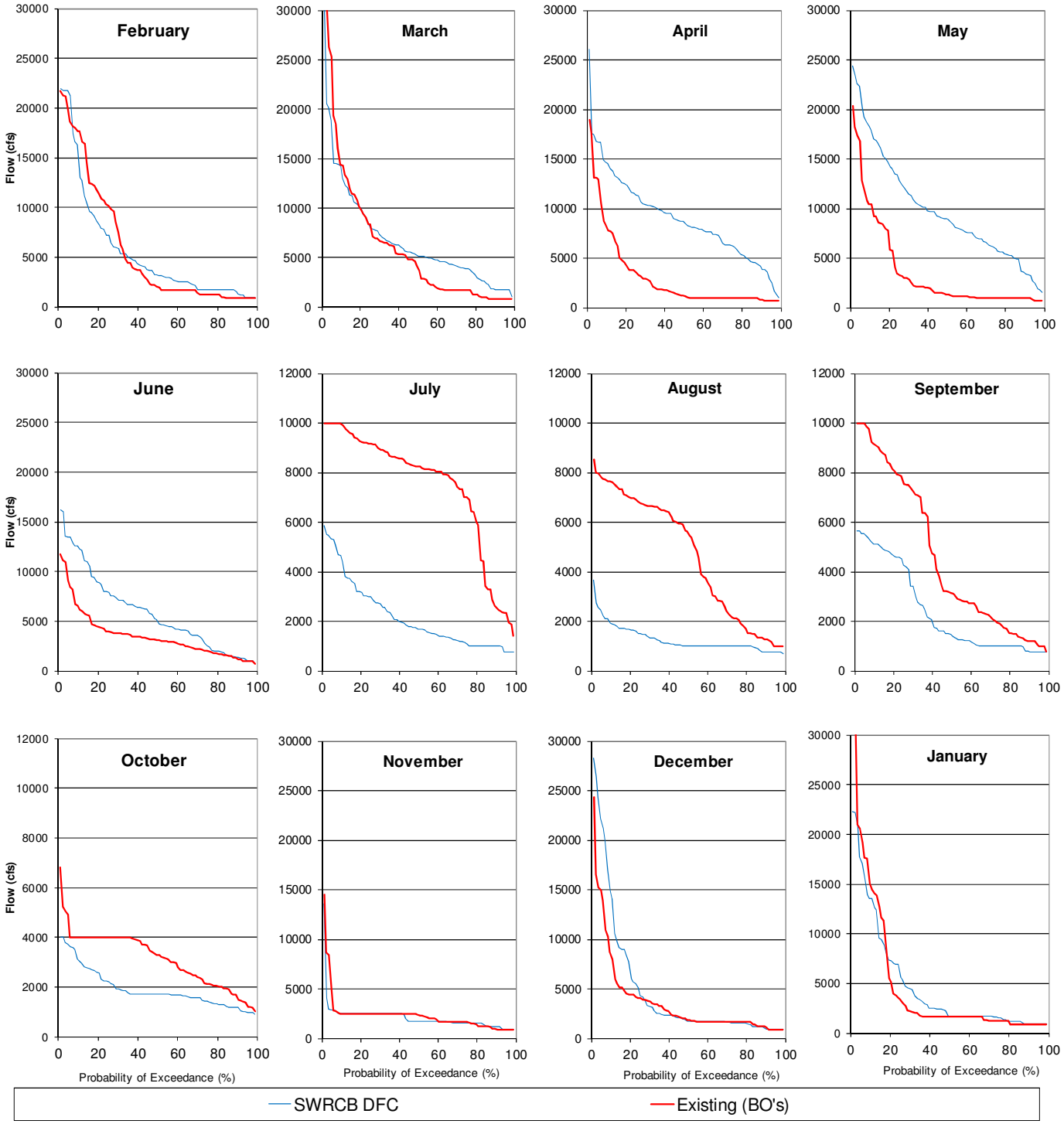


Figure 42 - Change in San Joaquin River at Vernalis - SWRCB DFC minus Existing (BO's)

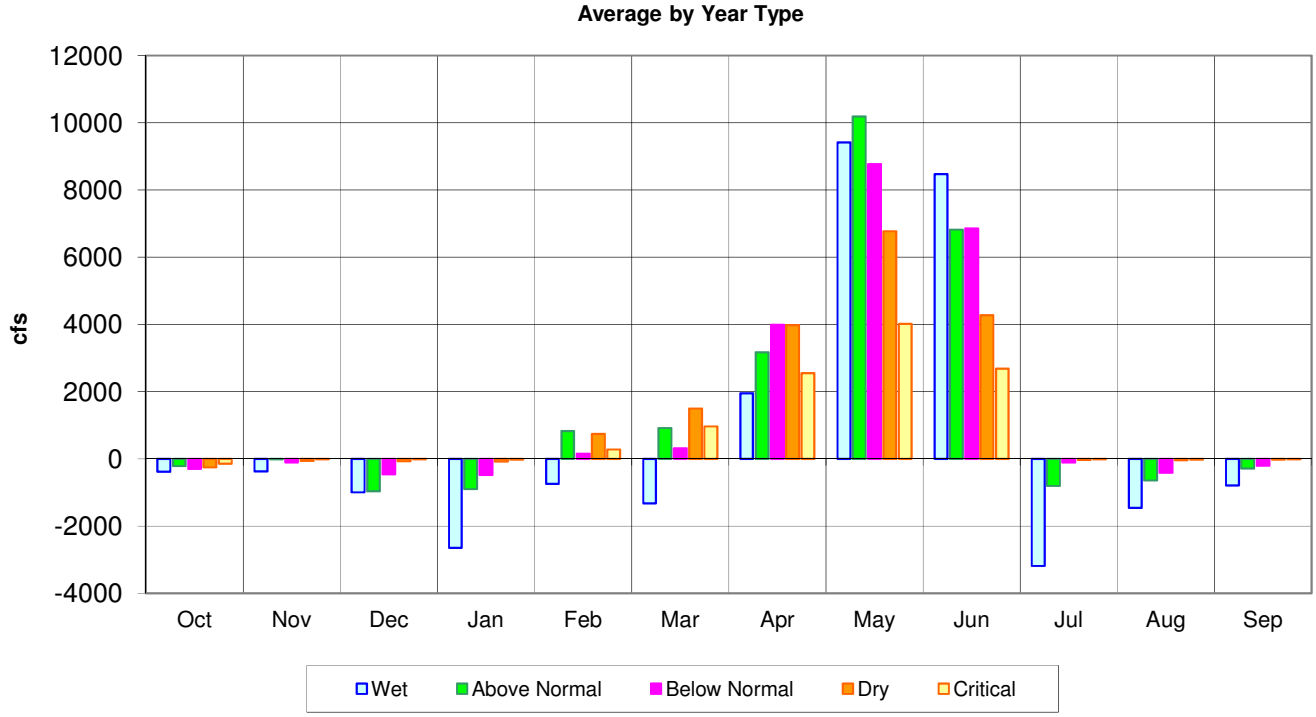


Figure 43 - Annual Change in San Joaquin River at Vernalis - SWRCB DFC minus Existing (BO's)

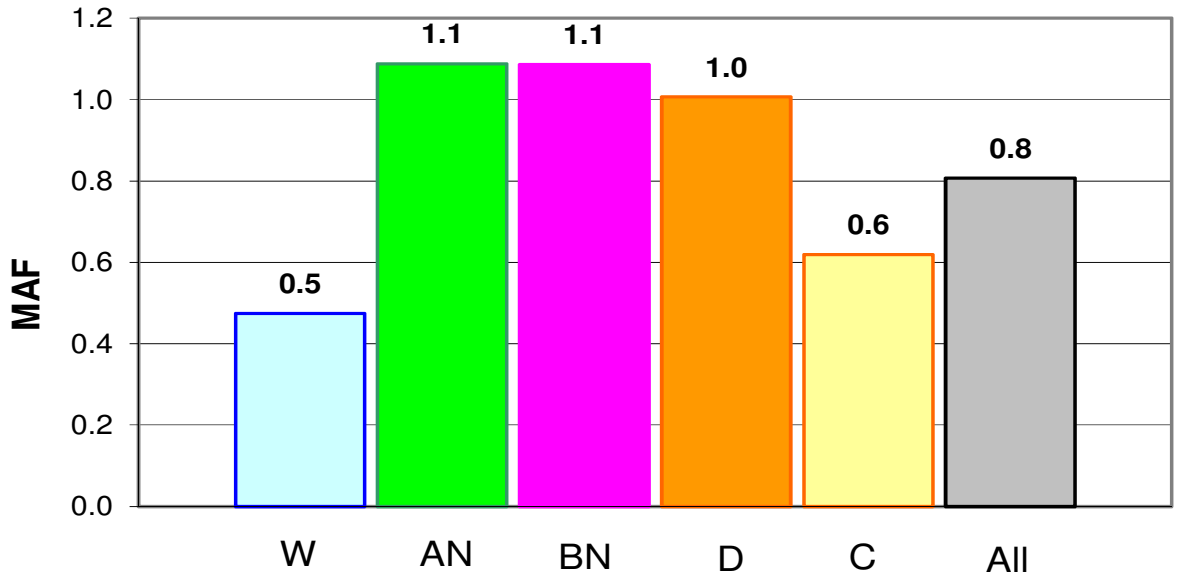


Figure 44 - Monthly San Joaquin River Flow at Vernalis for Existing (BO's) and SWRCB DFC

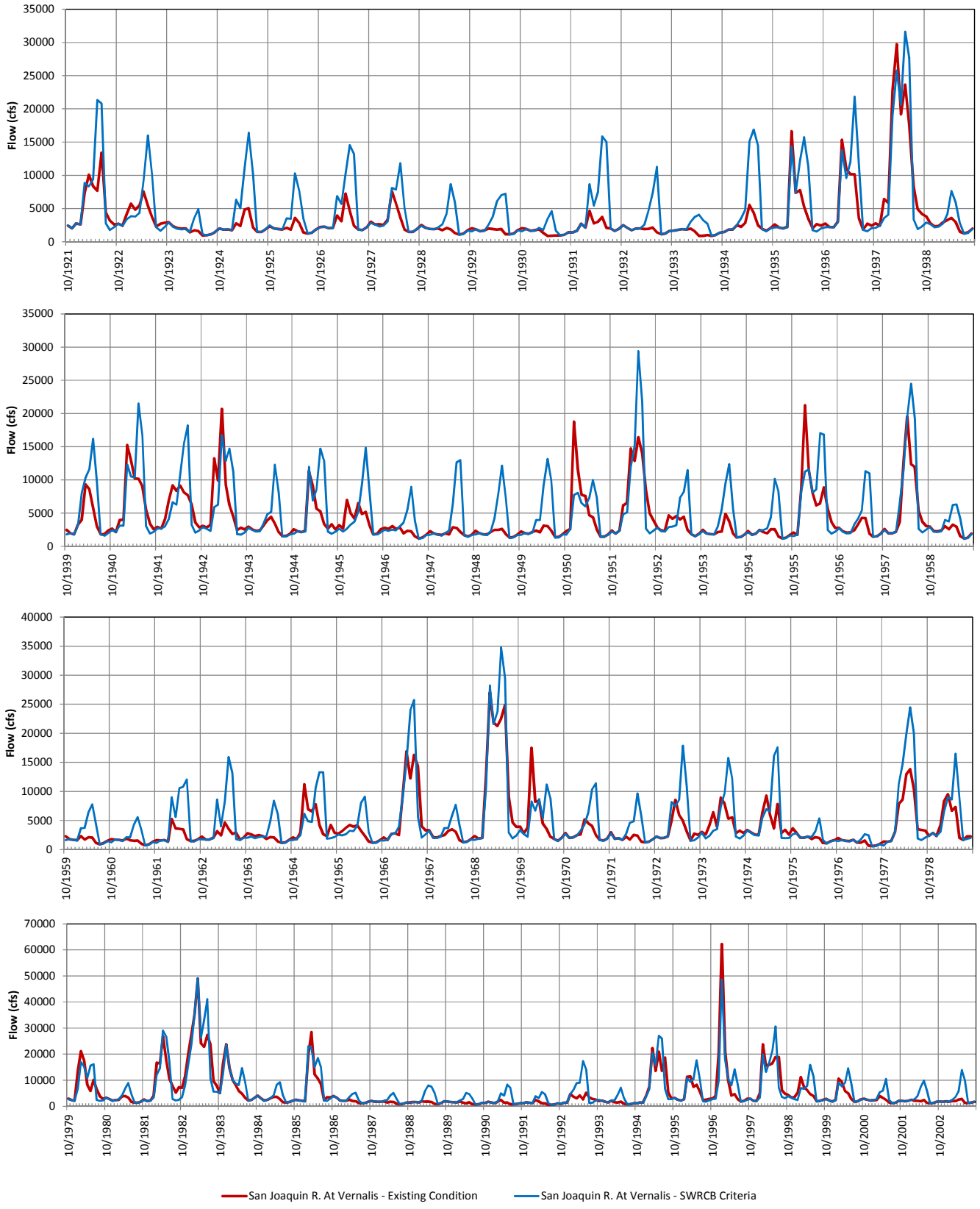


Figure 45 is shown with the SWRCB DFC San Luis Reservoir fills in one year (1983).

Figure 45 - San Luis Reservoir Annual Maximum Storage for Existing (BO's) and SWRCB DFC

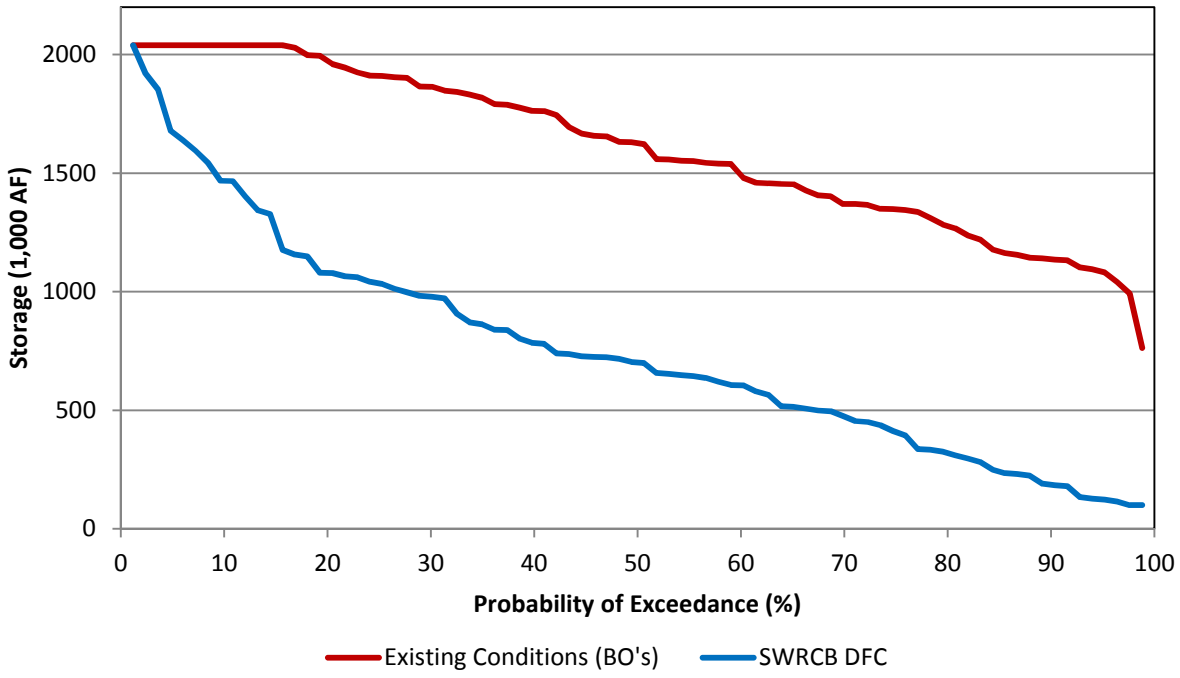


Figure 46 is shown with the SWRCB DFC San Luis reaches dead pool in all but 2 years (1983 and 1965) and remains at dead pool for several months in most years.

Figure 46 - San Luis Reservoir Annual Low Point in Storage for Existing (BO's) and SWRCB DFC

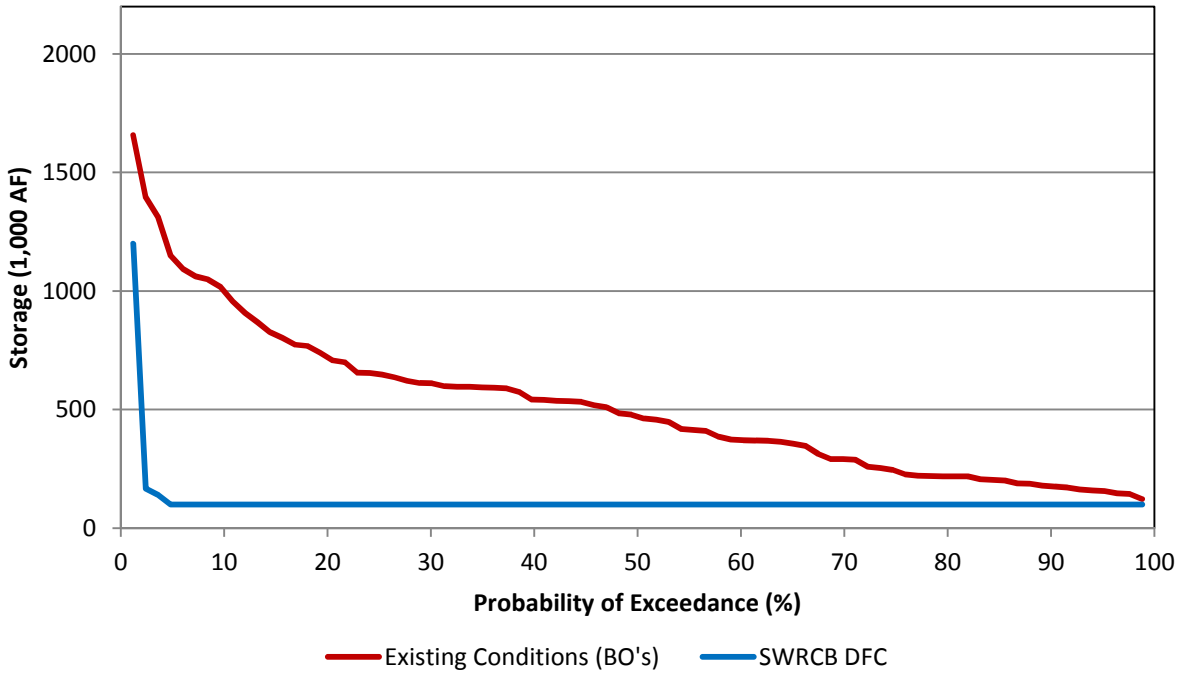
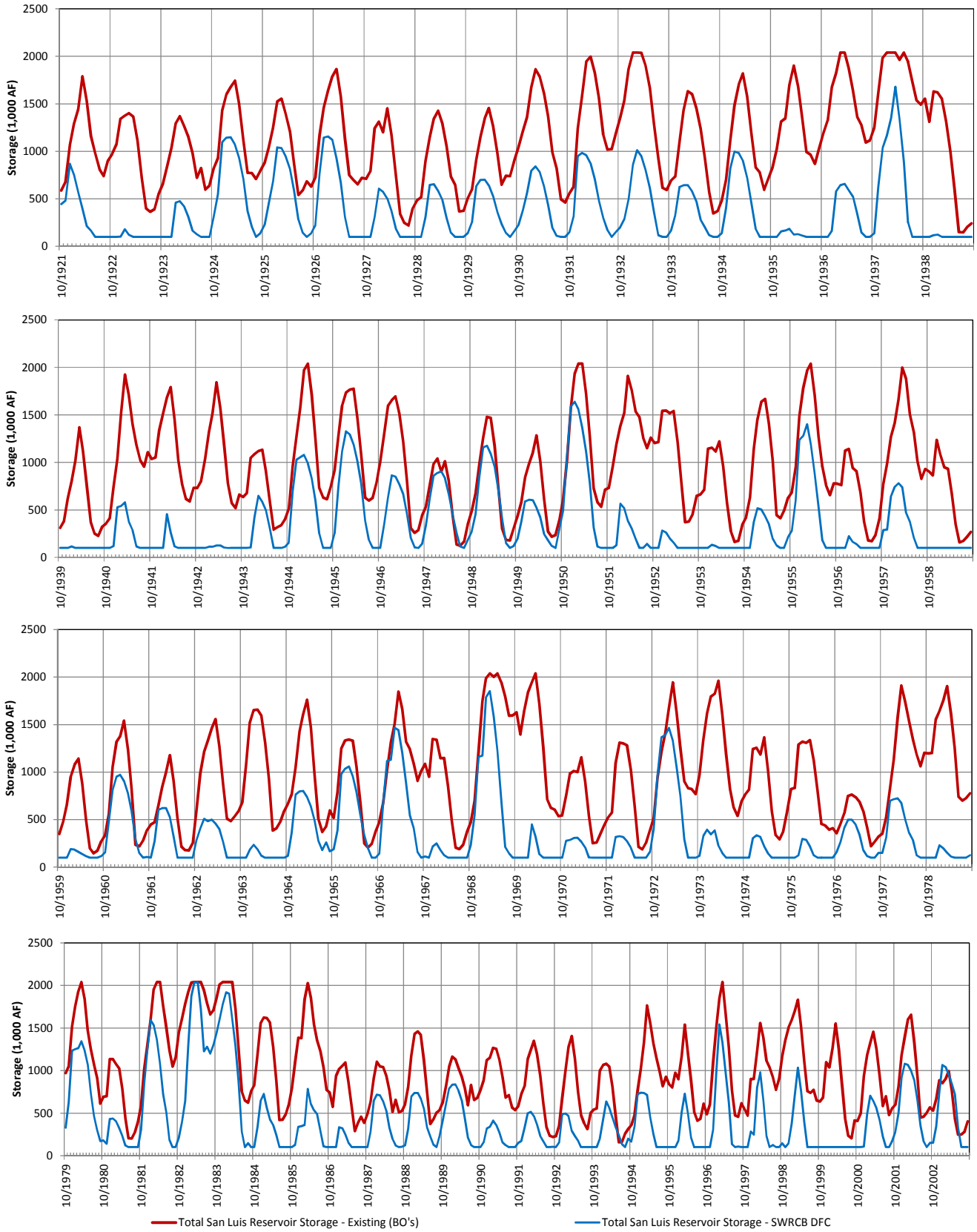
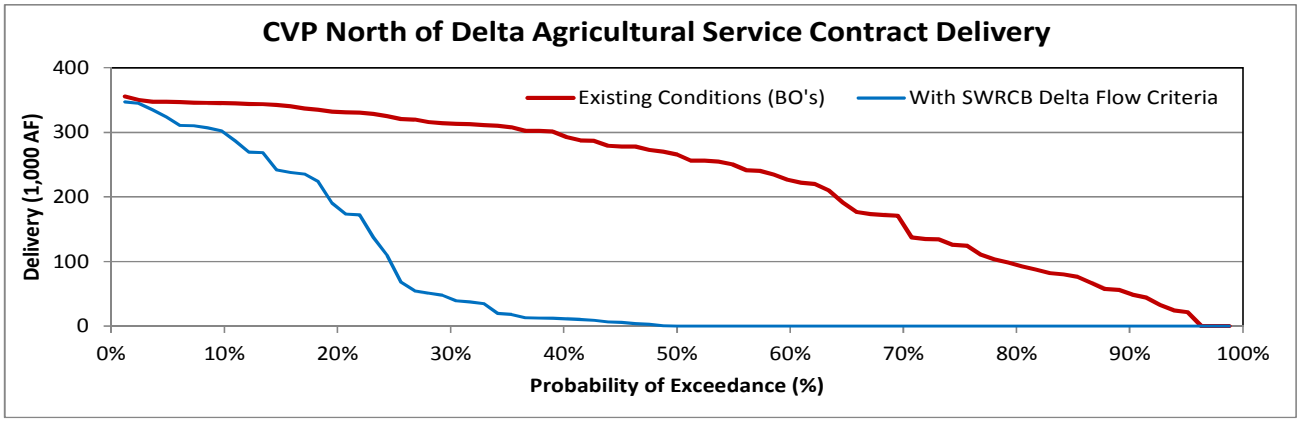
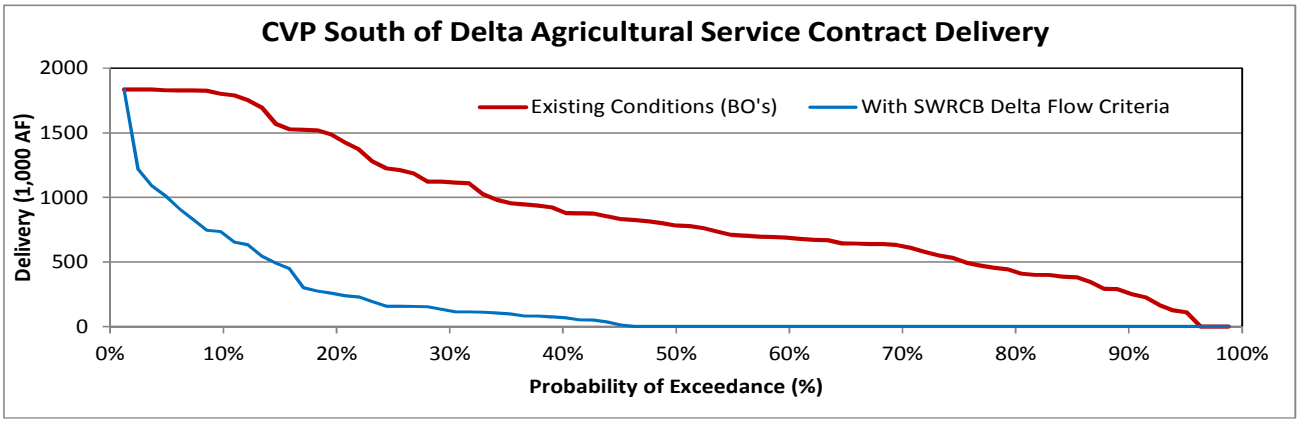
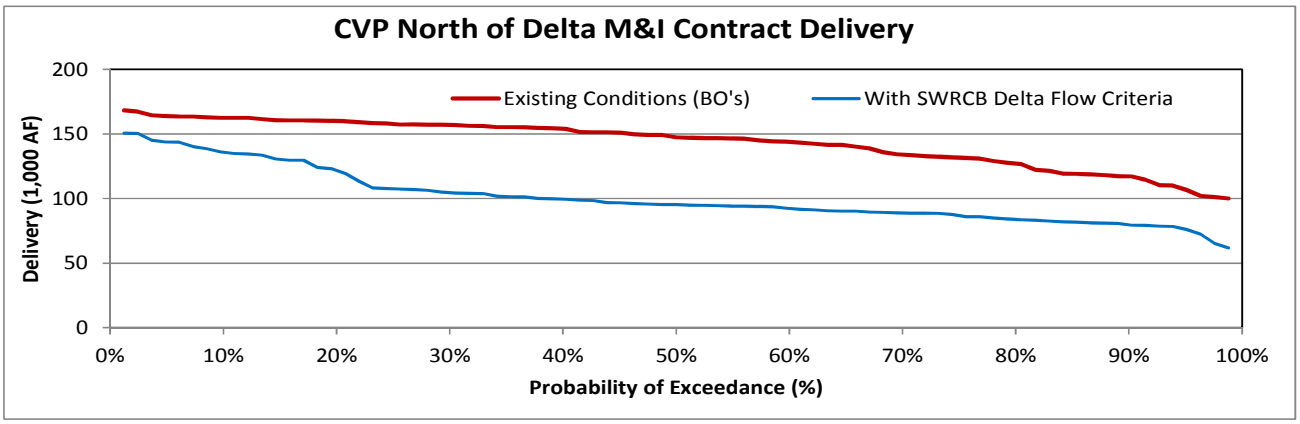


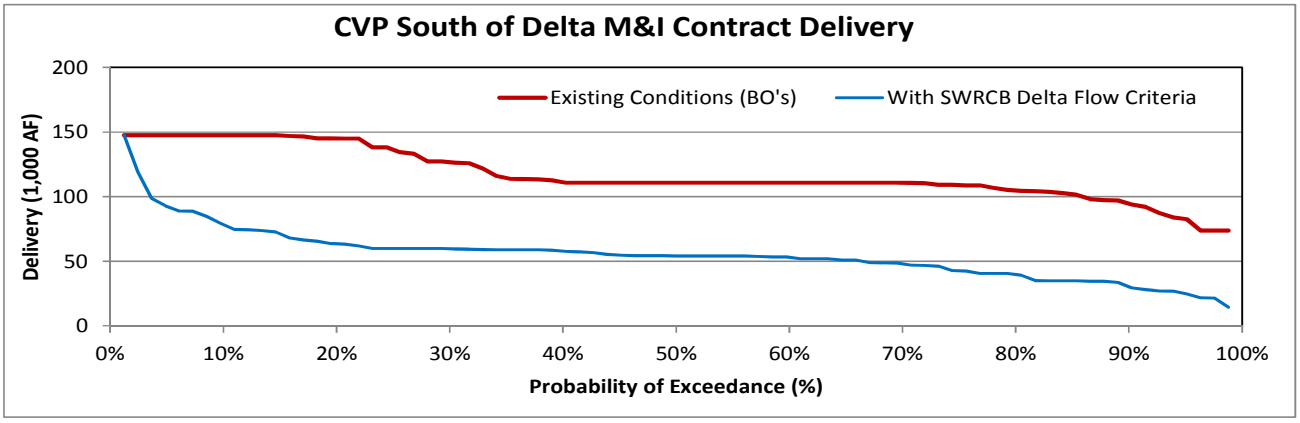
Figure 47 - Total San Luis Reservoir Storage for Existing (BO's) and SWRCB DFC

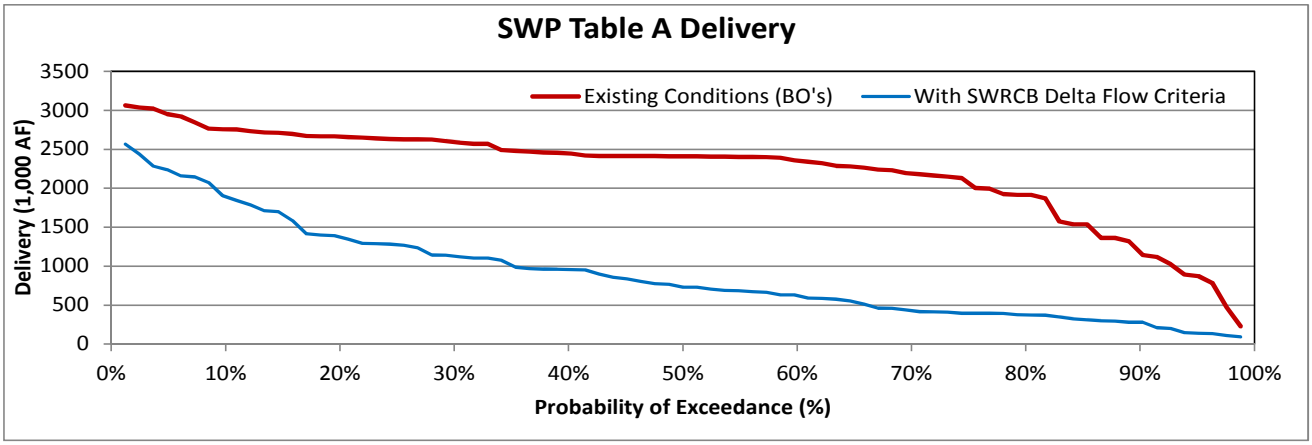


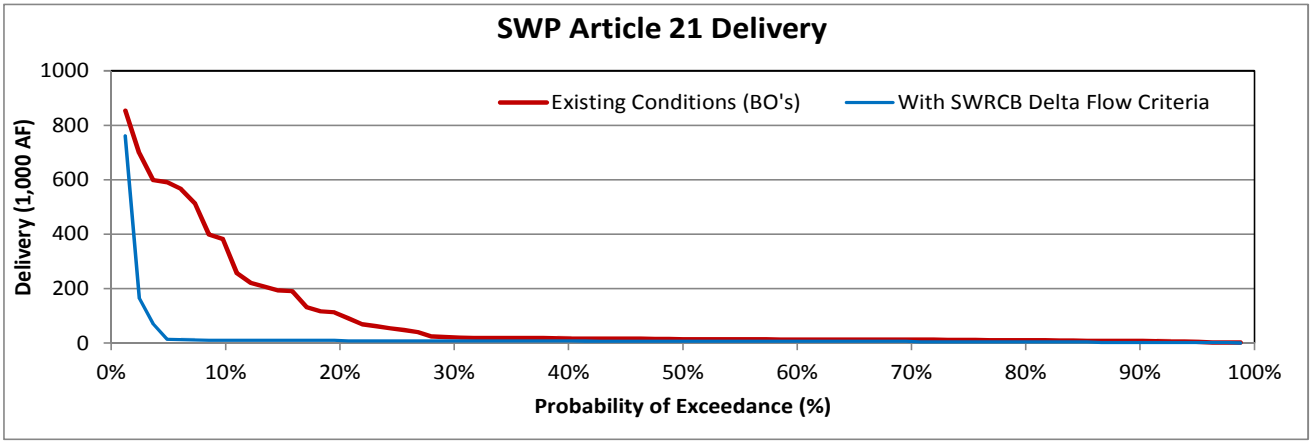

CVP North of Delta Agricultural Service Contract Delivery
Existing Conditions (BO's)
With SWRCB Delta Flow Criteria
Delivery (1,000 AF)
400
300
200
100
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability of Exceedance (%)

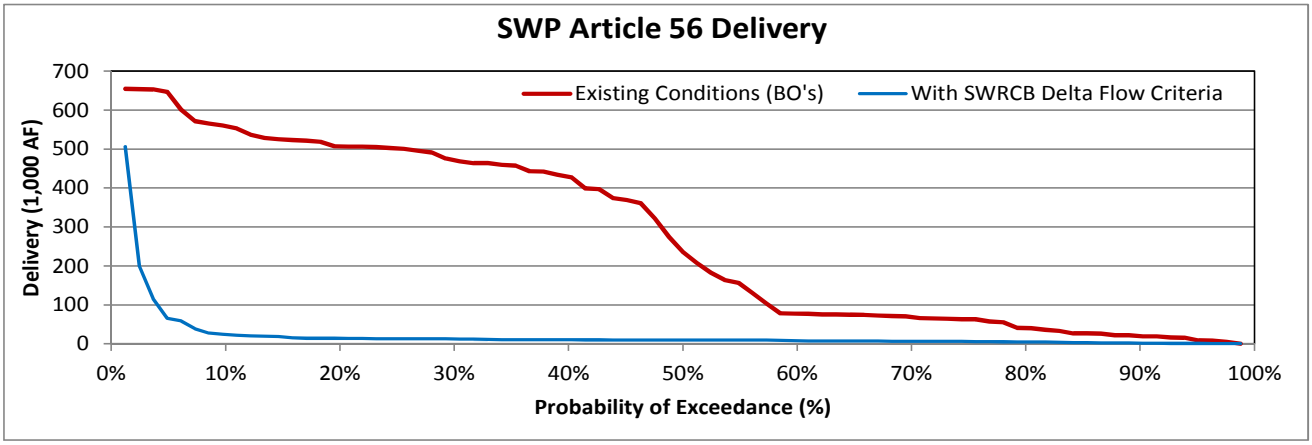

CVP South of Delta Agricultural Service Contract Delivery
Existing Conditions (BO's)
With SWRCB Delta Flow Criteria
Delivery (1,000 AF)
2000
1500
1000
500
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability of Exceedance (%)


CVP North of Delta M&I Contract Delivery
Existing Conditions (BO's)
With SWRCB Delta Flow Criteria
Delivery (1,000 AF)
200
150
100
50
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability of Exceedance (%)


CVP South of Delta M&I Contract Delivery
Existing Conditions (BO's)
With SWRCB Delta Flow Criteria
Delivery (1,000 AF)
200
150
100
50
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability of Exceedance (%)

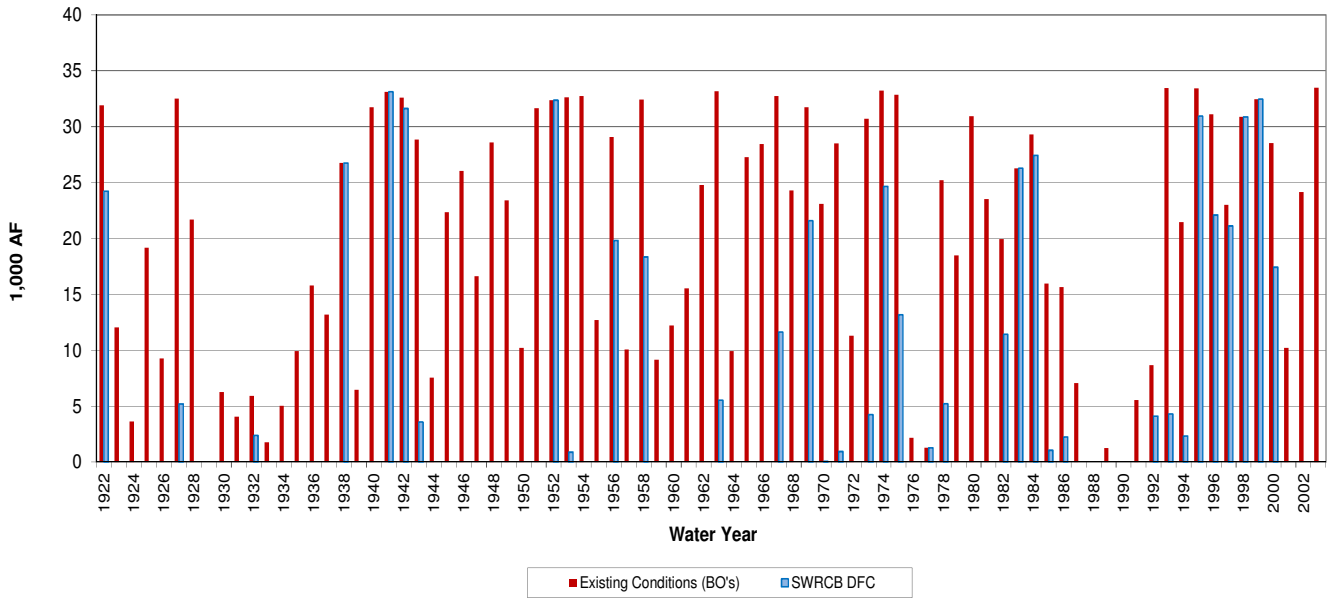

SWP Table A Delivery
Existing Conditions (BO's)
With SWRCB Delta Flow Criteria
Delivery (1,000 AF)
3500
3000
2500
2000
1500
1000
500
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability of Exceedance (%)


SWP Article 21 Delivery
Existing Conditions (BO's)
With SWRCB Delta Flow Criteria
Delivery (1,000 AF)
1000
800
600
400
200
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability of Exceedance (%)


SWP Article 56 Delivery
Existing Conditions (BO's)
With SWRCB Delta Flow Criteria
Delivery (1,000 AF)
700
600
500
400
300
200
100
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Probability of Exceedance (%)

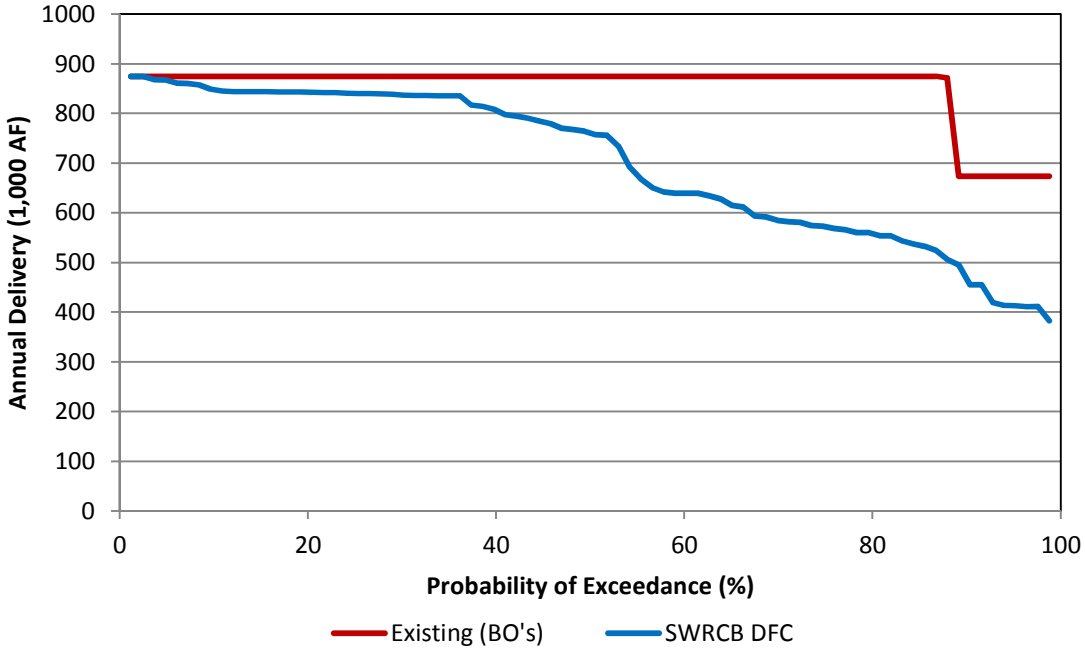
Delivery is not frequent enough to sustain surface water delivery system with SWRCB DFC (**Figure 48**).

Figure 48 - CVP North of Delta Ag Service Contract Delivery for Existing (BO's) and SWRCB DFC



Decrease in CVP Exchange Contract delivery requires releases from Friant to satisfy contract terms (**Figure 49**).

Figure 49 - CVP South of Delta Exchange Contract Delivery for Existing (BO's) and SWRCB DFC



Delivery is shorted when Shasta and Trinity Reservoirs reach dead pool and instream requirements can not be satisfied (**Figure 50**).

Figure 50 - CVP Sacramento Valley Settlement Contract Delivery for Existing (BO's) and SWRCB DFC

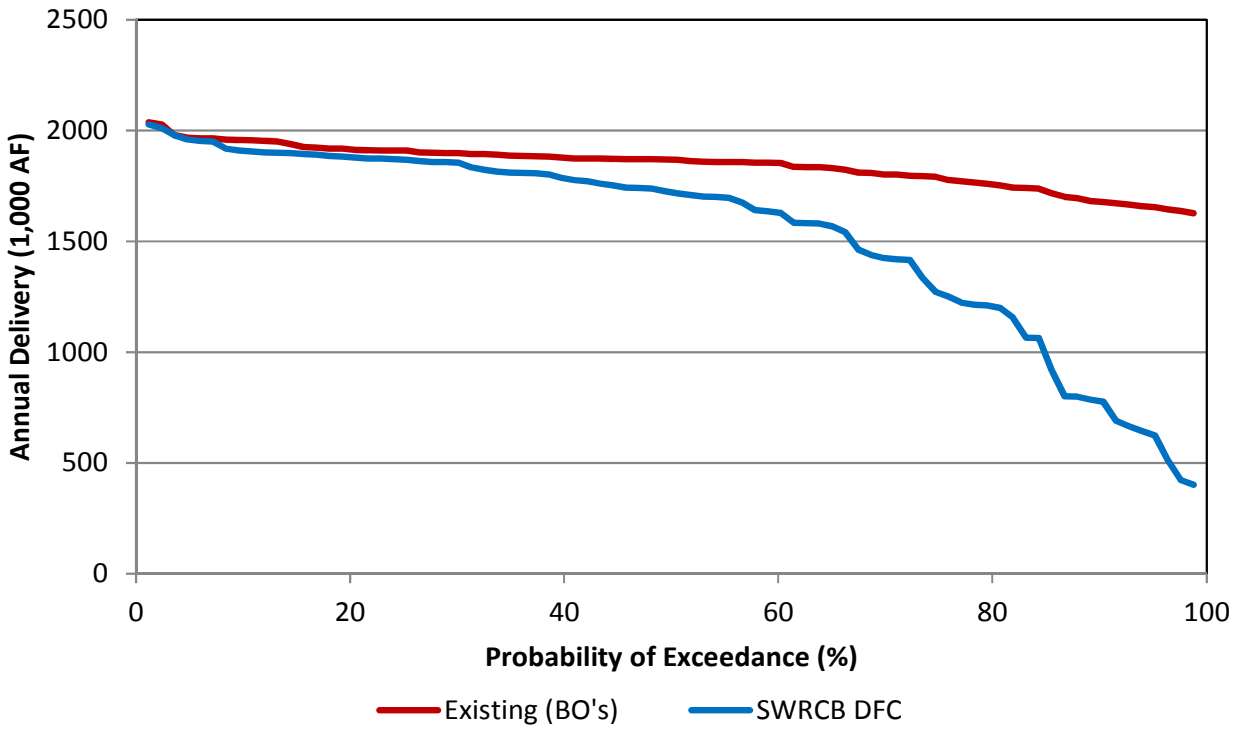
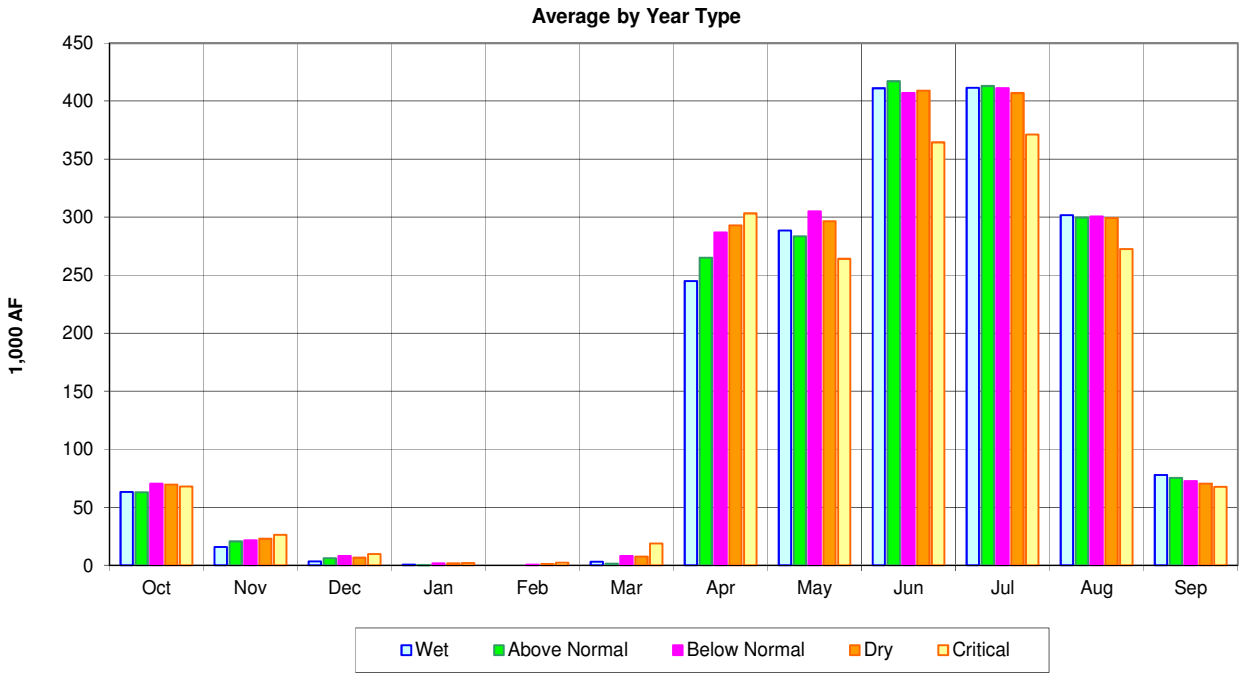
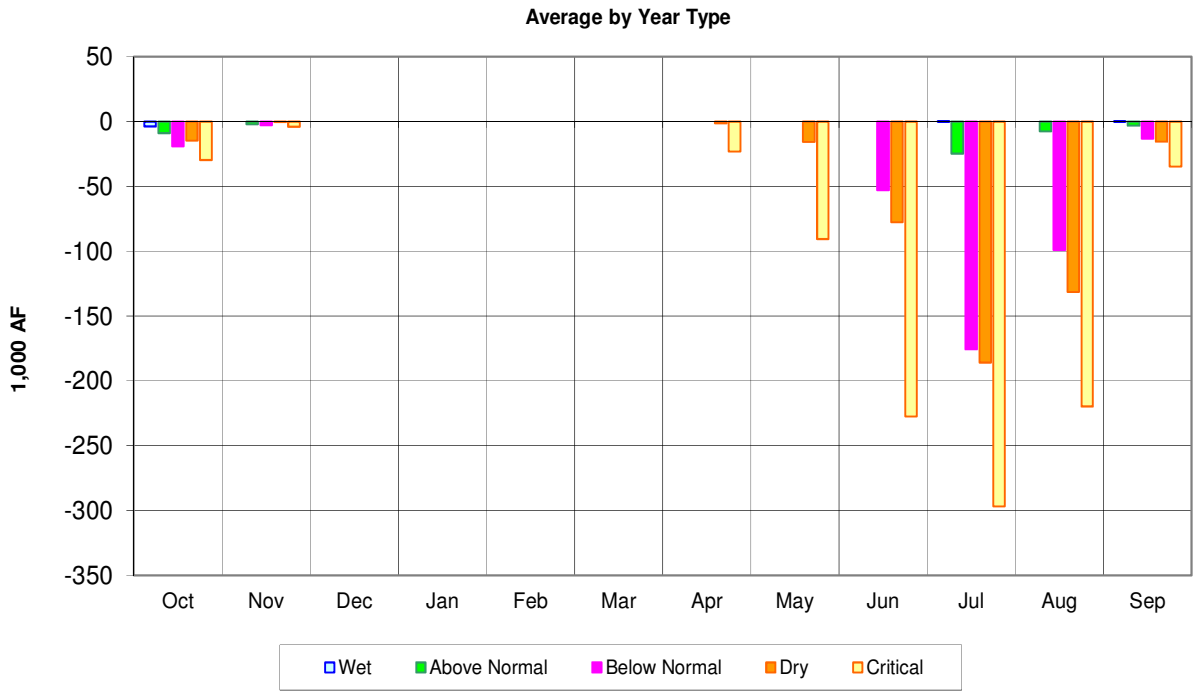


Figure 51 - CVP Sacramento Valley Settlement Contract Delivery for Existing (BO's)



CalSim II is designed to satisfy Sacramento CVP contracts at 100% in normal Shasta year types and 75% in critical Shasta year types and does not dynamically cut these diversions further than their contract allows. The SWRCB DFC require enough water from upstream reservoirs to cause them to hit dead pool and render them unable to satisfy these senior water rights as well as instream flow requirements. Deliveries are cut at the time upstream reservoirs hit dead pool resulting in unrealistic delivery patterns that are high in the spring and low during summer (**Figure 52**).

Figure 52 - Change in CVP Sacramento Valley Settlement Contract Delivery for Existing (BO's)



4.3 Characteristics of Hydropower Conditions with the SWRCB DFC

The SWRCB DFC causes the CVP and SWP to dramatically alter reservoir operations as described in the previous pages. Generally these operational changes lead to increased reservoir releases in the spring, decreased reservoir releases in the summer (see pages 16, 22, 25), decreased reservoir carryover storage (see pages 16, 22, 25), and decreased Delta export pumping. As a result of these changes, the timing and magnitude of generation at Project hydropower facilities is distorted from historical norms and the Project pumping loads associated with water deliveries south of the Delta shrink radically with the loss of exports (Average annual reduction in export = 2.8 MAF, see page 12).

As noted on page 19*, "The SWRCB DFC are very extreme and CalSim II was not designed to address these circumstances, therefore the logic that balances Trinity and Shasta Reservoir storage properly for existing (BO's) conditions may not be suitable when operating to satisfy the SWRCB flow criteria. Logic may need to be developed that isolates the Trinity operation from the Sacramento River Basin. Because Trinity River imports are increased in the SWRCB DFC model simulation there is likely an underestimate of hydropower impacts"*. The Trinity operations logic problem has not yet been addressed in CalSim II, but a rough attempt to compensate for this overly ambitious import of Trinity water and resulting increase in generation is presented as an alternative.

4.4 Hydropower Modeling Tools

CalSim II does not contain an ability to directly calculate hydropower production or use. Instead, power results are determined using CalSim II modeling results post-processed in two spreadsheet models, Long-Term Gen for the CVP and SWP Gen for the State water Project. Hydropower effects of the SWRCB DFC presented in this handout are determined as the difference between the existing conditions CalSim II study and the SWRCB DFC CalSim II study. By necessity, since CalSim II is a monthly time-step model, the hydropower results are presented as monthly values. Additional analyses on a shorter time-step may be desirable but presently available tools are not up to that task.

4.5 CVP and SWP Hydropower Results

The following pages, 50 through 71, contain the results of the monthly CVP and SWP hydropower analysis.

Figure 53 – Annual CVP Generation at Load Center

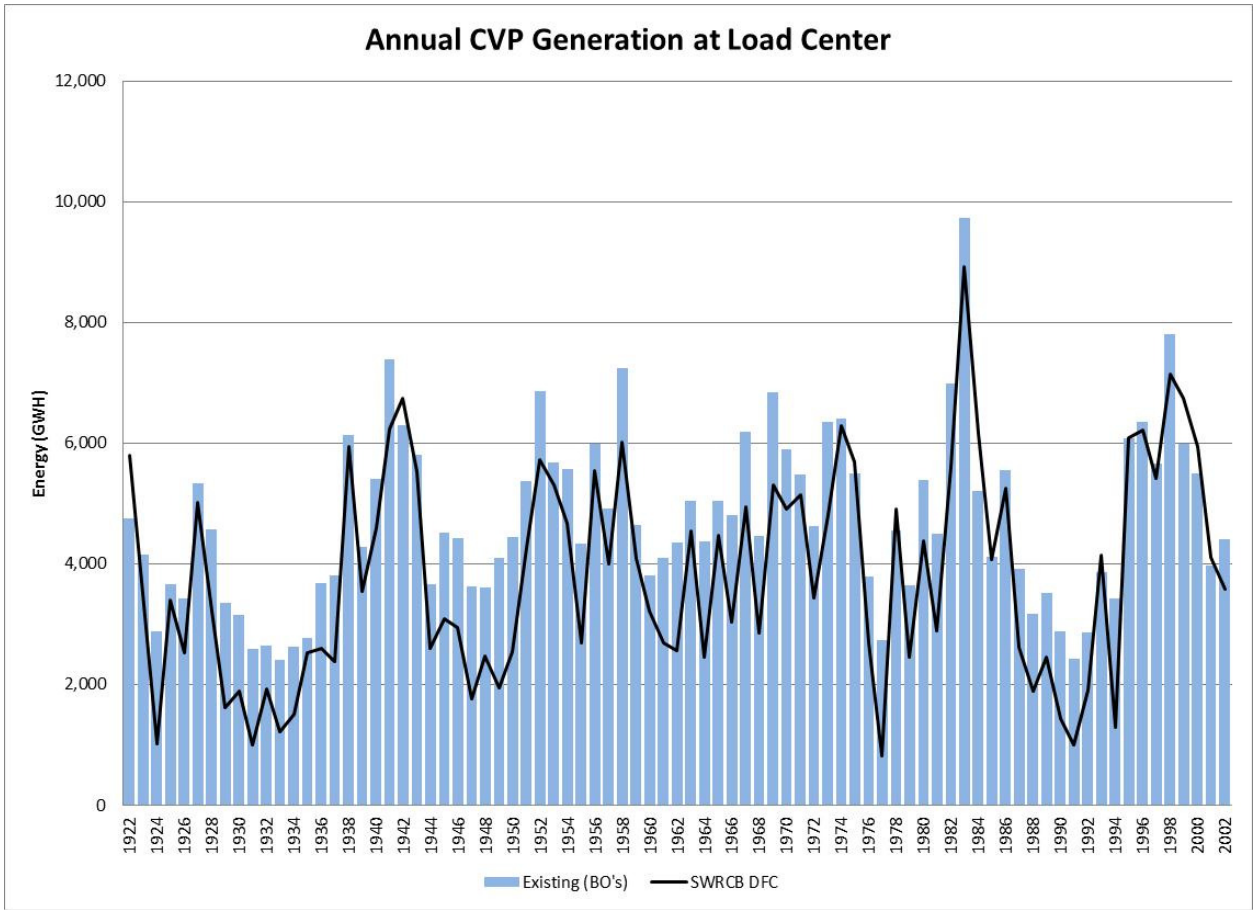


Table 2 – CVP Energy Load Center (GWH)

	Water Year Type					
	Wet	Above Normal	Below Normal	Dry	Critical	All Years
Existing (BO's) and SWRCB Studies						
Existing (BO's)	6,263	5,016	4,090	3,850	3,079	4,714
SWRCB DFC	5,731	4,597	2,929	2,835	1,524	3,835
Change from Existing (BO's)						
Existing (BO's)	0	0	0	0	0	0
SWRCB DFC	-532	-419	-1,162	-1,015	-1,555	-879
% Change	-8%	-8%	-28%	-26%	-51%	-19%

Figure 54 – Annual Net CVP Generation at Load Center

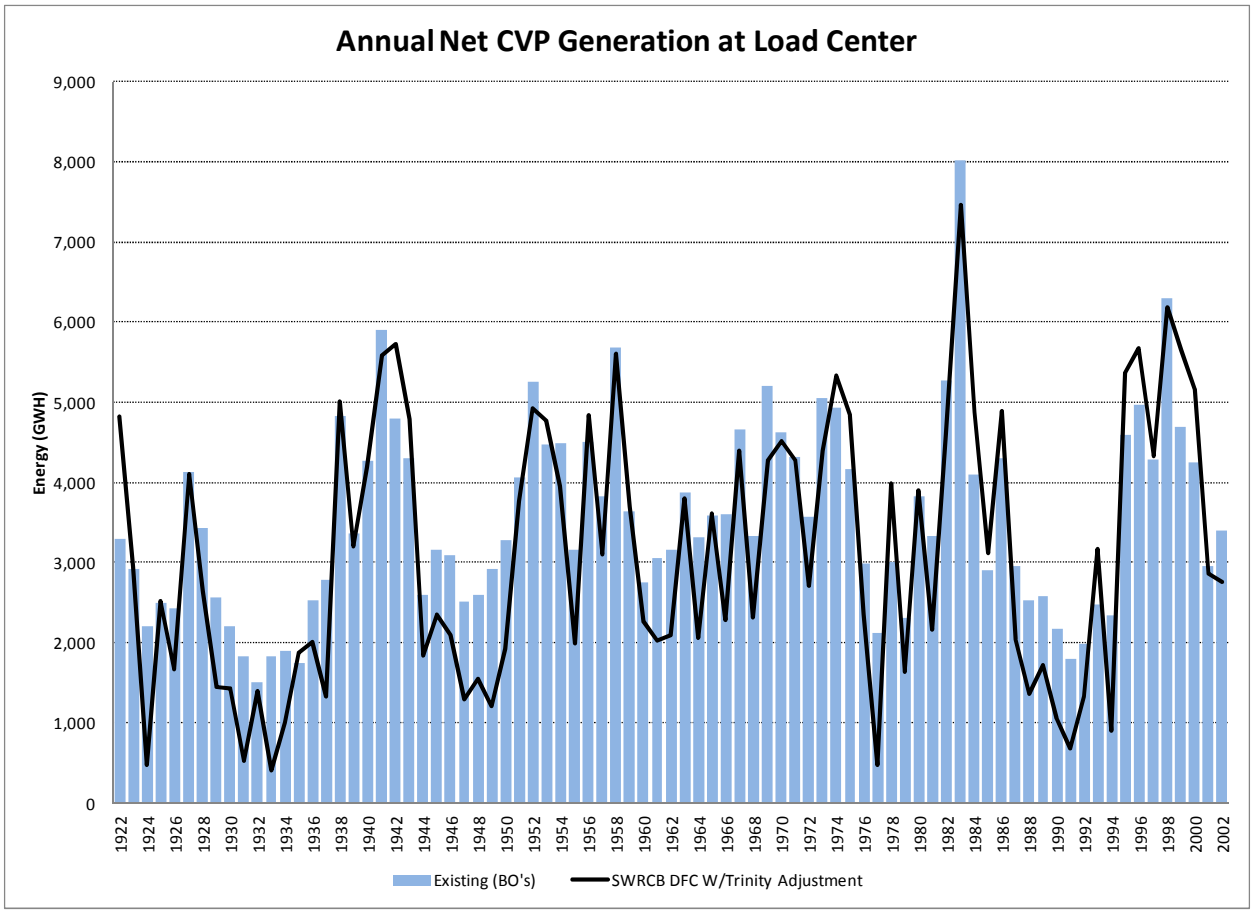


Table 3 – CVP Energy at Load Center (GWH)

	Water Year Type					
	Wet	Above Normal	Below Normal	Dry	Critical	All Years
Existing (BO's) and SWRCB DFC W/Trinity Adjustment Studies						
Existing (BO's)	6,263	5,016	4,090	3,850	3,079	4,714
SWRCB DFC W/Trinity Adjustment	5,550	4,287	2,717	2,640	1,538	3,656
Change from Existing (BO's)						
Existing (BO's)	0	0	0	0	0	0
SWRCB DFC W/Trinity Adjustment	-713	-730	-1,374	-1,210	-1,541	-1,058
% Change	-11%	-15%	-34%	-31%	-50%	-22%

Figure 55 – Annual SWP Generation at Load Center

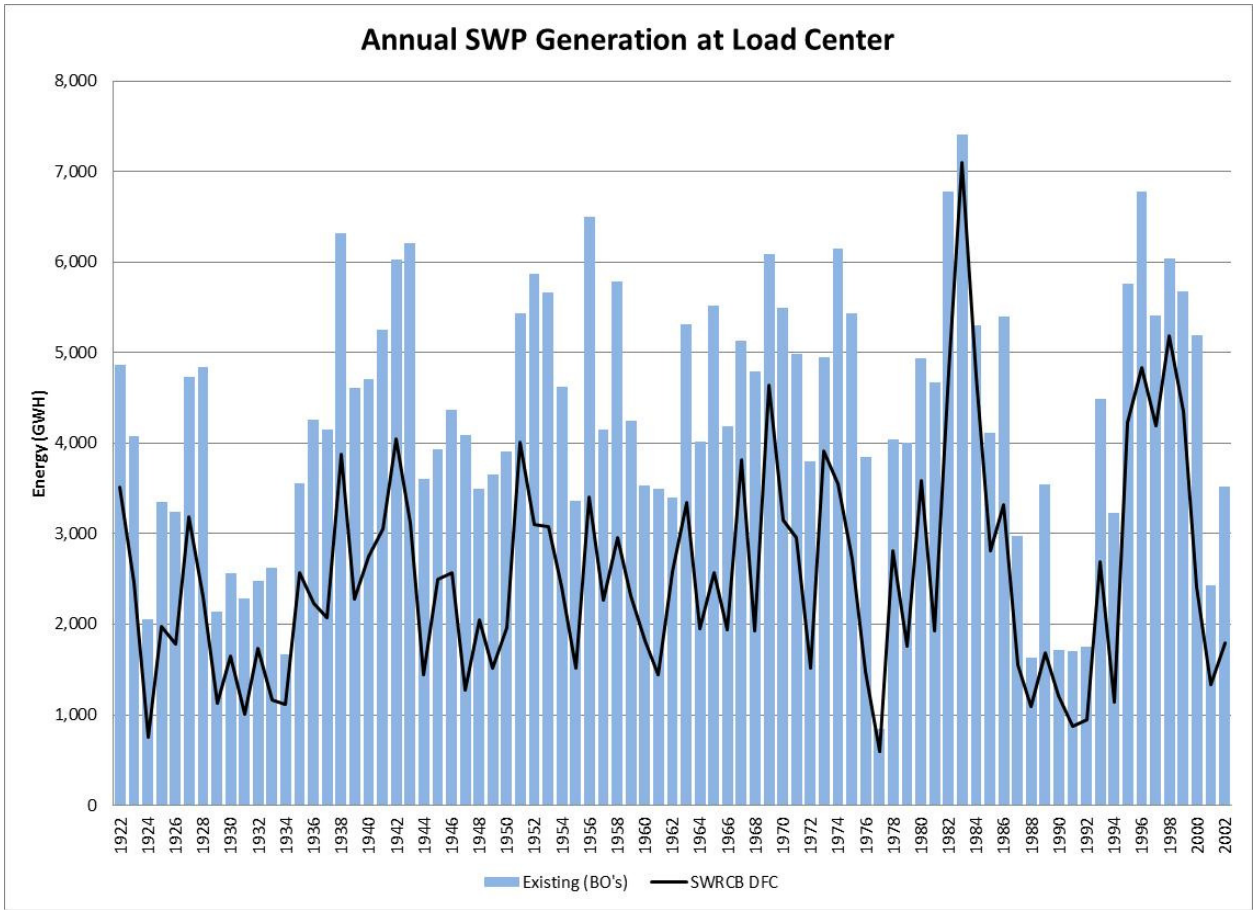


Table 4 – SWP Energy at Load Center (GWH)

	Water Year Type					
	Wet	Above Normal	Below Normal	Dry	Critical	All Years
Existing (BO's) and SWRCB DFC Studies						
Existing (BO's)	5,730	4,640	4,021	3,520	2,348	4,298
SWRCB DFC	3,956	2,808	1,984	1,766	1,126	2,556
Change from Existing (BO's)						
Existing (BO's)	0	0	0	0	0	0
SWRCB DFC	-1,774	-1,832	-2,037	-1,754	-1,222	-1,742
% Change	-31%	-39%	-51%	-50%	-52%	-41%

Figure 56 – Annual CVP Project Use Load at Load Center

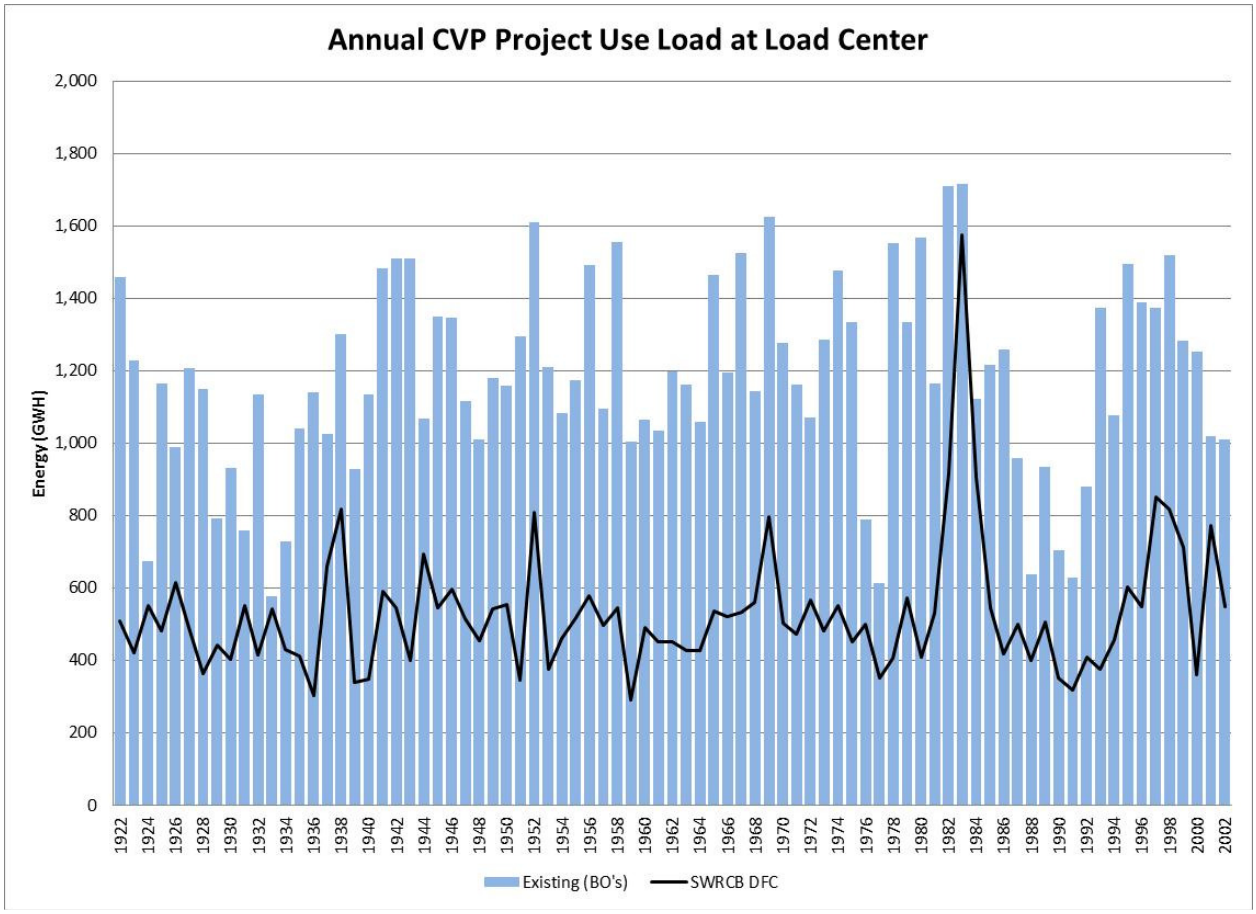


Table 5 - CVP PU Energy at Load Center (GWH)

	Water Year Type					
	Wet	Above Normal	Below Normal	Dry	Critical	All Years
Existing (BO's) and SWRCB DFC Studies						
Existing (BO's)	1,399	1,242	1,171	1,073	787	1,176
SWRCB DFC	706	487	430	467	403	530
Change from Existing (BO's)						
Existing (BO's)	0	0	0	0	0	0
SWRCB DFC	-693	-756	-741	-605	-384	-646
% Change	-50%	-61%	-63%	-56%	-49%	-55%

Figure 57 – Annual CVP Project Use Load at Load Center

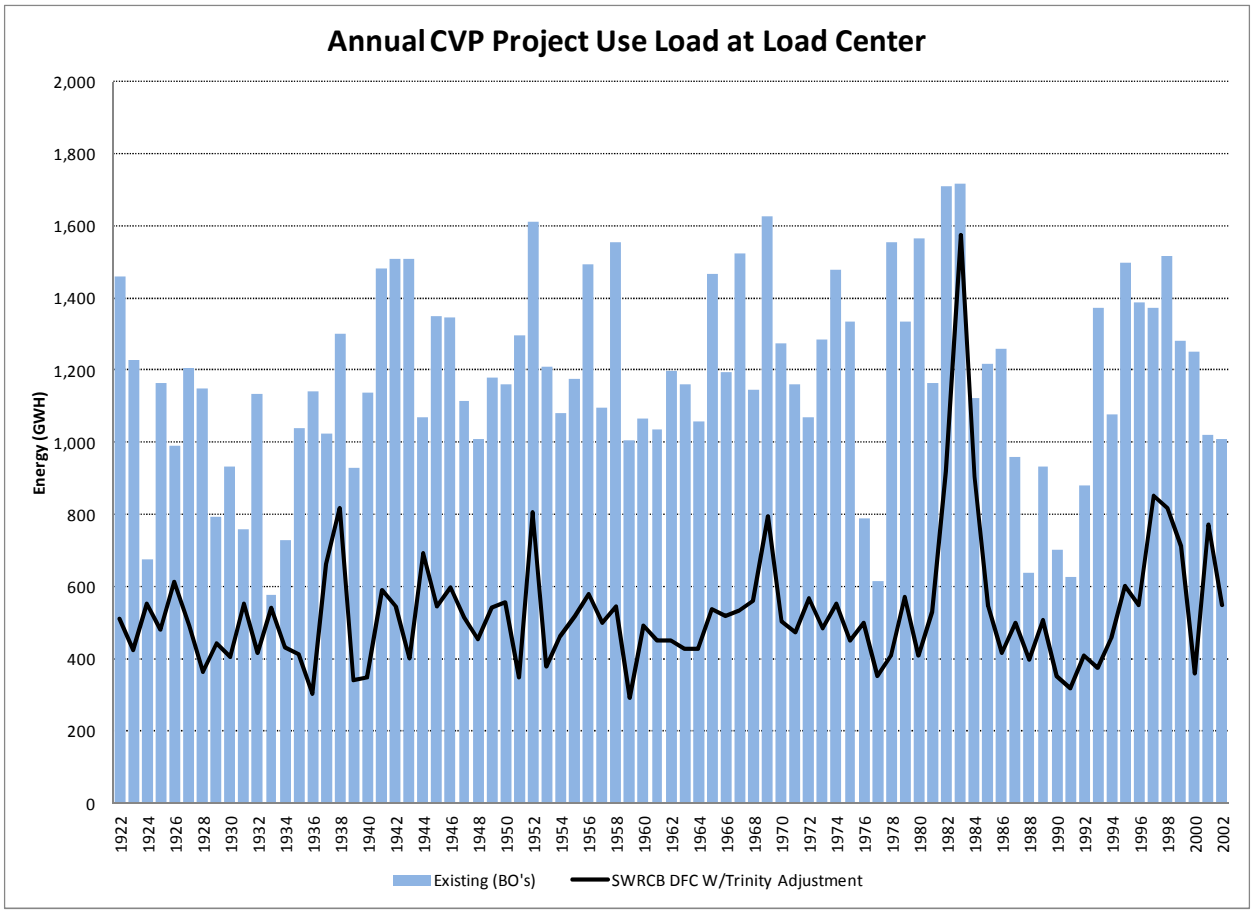


Table 6 - CVP PU Energy at Load Center (GWH)

	Water Year Type					
	Wet	Above Normal	Below Normal	Dry	Critical	All Years
Existing (BO's) and SWRCB DFC W/Trinity Adjustment Studies						
Existing (BO's)	1,399	1,242	1,171	1,073	787	1,176
SWRCB DFC W/Trinity Adjustment	706	487	430	467	403	530
Change from Existing (BO's)						
Existing (BO's)	0	0	0	0	0	0
SWRCB DFC W/Trinity Adjustment	-693	-756	-741	-605	-384	-646
% Change	-50%	-61%	-63%	-56%	-49%	-55%

Figure 58 – Annual SWP Project Use Load at Load Center

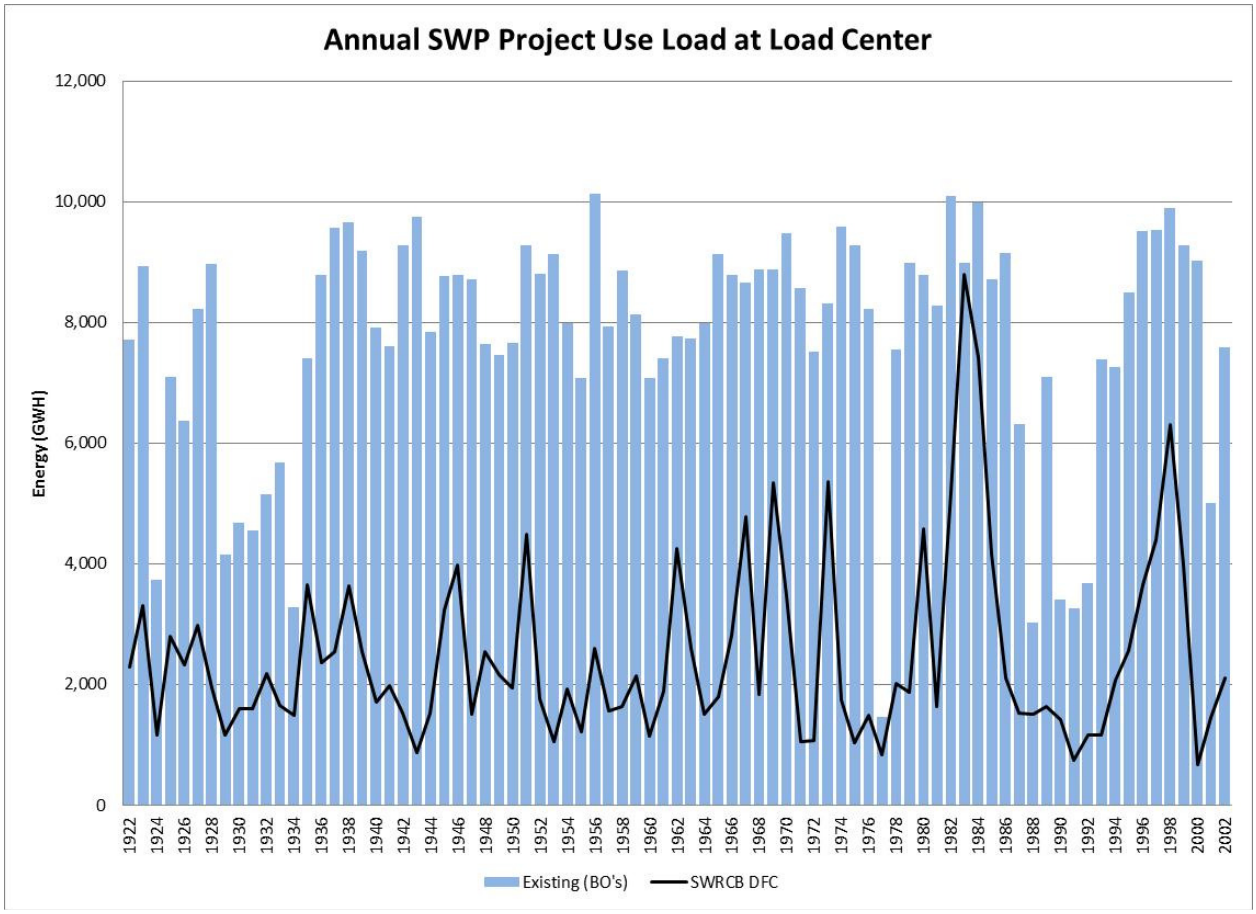


Table 7 - SWP PU Energy at Load Center (GWH)

	Water Year Type					
	Wet	Above Normal	Below Normal	Dry	Critical	All Years
Existing (BO's) and SWRCB DFC Studies						
Existing (BO's)	9,061	8,169	8,295	7,153	4,770	7,753
SWRCB DFC	3,427	2,442	2,084	2,178	1,574	2,508
Change from Existing (BO's)						
Existing (BO's)	0	0	0	0	0	0
SWRCB DFC	-5,635	-5,726	-6,212	-4,975	-3,196	-5,245
% Change	-62%	-70%	-75%	-70%	-67%	-68%

Figure 59 – Annual Net CVP Generation at Load Center

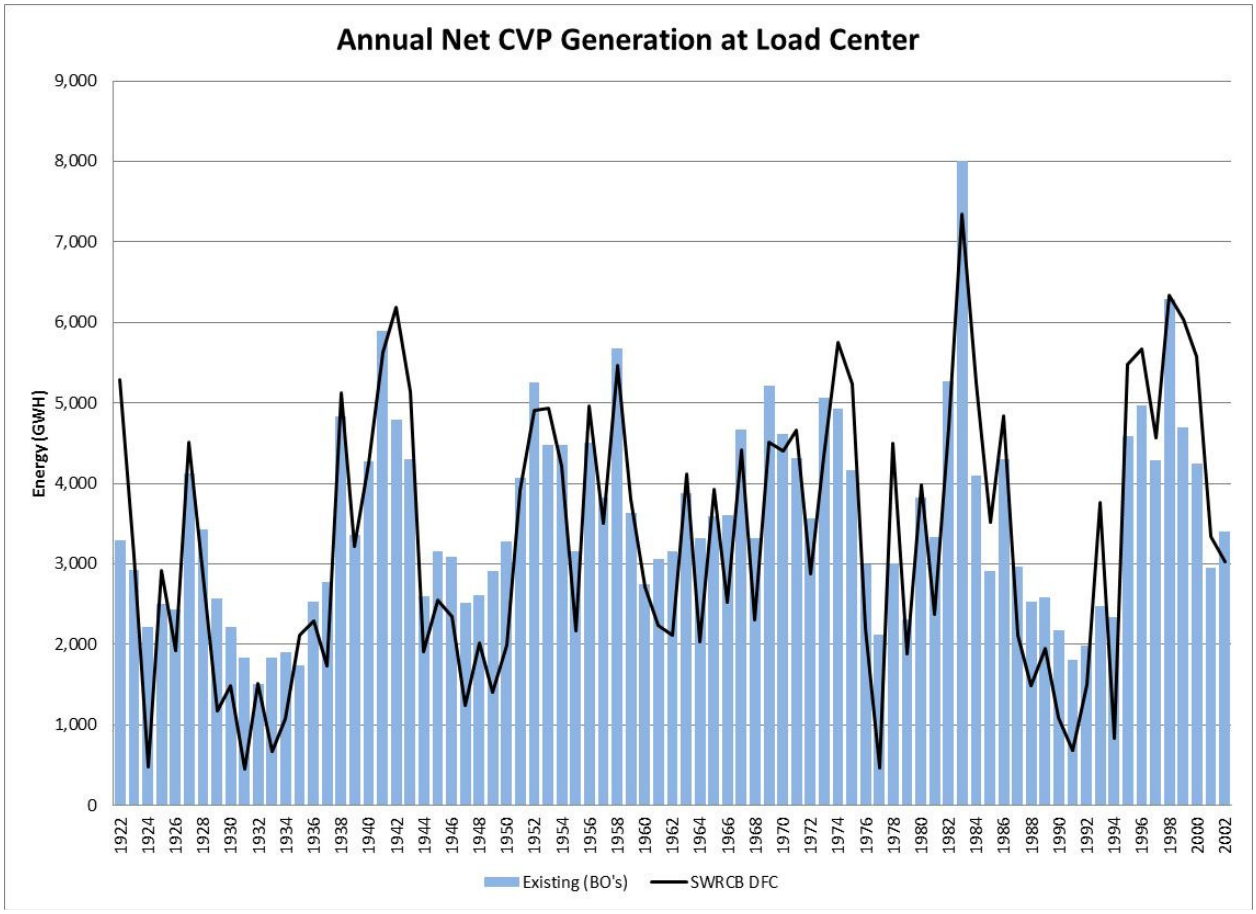


Table 8 - CVP Net Energy at Load Center (GWH)

	Water Year Type					
	Wet	Above Normal	Below Normal	Dry	Critical	All Years
Existing (BO's) and SWRCB DFC Studies						
Existing (BO's)	4,864	3,774	2,919	2,777	2,291	3,538
SWRCB DFC	5,025	4,110	2,499	2,368	1,120	3,305
Change from Existing (BO's)						
Existing (BO's)	0	0	0	0	0	0
SWRCB DFC	162	336	-421	-409	-1,171	-233
% Change	3%	9%	-14%	-15%	-51%	-7%

Figure 60 – Annual CVP Generation at Load Center

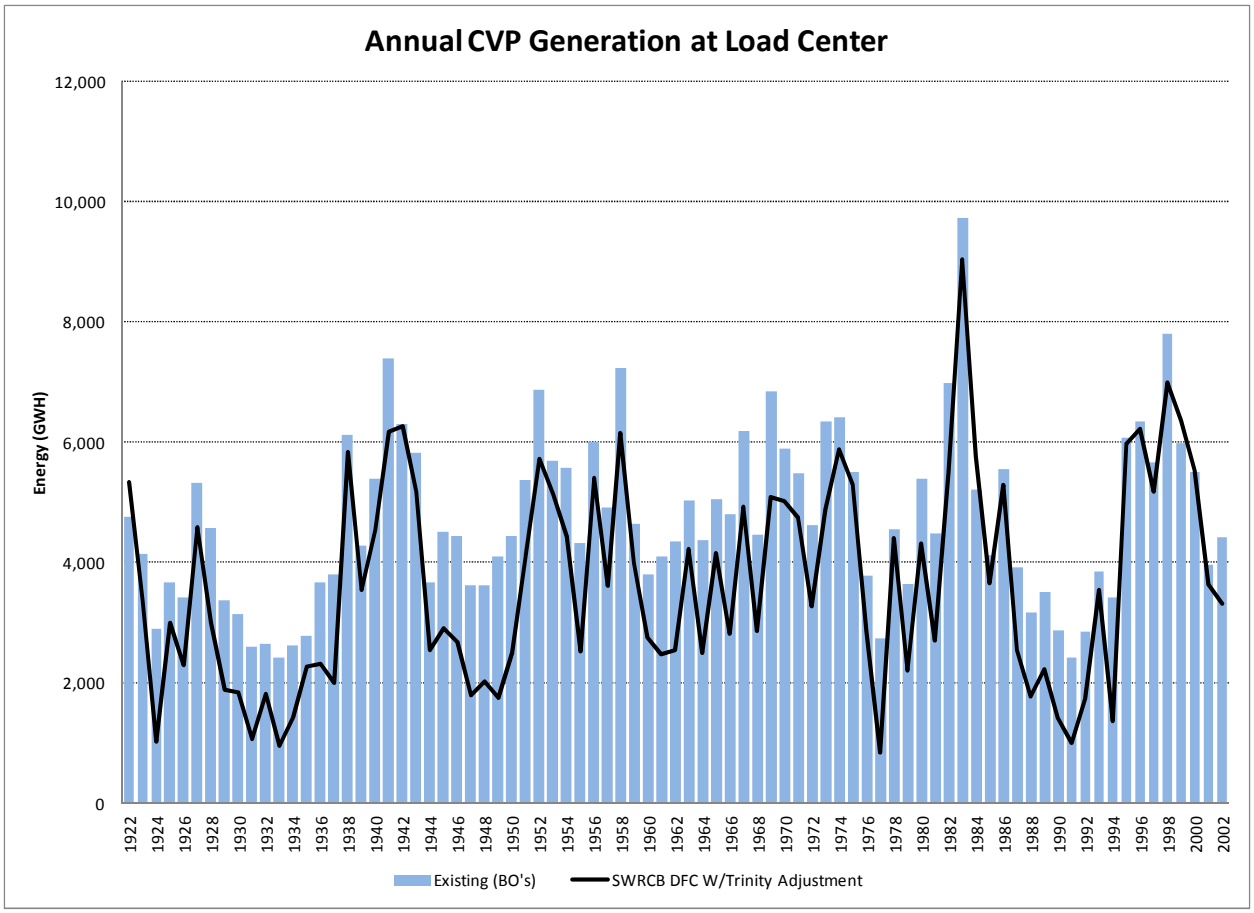


Table 9 - CVP Net Energy at Load Center (GWH)

	Water Year Type					
	Wet	Above Normal	Below Normal	Dry	Critical	All Years
Existing (BO's) and SWRCB DFC W/Trinity Adjustment Studies						
Existing (BO's)	4,864	3,774	2,919	2,777	2,291	3,538
SWRCB DFC W/Trinity Adjustment	4,844	3,800	2,287	2,173	1,135	3,126
Change from Existing (BO's)						
Existing (BO's)	0	0	0	0	0	0
SWRCB DFC W/Trinity Adjustment	-19	26	-633	-604	-1,157	-412
% Change	0%	1%	-22%	-22%	-50%	-12%

Figure 61 - Annual Net SWP Generation at Load Center

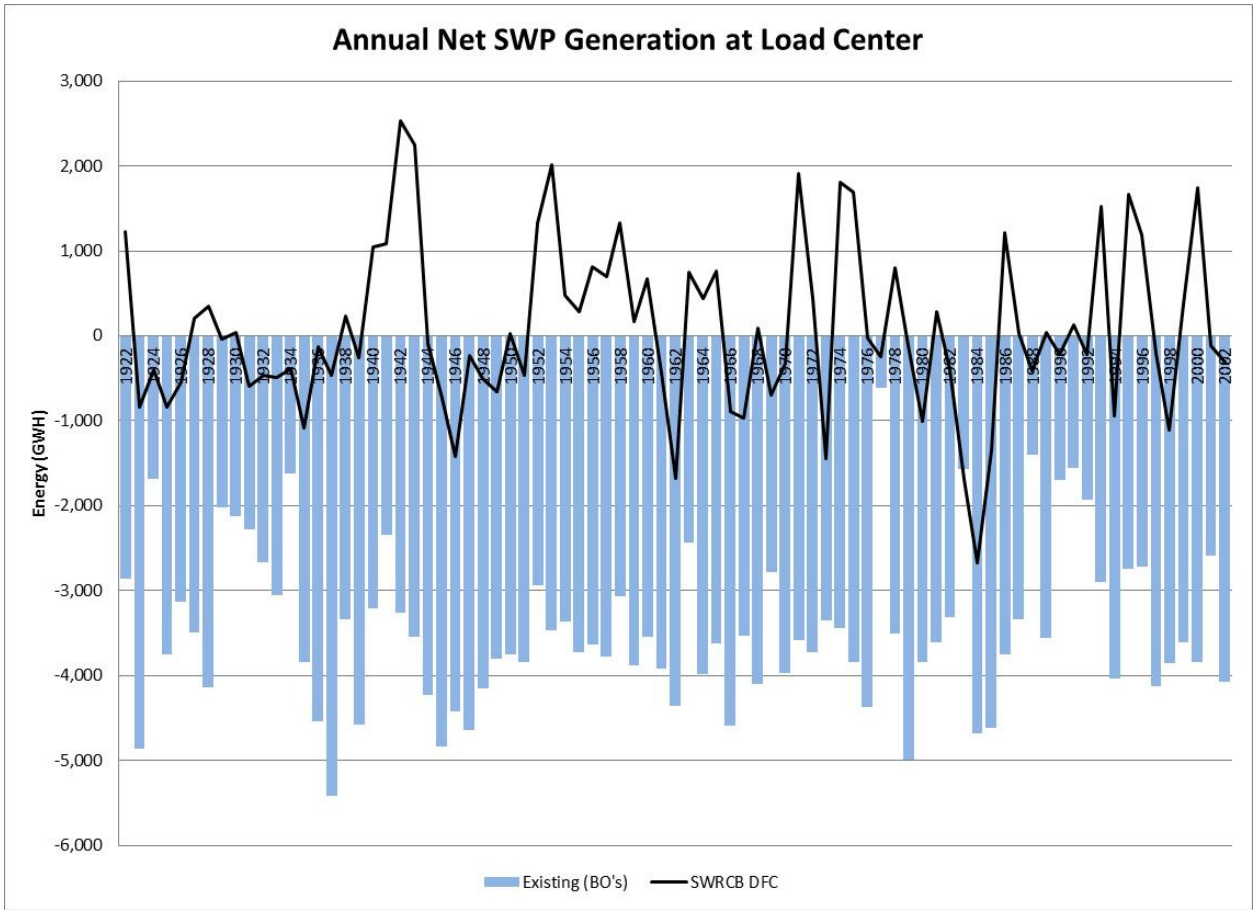
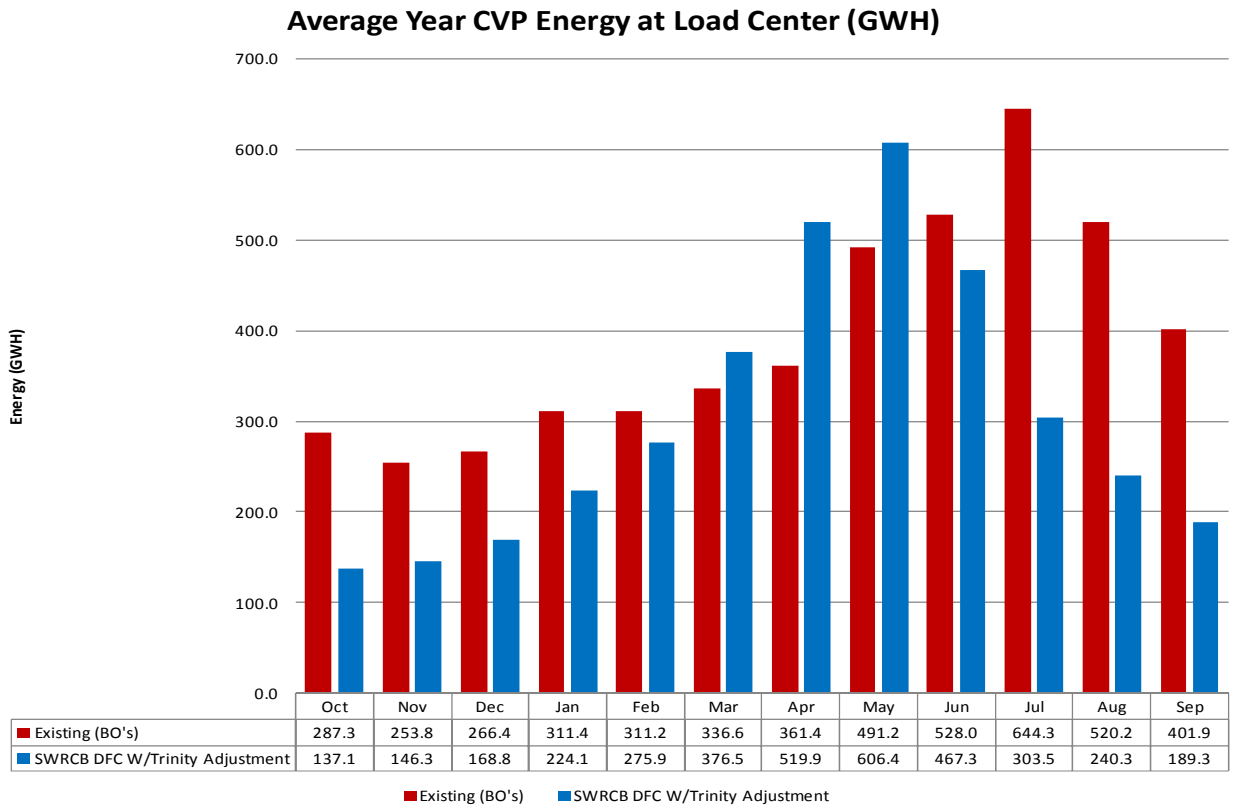


Table 10 - SWP Net Energy at Load Center (GWH)

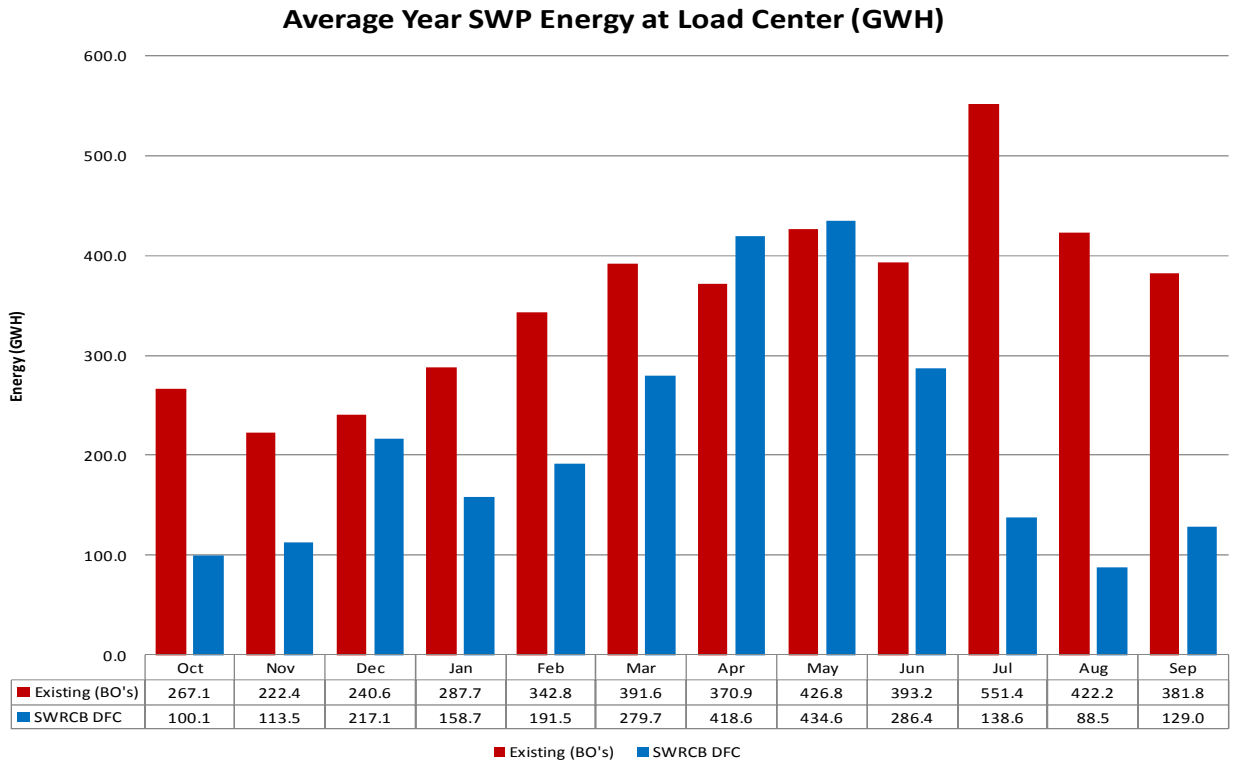
	Water Year Type					
	Wet	Above Normal	Below Normal	Dry	Critical	All Years
Existing (BO's) and SWRCB DFC Studies						
Existing (BO's)	-3,332	-3,529	-4,275	-3,633	-2,422	-3,455
SWRCB DFC	529	366	-100	-412	-448	48
Change from Existing (BO's)						
Existing (BO's)	0	0	0	0	0	0
SWRCB DFC	3,861	3,895	4,175	3,221	1,974	3,503
% Change	116%	110%	98%	89%	82%	101%

Figure 62 – Average Year CVP Energy at Load Center (GWH)



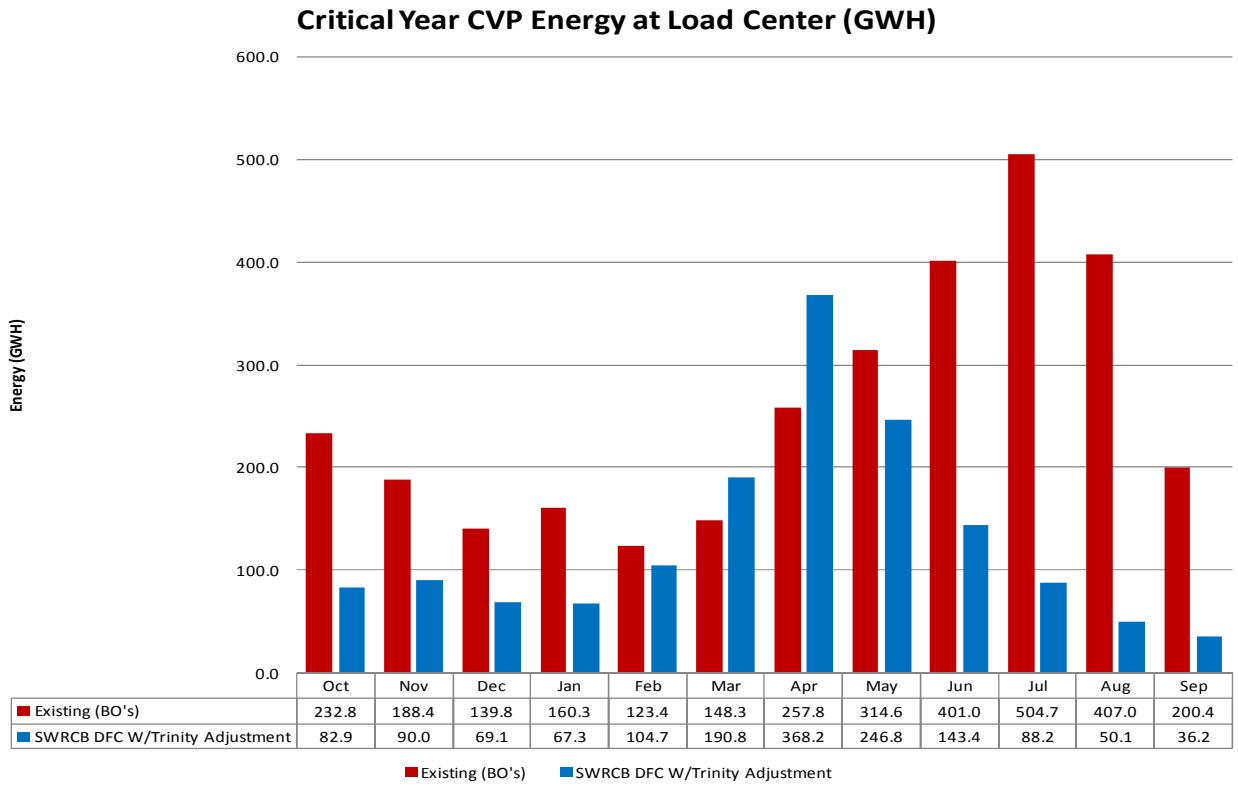
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Existing (BO's)	287.3	253.8	266.4	311.4	311.2	336.6	361.4	491.2	528.0	644.3	520.2	401.9
SWRCB DFC W/Trinity Adjustment	137.1	146.3	168.8	224.1	275.9	376.5	519.9	606.4	467.3	303.5	240.3	189.3

Figure 63 – Average Year SWP Energy at Load Center (GWH)



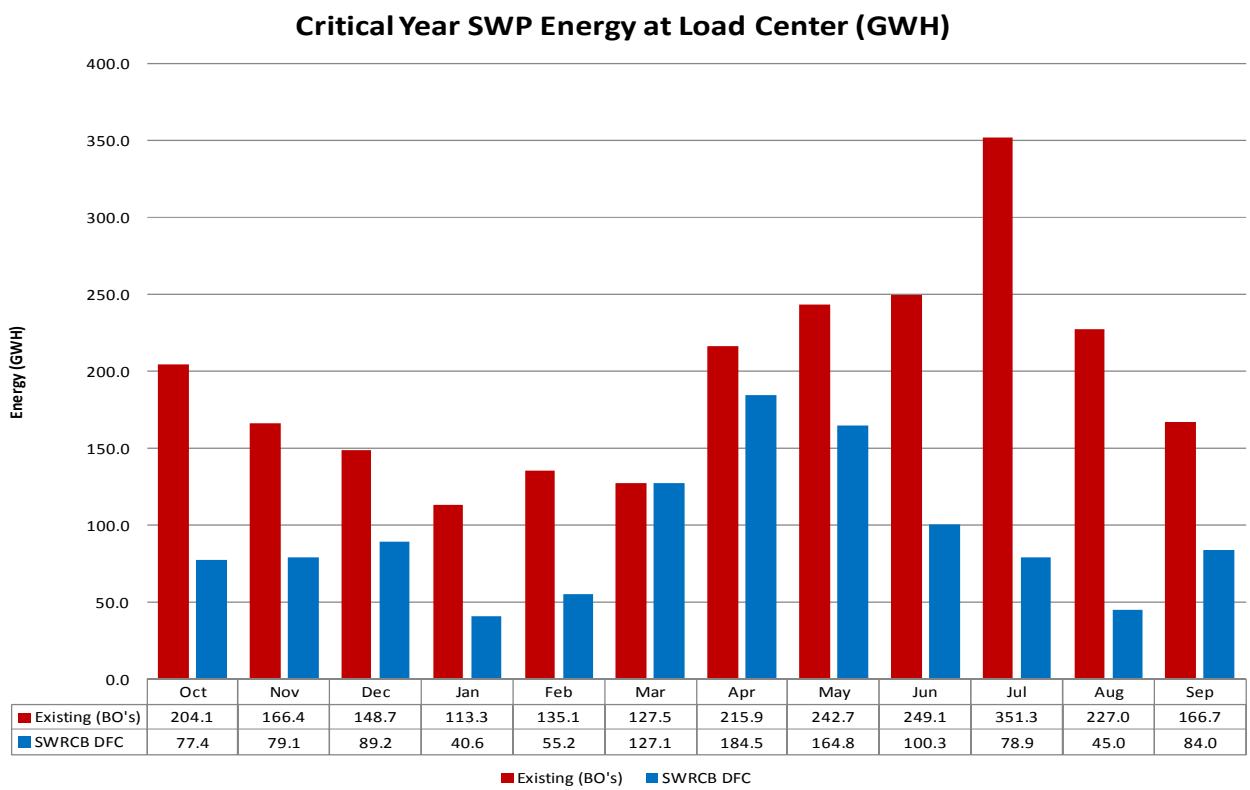
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Existing (BO's)	267.1	222.4	240.6	287.7	342.8	391.6	370.9	426.8	393.2	551.4	422.2	381.8
SWRCB DFC	100.1	113.5	217.1	158.7	191.5	279.7	418.6	434.6	286.4	138.6	88.5	129.0

Figure 64 - Critical Year CVP Energy at Load Center (GWH)



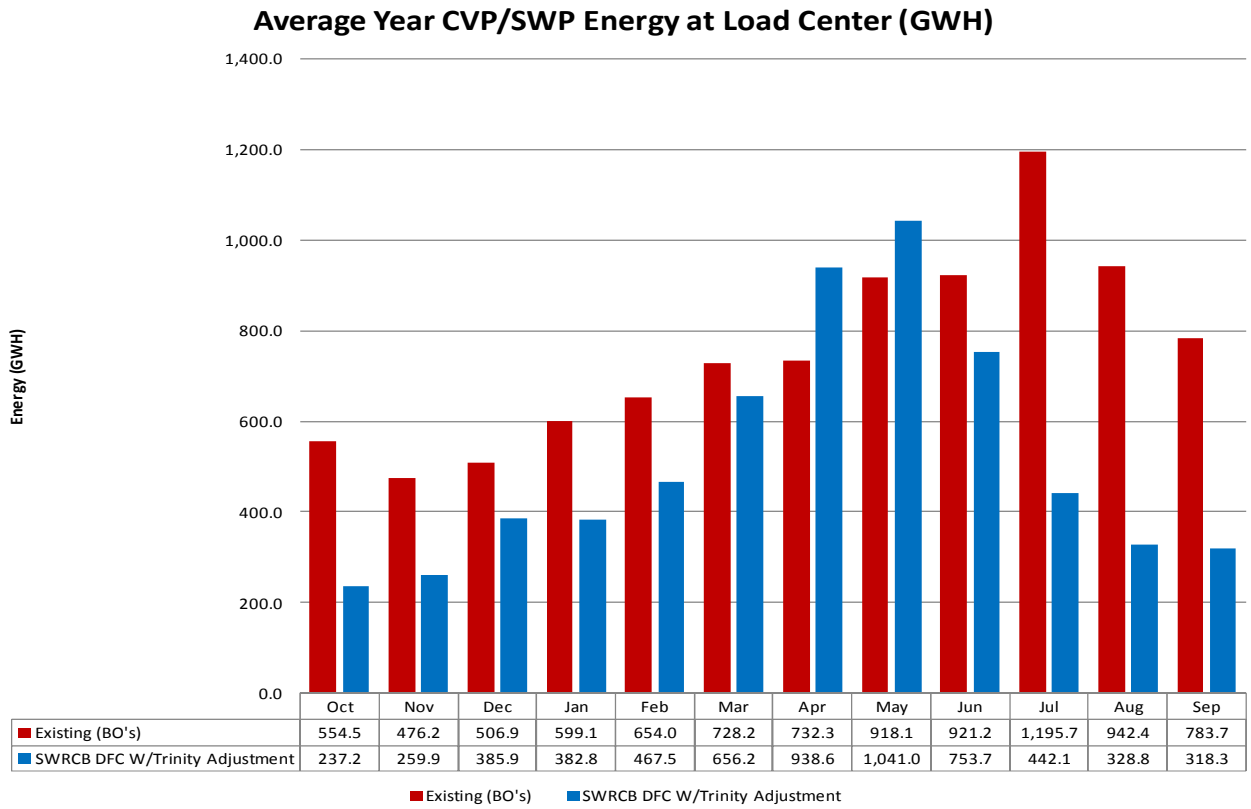
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Existing (BO's)	232.8	188.4	139.8	160.3	123.4	148.3	257.8	314.6	401.0	504.7	407.0	200.4
SWRCB DFC W/Trinity Adjustment	82.9	90.0	69.1	67.3	104.7	190.8	368.2	246.8	143.4	88.2	50.1	36.2

Figure 65 - Critical Year CVP Energy at Load Center (GWH)



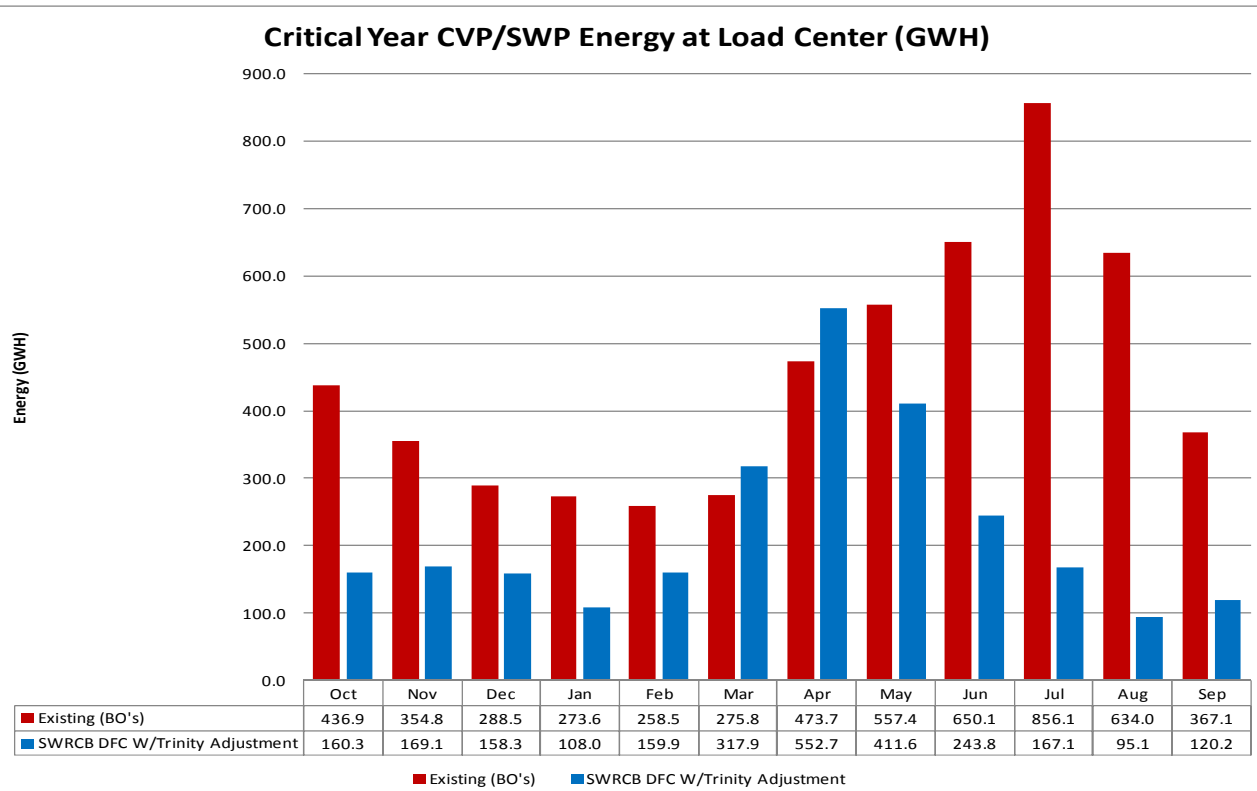
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Existing (BO's)	204.1	166.4	148.7	113.3	135.1	127.5	215.9	242.7	249.1	351.3	227.0	166.7
SWRCB DFC	77.4	79.1	89.2	40.6	55.2	127.1	184.5	164.8	100.3	78.9	45.0	84.0

Figure 66 – Average Year CVP/SWP Energy at Load Center (GWH)



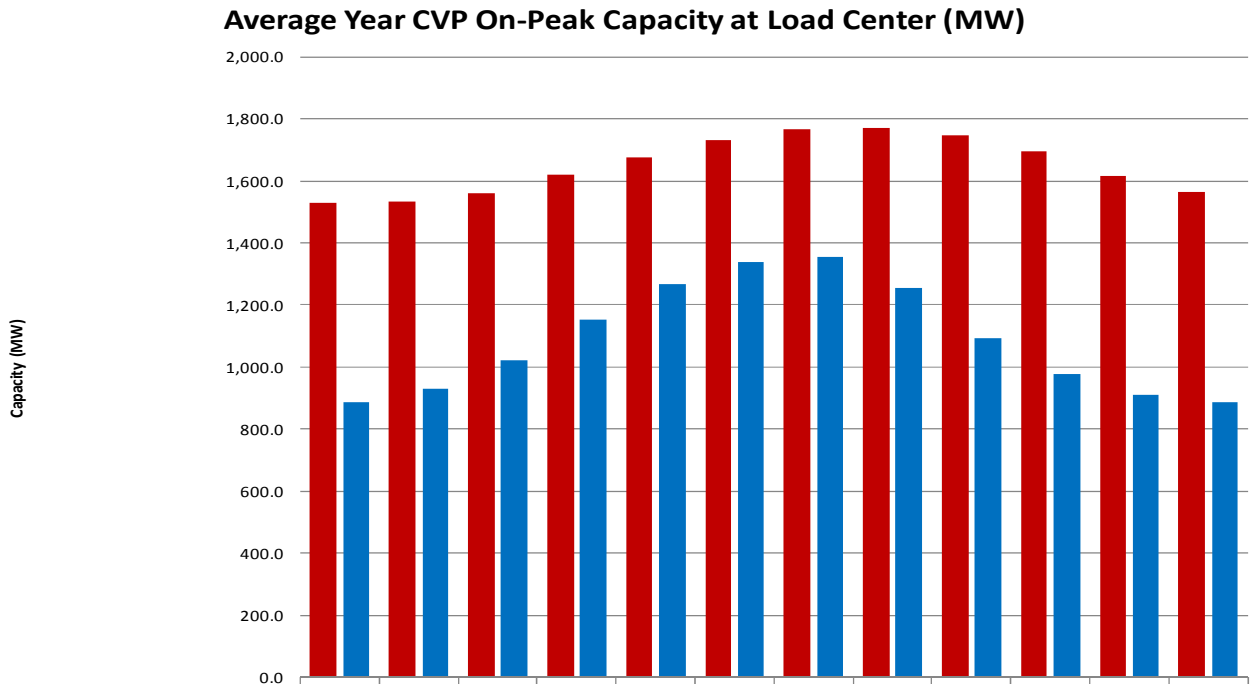
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Existing (BO's)	554.5	476.2	506.9	599.1	654.0	728.2	732.3	918.1	921.2	1,195.7	942.4	783.7
SWRCB DFC W/Trinity Adjustment	237.2	259.9	385.9	382.8	467.5	656.2	938.6	1,041.0	753.7	442.1	328.8	318.3

Figure 67 – Critical Year CVP/SWP Energy at Load Center (GWH)



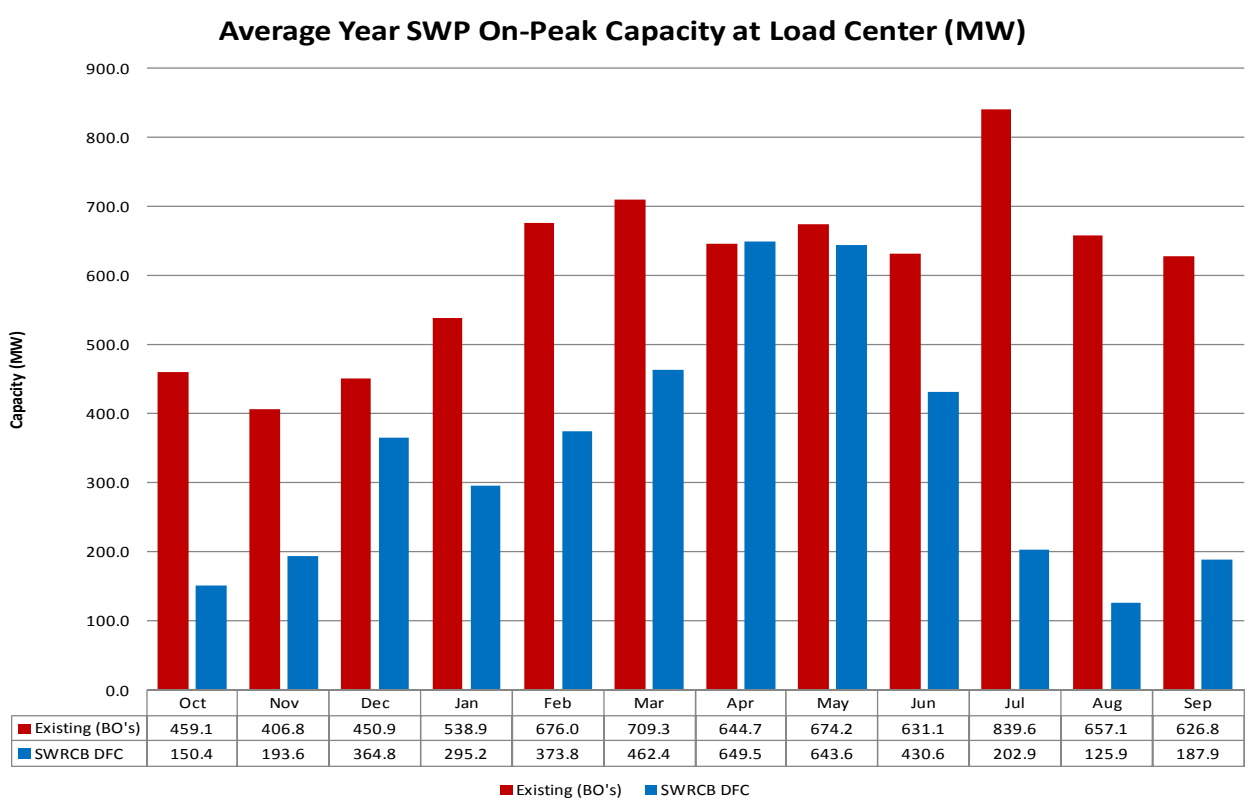
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Existing (BO's)	436.9	354.8	288.5	273.6	258.5	275.8	473.7	557.4	650.1	856.1	634.0	367.1
SWRCB DFC W/Trinity Adjustment	160.3	169.1	158.3	108.0	159.9	317.9	552.7	411.6	243.8	167.1	95.1	120.2

Figure 68 – Average Year CVP On-Peak Capacity at Load Center (MW)



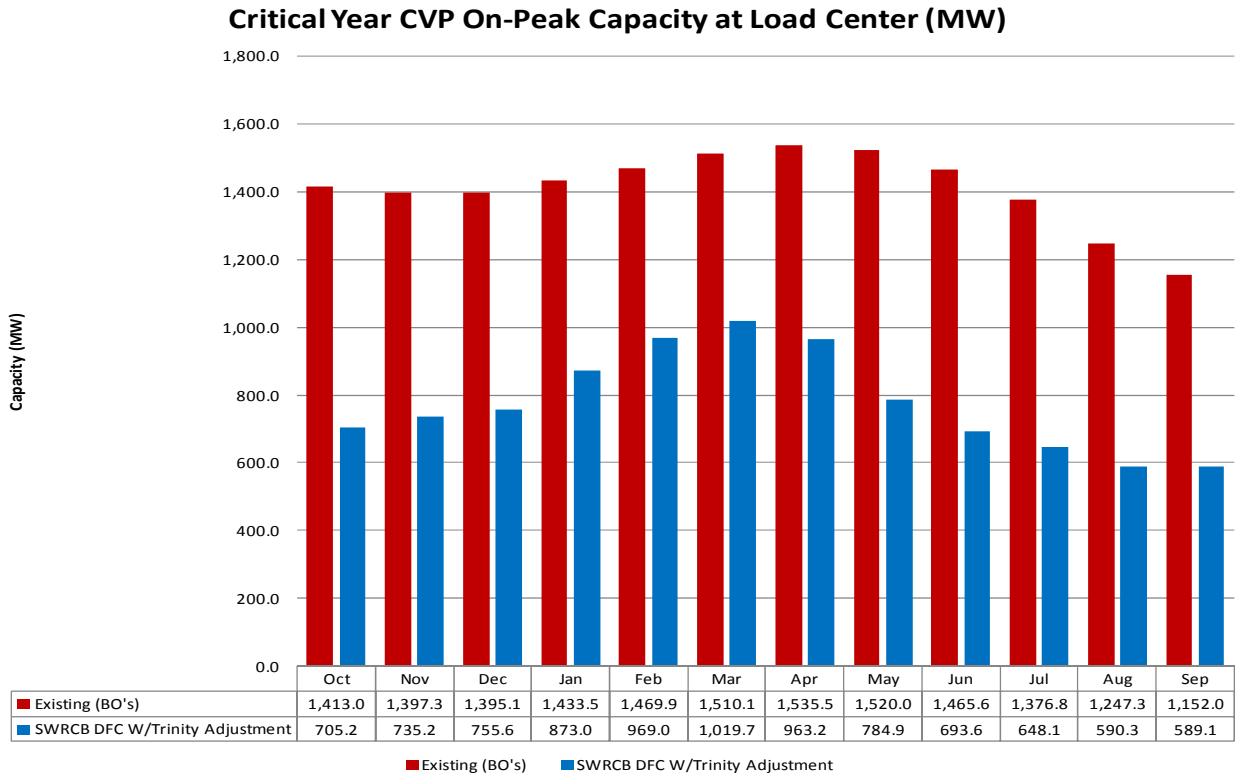
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Existing (BO's)	1,529.8	1,533.0	1,561.3	1,620.3	1,677.0	1,730.0	1,765.2	1,770.6	1,748.0	1,694.6	1,614.6	1,563.0
SWRCB DFC W/Trinity Adjustment	888.3	930.6	1,020.7	1,152.6	1,265.2	1,340.0	1,354.3	1,253.8	1,093.5	977.9	910.1	887.0

Figure 69 – Average Year SWP On-Peak Capacity at Load Center (MW)



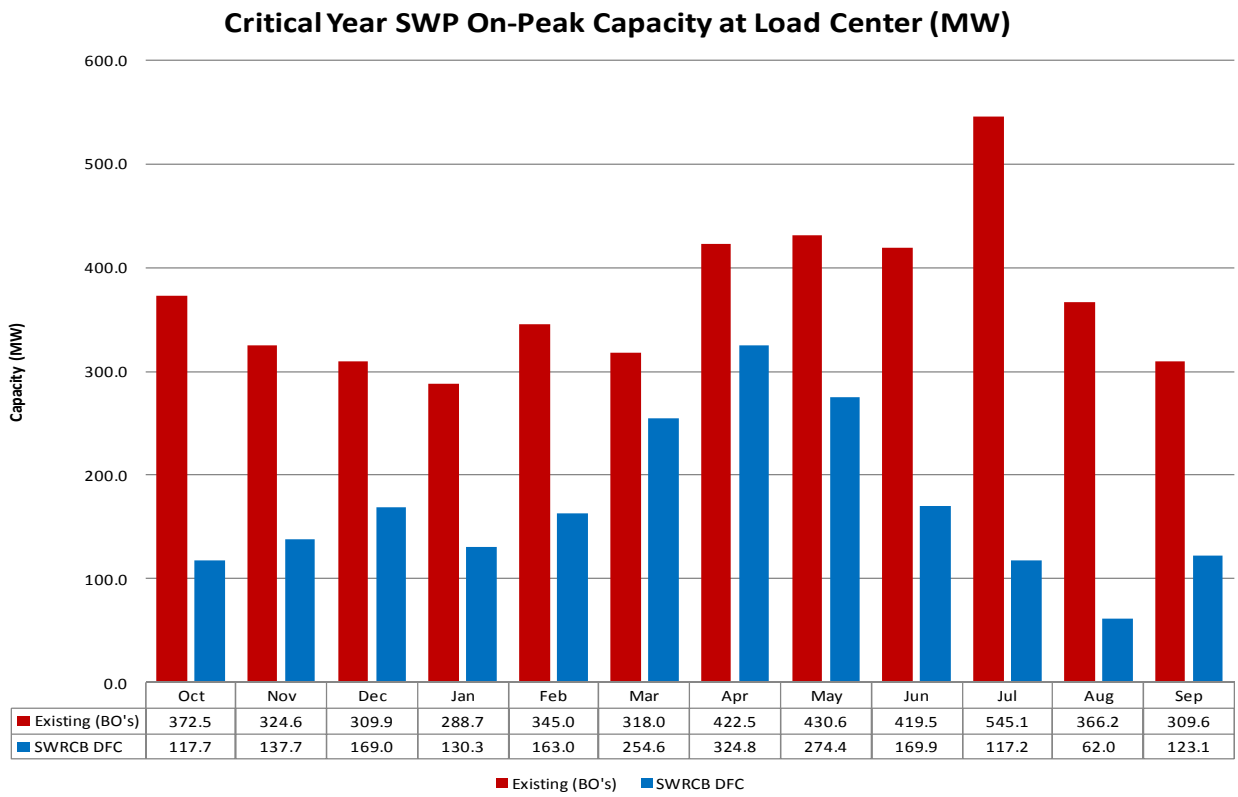
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Existing (BO's)	459.1	406.8	450.9	538.9	676.0	709.3	644.7	674.2	631.1	839.6	657.1	626.8
SWRCB DFC	150.4	193.6	364.8	295.2	373.8	462.4	649.5	643.6	430.6	202.9	125.9	187.9

Figure 70 - Critical Year CVP Energy On-Peak Capacity at Load Center (MW)



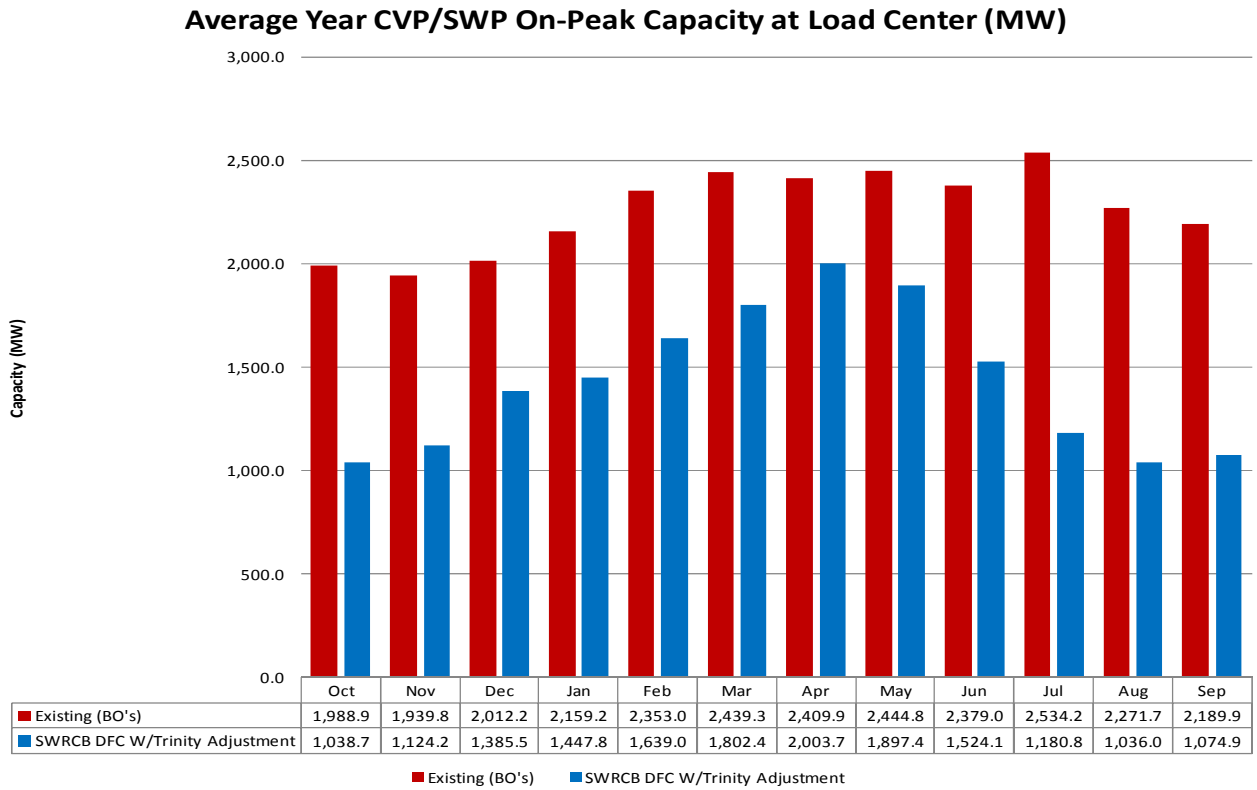
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Existing (BO's)	1,413.0	1,397.3	1,395.1	1,433.5	1,469.9	1,510.1	1,535.5	1,520.0	1,465.6	1,376.8	1,247.3	1,152.0
SWRCB DFC W/Trinity Adjustment	705.2	735.2	755.6	873.0	969.0	1,019.7	963.2	784.9	693.6	648.1	590.3	589.1

Figure 71 - Critical Year SWP On-Peak Capacity at Load Center (MW)



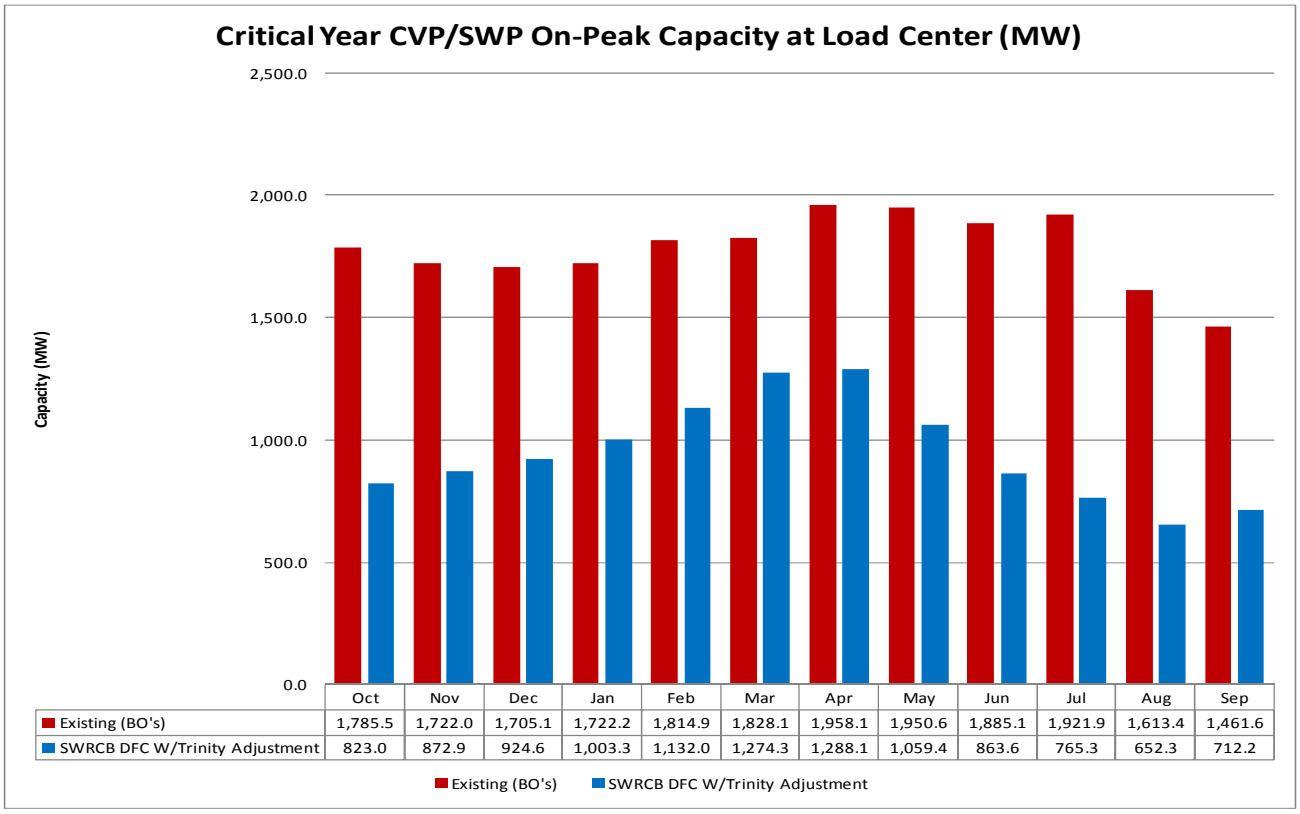
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Existing (BO's)	372.5	324.6	309.9	288.7	345.0	318.0	422.5	430.6	419.5	545.1	366.2	309.6
SWRCB DFC	117.7	137.7	169.0	130.3	163.0	254.6	324.8	274.4	169.9	117.2	62.0	123.1

Figure 72 – Average Year CVP/SWP On-Peak Capacity at Load Center (MW)



	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Existing (BO's)	1,988.9	1,939.8	2,012.2	2,159.2	2,353.0	2,439.3	2,409.9	2,444.8	2,379.0	2,534.2	2,271.7	2,189.9
SWRCB DFC W/Trinity Adjustment	1,038.7	1,124.2	1,385.5	1,447.8	1,639.0	1,802.4	2,003.7	1,897.4	1,524.1	1,180.8	1,036.0	1,074.9

Figure 73 – Critical Year CVP/SWP On-Peak Capacity at Load Center (MW)



	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Existing (BO's)	1,785.5	1,722.0	1,705.1	1,722.2	1,814.9	1,828.1	1,958.1	1,950.6	1,885.1	1,921.9	1,613.4	1,461.6
SWRCB DFC W/Trinity Adjustment	823.0	872.9	924.6	1,003.3	1,132.0	1,274.3	1,288.1	1,059.4	863.6	765.3	652.3	712.2

Table 11 – Combined CVP/SWP Energy at Load Center (GWH)

	Water Year Type					
	Wet	Above Normal	Below Normal	Dry	Critical	All Years
Existing (BO's) and SWRCB DFC W/Trinity Adjustment Studies						
Existing (BO's)	11,992	9,656	8,111	7,370	5,426	9,012
SWRCB DFC W/Trinity Adjustment	9,506	7,095	4,700	4,406	2,664	6,212
Change from Existing (BO's)						
Existing (BO's)	0	0	0	0	0	0
SWRCB DFC W/Trinity Adjustment	-2,486	-2,561	-3,411	-2,964	-2,763	-2,800
% Change	-21%	-27%	-42%	-40%	-51%	-31%

Table 12 - Combined CVP/SWP Energy at Load Center (GWH)

	Water Year Type					
	Wet	Above Normal	Below Normal	Dry	Critical	All Years
Existing (BO's) and SWRCB DFC W/Trinity Adjustment Studies						
Existing (BO's)	10,460	9,411	9,466	8,226	5,557	8,929
SWRCB DFC W/Trinity Adjustment	4,132	2,929	2,514	2,645	1,977	3,038
Change from Existing (BO's)						
Existing (BO's)	0	0	0	0	0	0
SWRCB DFC W/Trinity Adjustment	-6,328	-6,482	-6,953	-5,581	-3,580	-5,891
% Change	-60%	-69%	-73%	-68%	-64%	-66%

Table - Combined CVP/SWP Net Energy at Load Center (GWH)

	Water Year Type					
	Wet	Above Normal	Below Normal	Dry	Critical	All Years
Existing (BO's) and SWRCB DFC W/Trinity Adjustment Studies						
Existing (BO's)	1,532	245	-1,355	-856	-131	83
SWRCB DFC W/Trinity Adjustment	5,374	4,166	2,187	1,761	687	3,174
Change from Existing (BO's)						
Existing (BO's)	0	0	0	0	0	0
SWRCB DFC W/Trinity Adjustment	3,841	3,921	3,542	2,617	818	3,091
% Change	251%	1601%	261%	306%	625%	3711%

Table 13 – Power and Pumping Cost Report Metrics, CVP Long-Term Gen Model Results

Power and Pumping Cost Reporting Metrics

CVP Long-Term Gen Model Results				Existing	SWRCB DFC W/TRN Adj	Difference
CVP Facilities						
Power Facilities						
Capacity	Total of all Facilities at load center	(MW)	Long Term	1,650	1,088	-563
			Driest Periods	1,368	786	-581
Energy Generation	Total of all Facilities at load center	(GWh)	Long Term	4,709	3,651	-1,058
			Driest Periods	3,004	1,669	-1,336
Generation Revenue	Total of all Facilities	($1,000)	Long Term	276,795	206,417	-70,378
			Driest Periods	177,262	91,956	-85,306
Pumping Facilities						
Energy Use	Total of all Facilities at load center	(GWh)	Long Term	1,176	529	-647
			Driest Periods	790	437	-353
Power Costs	Total of all Facilities	($1,000)	Long Term	60,770	27,562	-33,208
			Driest Periods	41,127	22,983	-18,144
Losses						
Foregone Energy	Total of all Facilities	(GWh)	Long Term	255	274	19
			Driest Periods	20	51	31
Transmission Losses	Total of all Facilities	(GWh)	Long Term	201	156	-45
			Driest Periods	128	68	-59
Tot al						
Net Generation	Total of all Facilities	(GWh)	Long Term	3,533	3,122	-411
			Driest Periods	2,214	1,231	-983
Net Revenue	Total of all Facilities	($1,000)	Long Term	216,024	178,855	-37,170
			Driest Periods	136,135	68,973	-67,162

Notes:
1. Long Term is the average quantity for the calendar years 1922-2002.
2. Driest Periods is the average quantity for the calendar years 1929-1934, 1976-1977, and 1987-1992.
3. 2009 Forecast (in 2007 $); Prices are forward prices as of 08/25/2009 and were developed by DWR power portfolio section.(extrapolated from a linear trend that was fitted to the estimates beginning in late 2009 and ending in 2039)

Table 14 - Power and Pumping Cost Report Metrics, SWP Gen Results

Power and Pumping Cost Reporting Metrics

SWP Gen Results				Existing	SWRCB DFC	Difference
SWP Facilities						
Power Facilities						
Capacity	Total of all Facilities at load center	(MW)	Long Term	610	339	-271
			Driest Periods	364	186	-179
Energy Generation	Total of all Facilities at load center	(GWh)	Long Term	4,299	2,548	-1,750
			Driest Periods	2,269	1,229	-1,040
Generation Revenue	Total of all Facilities	($1,000)	Long Term	248,338	141,999	-106,338
			Driest Periods	131,298	68,415	-62,883
Pumping Facilities						
Energy Use	Total of all Facilities at load center	(GWh)	Long Term	7,740	2,479	-5,261
			Driest Periods	4,570	1,433	-3,137
Power Costs	Total of all Facilities	($1,000)	Long Term	402,469	127,827	-274,641
			Driest Periods	236,799	73,590	-163,209
Losses						
Foregone Energy	Total of all Facilities	(GWh)	Long Term	75	78	3
			Driest Periods	1	5	4
Transmission Losses	Total of all Facilities	(GWh)	Long Term	141	101	-39
			Driest Periods	71	48	-23
Total						
Net Generation	Total of all Facilities	(GWh)	Long Term	-3,441	69	3,511
			Driest Periods	-2,300	-204	2,097
Net Revenue	Total of all Facilities	($1,000)	Long Term	-154,131	14,172	168,303
			Driest Periods	-105,501	-5,175	100,326

Notes:
1. Long Term is the average quantity for the calendar years 1922-2002.
2. Driest Periods is the average quantity for the calendar years 1929-1934, 1976-1977, and 1987-1992.
3. 2009 Forecast (in 2007 $); Prices are forward prices as of 08/25/2009 and were developed by DWR power portfolio section.(extrapolated from a linear trend that was fitted to the estimates beginning in late 2009 and ending in 2039)

4.6 Cost Estimates for Loss of M&I Supplies South of the Delta

When comparing the existing conditions, there are significant reductions in the SWP Delta exports with the SWRCB DFC that translate into a significant savings in pumping costs for the SWP. It has been suggested that an alternative comparison which recognizes that the M&I water lost with reduced Delta exports could be replaced with an equivalent amount of water produced using desalinization.

An estimate of desalinization cost (independent of conveyance) was determined to range between 3,260 and 4,900 kWh/AF (**Table 15**).

Table 15 - Power and Pumping Cost Reporting Metrics, Combined Model Results with Desal (3,260 kWh/AF)

Power and Pumping Cost Reporting Metrics

Combined Model Results With Desal (3,260 kWh/AF)				Existing	SWRCB DFC W/TRN Adj	Difference
Combined CVP and SWP Facilities						
Power Facilities						
Energy Generation	Total of all Facilities at load center	(GWh)	Long Term	9,008	6,199	-2,808
Generation Revenue	Total of all Facilities	($1,000)	Long Term	525,133	348,416	-176,716
Pumping Facilities						
Energy Use	Total of all Facilities at load center	(GWh)	Long Term	8,916	3,008	-5,908
Power Costs	Total of all Facilities	($1,000)	Long Term	463,239	155,390	-307,850
Desal						
Energy Use	Total of all Facilities at load center	(GWh)	Long Term	0	3,514	3,514
Power Costs	Total of all Facilities	($1,000)	Long Term	0	181,508	181,508
Total						
Net Generation	Total of all Facilities	(GWh)	Long Term	92	-323	-415
Net Revenue	Total of all Facilities	($1,000)	Long Term	61,894	11,519	-50,375

Notes: 1. Long Term is the average quantity for the calendar years 1922-2002.
2. 2009 Forecast (in 2007 $); Prices are forward prices as of 08/25/2009 and were developed by DWR power portfolio section.(extrapolated from a linear trend that was fitted to the estimates beginning in late 2009 and ending in 2039)

Table 16 - Power and Pumping Cost Reporting Metrics, Combined Model Results with Desal (4,900 kWh/AF)

Power and Pumping Cost Reporting Metrics

Combined Model Results With Desal (4,900 kWh/AF)				Existing	SWRCB DFC W/TRN Adj	Difference
Combined CVP and SWP Facilities						
Power Facilities						
Energy Generation	Total of all Facilities at load center	(GWh)	Long Term	9,008	6,199	-2,808
Generation Revenue	Total of all Facilities	($1,000)	Long Term	525,133	348,416	-176,716
Pumping Facilities						
Energy Use	Total of all Facilities at load center	(GWh)	Long Term	8,916	3,008	-5,908
Power Costs	Total of all Facilities	($1,000)	Long Term	463,239	155,390	-307,850
Desal						
Energy Use	Total of all Facilities at load center	(GWh)	Long Term	0	5,282	5,282
Power Costs	Total of all Facilities	($1,000)	Long Term	0	272,830	272,830
Total						
Net Generation	Total of all Facilities	(GWh)	Long Term	92	-2,091	-2,183
Net Revenue	Total of all Facilities	($1,000)	Long Term	61,894	-79,803	-141,697

Notes: 1. Long Term is the average quantity for the calendar years 1922-2002.
2. 2009 Forecast (in 2007 $); Prices are forward prices as of 08/25/2009 and were developed by DWR power portfolio section.(extrapolated from a linear trend that was fitted to the estimates beginning in late 2009 and ending in 2039)

4.7 Characteristics of San Joaquin River Tributary Hydropower Conditions with the SWRCB DFC

The SWRCB DFC affects operations on the San Joaquin River and its tributaries presented here are the effects on the Stanislaus (New Melones), Tuolumne (Don Pedro), and Merced (Exchequer) rivers. (Note that results from the Stanislaus River operations at New Melones, a CVP facility have been included in the CVP results reported in Section 4.3.)

4.7.1 New Melones (CVP)

4.7.1.1 Energy

Table 17 - Energy (GWH)

	Water Year Type					
	W	AN	BN	D	C	All Years
Existing (BO's) and SWRCB DFC Study						
Existing (BO's)	603	508	429	400	305	467
SWRCB DFC	590	462	356	297	234	412
Change from Existing (BO's)						
Existing (BO's)	0	0	0	0	0	0
SWRCB DFC	-13	-47	-73	-103	-71	-55
% Change	-2%	-9%	-17%	-26%	-23%	-12%

4.7.1.2 Generation (GWH)

Table 18 - NM Generation – SWRCB DFC (Spreadsheet Model)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
W	15	6	3	2	24	53	83	158	131	45	43	27	590
AN	13	10	12	7	21	38	70	120	78	36	35	20	462
BN	11	6	4	5	10	30	59	97	60	27	27	18	356
D	15	9	6	6	9	26	49	68	39	26	29	16	297
C	9	8	6	5	10	23	38	47	28	21	23	17	234
All Ave	13	8	6	4	16	36	62	105	75	33	33	20	412

Table 19 - NM Generation – Existing (BO's) Study (Spreadsheet Model)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
W	30	12	12	22	16	58	75	91	81	80	74	52	603
AN	30	14	17	20	16	37	69	82	66	61	58	38	508
BN	30	10	7	10	10	27	65	71	54	56	54	35	429
D	28	12	8	9	10	20	56	68	50	54	52	32	400
C	17	11	7	7	10	20	37	49	40	42	40	25	305
All Ave	27	12	11	15	13	36	62	74	61	61	58	38	467

Table 20 - NM Generation – SWRCB DFC (Spreadsheet Model) minus NM Generation – Existing (BO's) Study (Spreadsheet Model)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
W	-14	-6	-9	-20	8	-5	8	67	50	-35	-32	-25	-13
AN	-17	-3	-5	-13	5	1	1	38	13	-25	-23	-18	-47
BN	-19	-4	-3	-5	0	3	-6	26	6	-29	-27	-16	-73
D	-12	-4	-3	-3	-1	6	-7	0	-11	-29	-24	-15	-103
C	-9	-2	-1	-2	0	3	1	-2	-12	-21	-18	-8	-71
All Ave	-14	-4	-5	-10	3	1	1	31	14	-28	-25	-17	-55

4.7.2 Don Pedro

4.7.2.1 Energy

Table 21- Energy (GWH)

	Water Year Type					
	W	AN	BN	D	C	All Years
Existing (BO's) and SWRCB DFC Study						
Existing (BO's)	865	652	481	450	288	584
SWRCB DFC	672	531	382	313	198	449
Change from Existing (BO's)						
Existing (BO's)	0	0	0	0	0	0
SWRCB DFC	-193	-120	-99	-137	-90	-135
% Change	-22%	-18%	-21%	-30%	-31%	-23%

4.7.2.2 Generation – GWH

Table 22 - DP Generation – SWRCB DFC (Spreadsheet Model)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
W	13	8	10	24	55	77	101	123	114	63	53	30	672
AN	12	5	14	16	41	52	82	115	105	37	32	19	531
BN	14	6	6	10	20	35	69	104	82	14	14	8	382
D	16	7	7	11	17	30	59	88	51	10	10	5	313
C	6	5	5	8	12	23	40	55	31	5	6	2	198
All Ave	12	6	9	15	32	48	74	100	81	30	27	15	449

Table 23 - DP Generation – Existing (BOs) Study (Spreadsheet Mode)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
W	25	10	21	49	80	109	105	101	124	121	74	45	865
AN	23	14	30	35	49	75	79	82	72	85	69	40	652
BN	24	8	10	14	16	44	66	70	61	73	60	34	481
D	29	10	9	14	14	37	57	64	60	70	57	30	450
C	21	8	6	11	11	22	35	39	37	44	36	18	288
All Ave	24	10	16	28	40	64	72	75	77	83	60	35	584

Table 24 - DP Generation – SWRCB DFC (Spreadsheet Model) minus DP Generation – Existing (BO's) Study (Spreadsheet Model)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
W	-12	-2	-11	-24	-25	-32	-4	21	-10	-58	-21	-14	-193
AN	-11	-8	-16	-19	-7	-22	4	33	32	-48	-37	-21	-120
BN	-10	-2	-4	-4	3	-9	3	34	21	-58	-46	-26	-99
D	-12	-3	-2	-3	3	-7	3	24	-9	-59	-46	-25	-137
C	-15	-3	-2	-3	1	1	5	16	-6	-39	-30	-16	-90
All Ave	-12	-4	-8	-12	-8	-16	1	25	4	-53	-34	-19	-135

4.7.3 Exchequer

4.7.3.1 Energy

Table 25 Energy (GWH)

	Water Year Type					
	W	AN	BN	D	C	All Years
Existing (BO's) and SWRCB DFC Study						
Existing (BO's)	521	373	282	281	175	349
SWRCB DFC	416	331	222	158	60	258
Change from Existing (BO's)						
Existing (BO's)	0	0	0	0	0	0
SWRCB DFC	-105	-42	-60	-123	-115	-90
% Change	-20%	-11%	-21%	-44%	-66%	-26%

4.7.3.2 Generation – GWH

Table 26 - Merced Generation - SWRCB DFC

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
W	5	2	5	12	32	41	58	72	71	53	44	21	416
AN	7	4	8	11	23	24	48	65	61	40	30	10	331
BN	6	2	3	2	5	17	35	52	47	28	21	4	222
D	5	3	2	3	4	14	27	36	30	20	13	1	158
C	3	1	1	1	1	4	8	15	12	7	6	1	60
All Ave	5	3	4	7	16	22	38	51	47	32	25	9	258

Table 27 - Merced Generation - Existing (BO's) Study w/o VAMP

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
W	12	8	16	29	40	39	37	73	77	75	79	35	521
AN	13	8	18	18	27	17	29	55	56	56	52	25	373
BN	12	7	6	7	7	17	30	41	49	51	40	17	282
D	14	8	7	7	8	20	33	41	46	47	35	15	281
C	10	4	4	4	4	11	21	28	30	30	23	6	175
All Ave	12	7	11	15	20	23	31	51	54	54	50	21	349

Table 28 - Merced Generation - SWRCB DFC minus Merced Generation - Existing (BO's) Study without VAMP

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
W	-7	-6	-11	-17	-9	2	21	-1	-6	-22	-35	-13	-105
AN	-6	-3	-10	-7	-4	7	19	10	5	-16	-22	-15	-42
BN	-6	-4	-3	-5	-2	0	5	10	-1	-23	-18	-14	-60
D	-8	-5	-5	-4	-4	-6	-6	-6	-16	-27	-22	-13	-123
C	-7	-3	-3	-3	-3	-7	-13	-13	-18	-23	-17	-5	-115
All Ave	-7	-4	-7	-8	-5	0	7	0	-7	-22	-24	-12	-90

DELTA OUTFLOWS AND OTHER STRESSORS

PUBLIC WATER AGENCIES SLDMWA/SWC

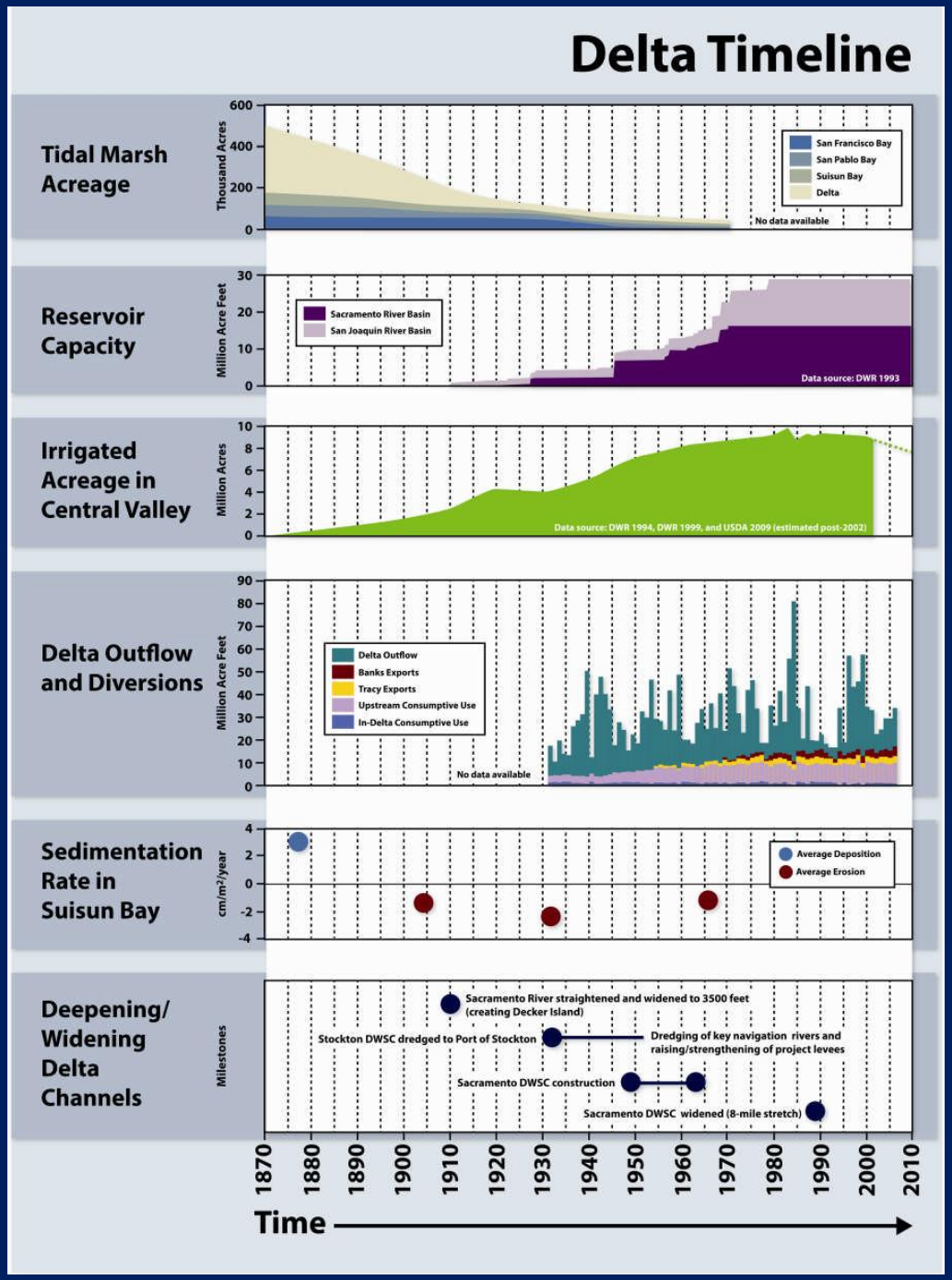
Key Points

- Regulation of flow should be considered as part of comprehensive set of actions intended to restore Delta ecosystem function(s);

- Need reasonable certainty that additional flow would provide targeted ecosystem function(s) given highly altered system and limited availability of water resources serving competing beneficial uses;

- Aspects of the science regarding outflow are uncertain and in dispute. Significant resources are being invested in science to reduce uncertainties, resolve disagreements, and identify future conservation measures.

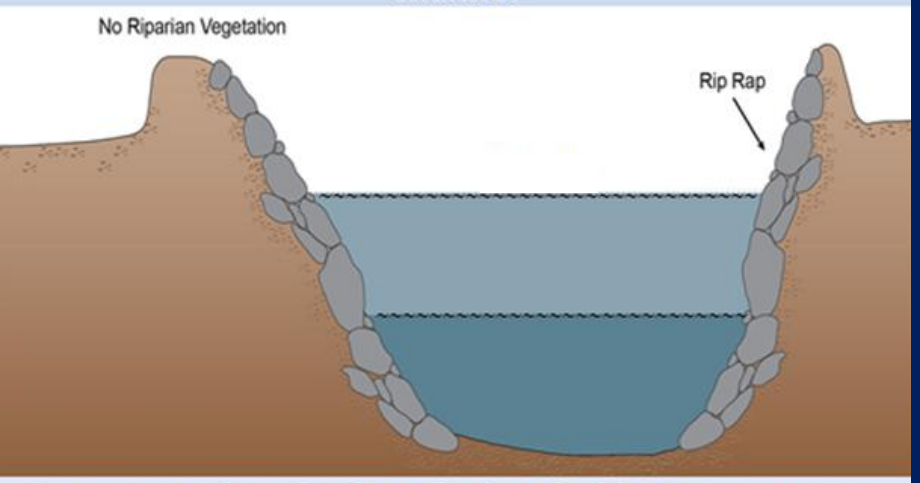
Environmental Context: Highly Altered System



Outflow
Exports
Consumptive Use

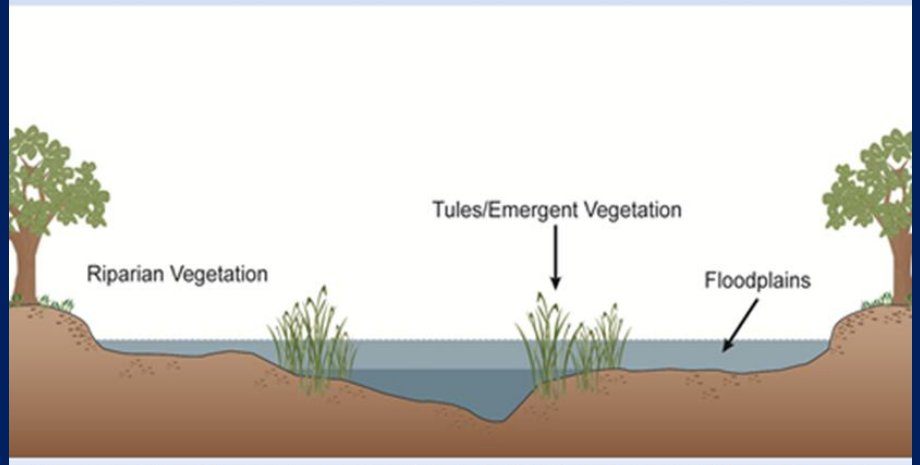
Need Reasonable Certainty the Changing Outflow Will Provide Targeted Ecosystem Functions

Flow functions are diminished in altered channel



Cross-section through a channelized reach of the Sacramento River showing change in habitat as a function of changes in river flow.

Changes in habitat can be a function of changes in river flow



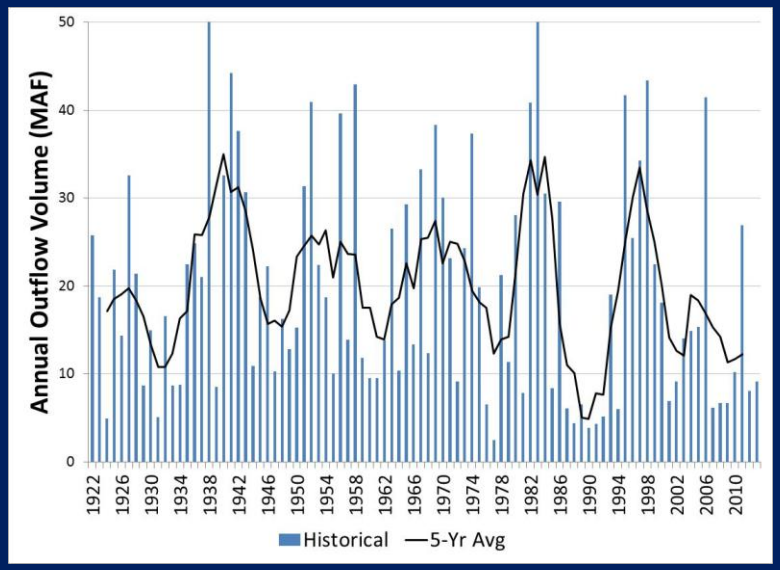
Cross section through a natural (historic) Sacramento River channel showing the change in habitat as a function of changes in river flow.

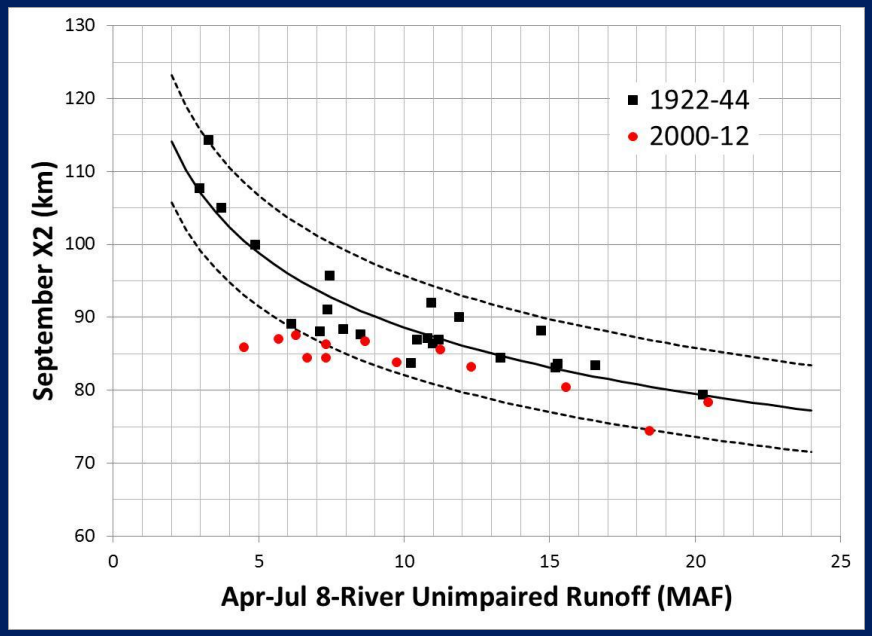
In the highly altered Bay-Delta ecosystem, function may not be improved with reservoir releases through leveed, riprapped channels. A suite of restoration approaches can restore habitat functions.

Disagreements About How Outflows Have Changed Over Time

There is no long-term annual trend in outflow.

Significant outflow variability continues to exist due to climatic variability.

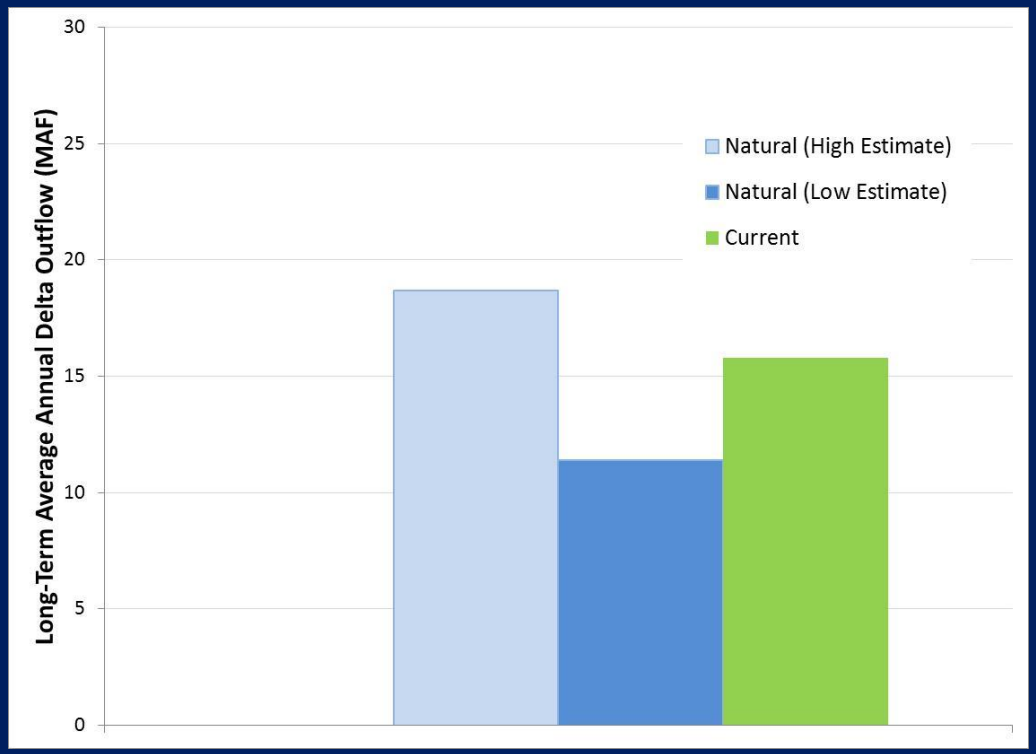




Fall X2 position does not resemble dry conditions regardless of water year type.

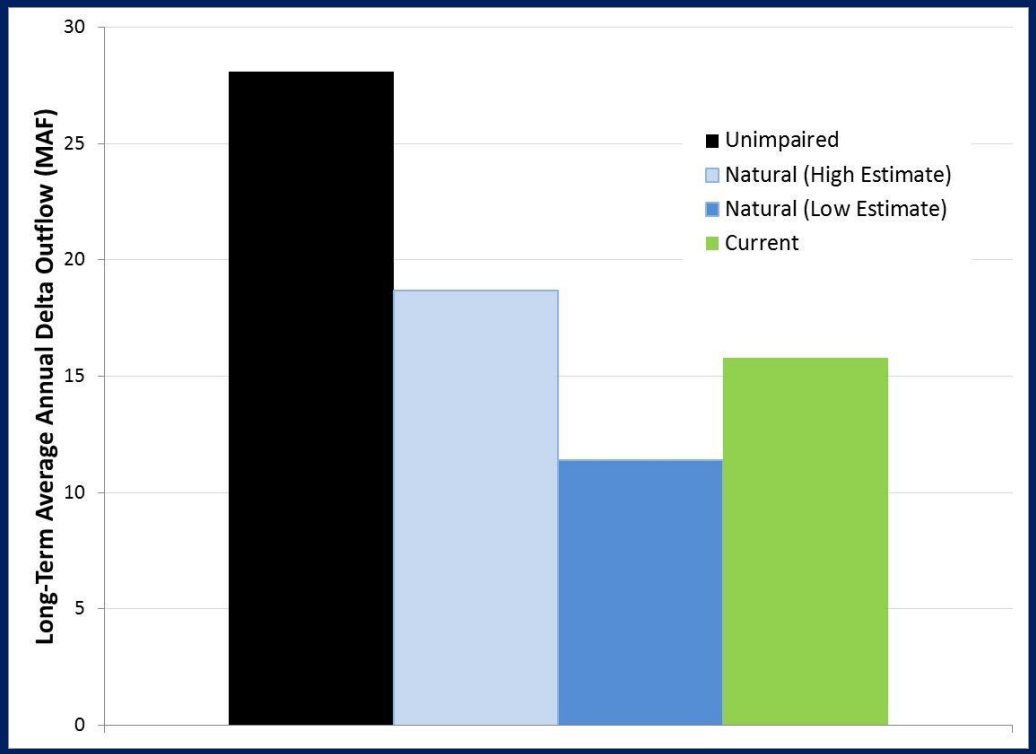
Rather, CVP-SWP operations augment the position of X2 following drier springs to resemble wetter conditions.

Disagreement About How Outflows Have Changed Since Predevelopment



Current annual outflow is about the same as pre-development outflow.

Disagreement About How Outflows Have Changed Since Predevelopment



Current annual outflow is about the same as pre-development outflow.

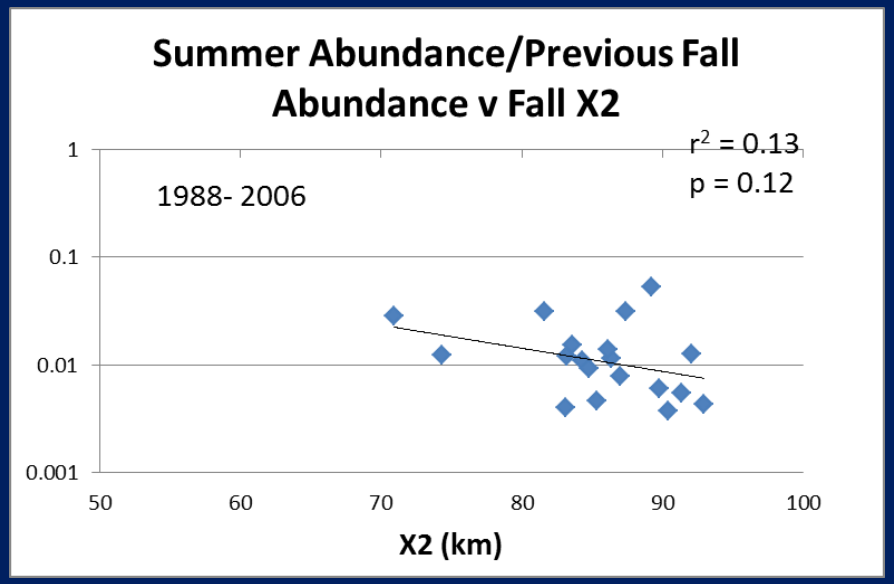
The unimpaired outflow calculation does not accurately represent pre-development outflow.

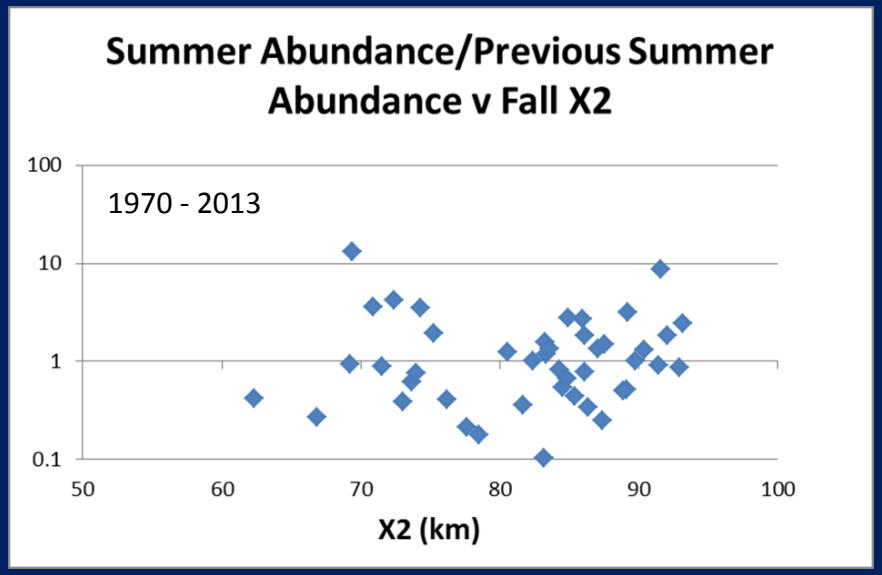
Critical Reviews of Statistical Analyses Highlight Uncertainties (Delta Smelt)

Statistical outcomes that vary widely depending on years of data and techniques used should be given weak consideration.

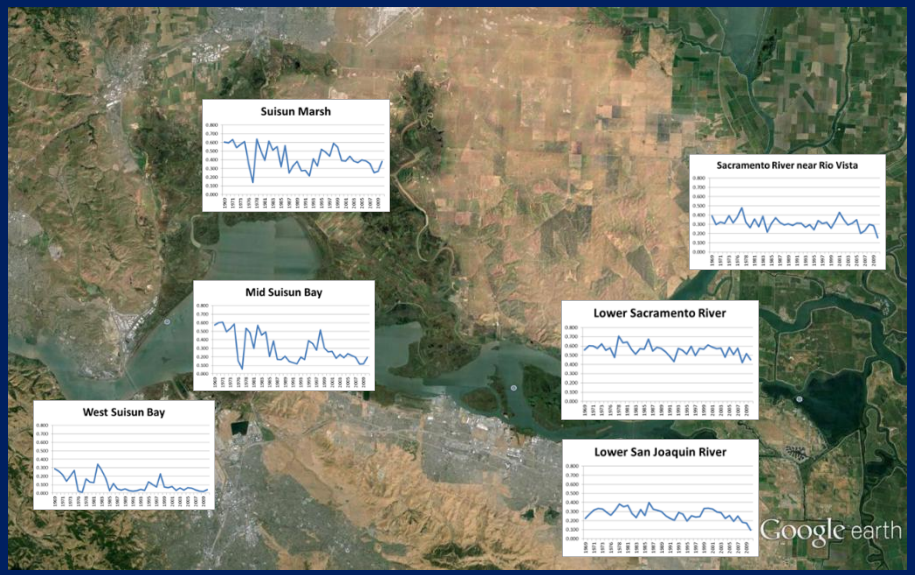
Peer reviews have raised questions about analyses underlying Fall X2 RPA.

Results of recent statistical analysis are inconclusive regarding relationship between abundance and Fall X2.



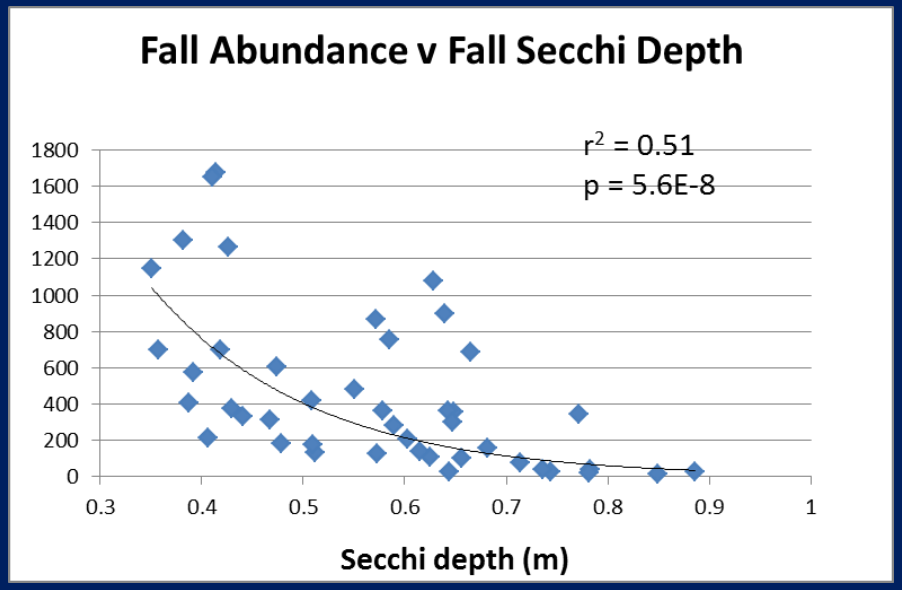


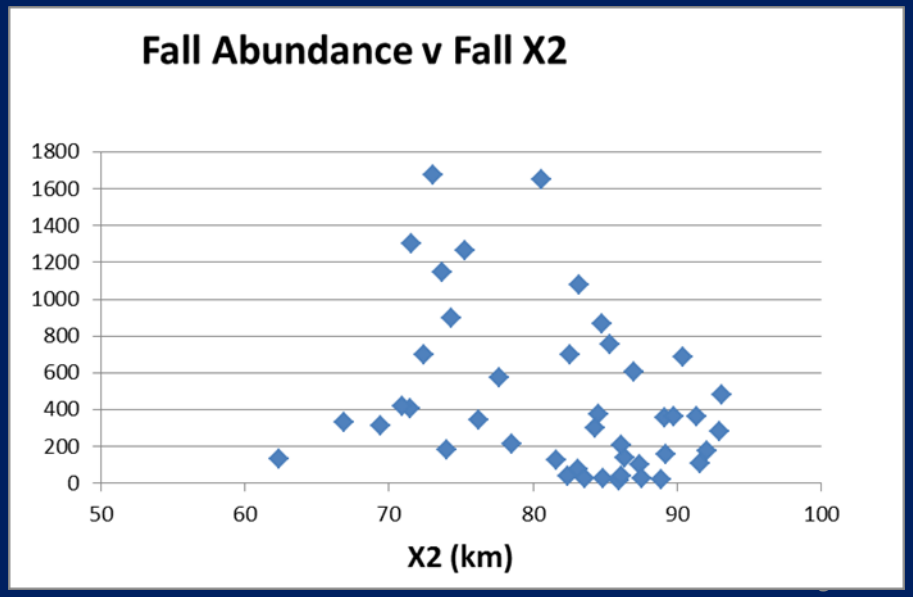
New Analysis Suggests New Perspective (Delta Smelt)



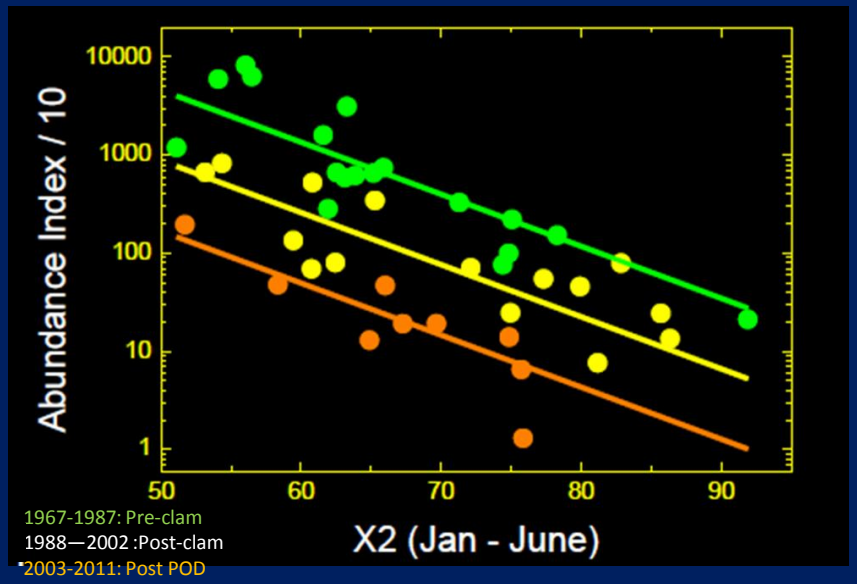
Feyrer *et al.* 2011 did not find significant relationship between abundance and Fall X2, creating a habitat index instead.

New analyses suggest habitat factor driving relationship between smelt presence/absence is Secchi depth not Fall X2.

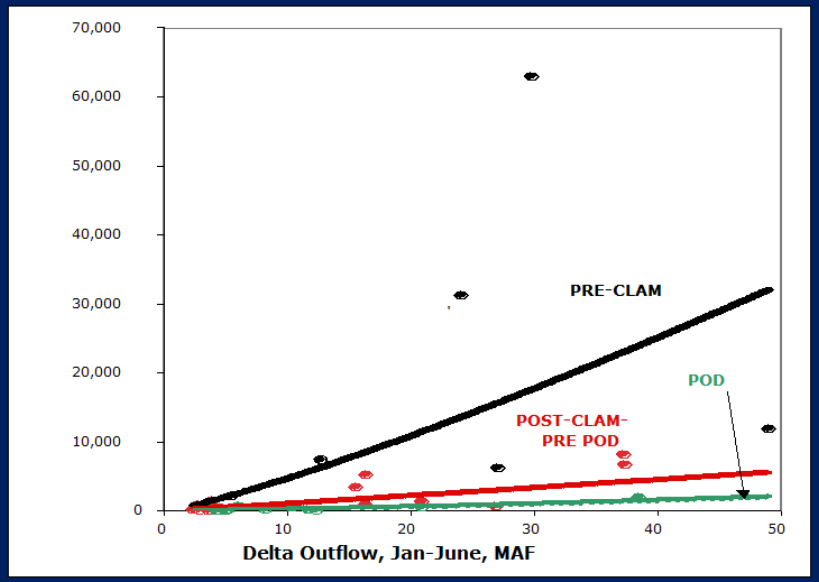


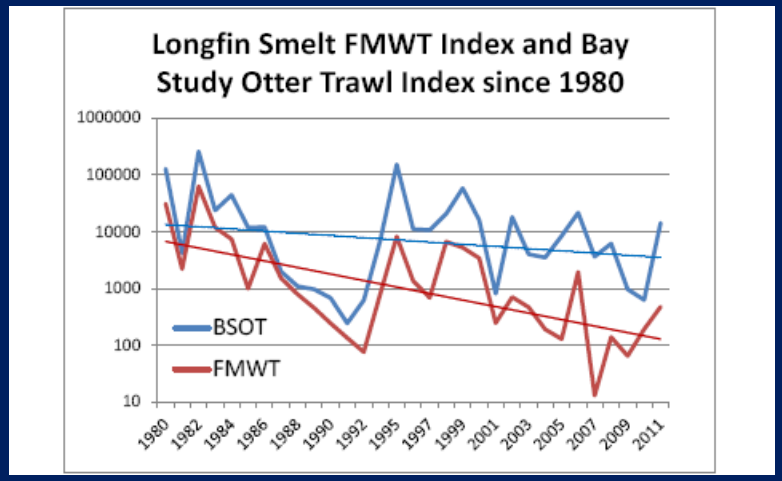


New Analyses Suggest New Perspective (Longfin smelt)



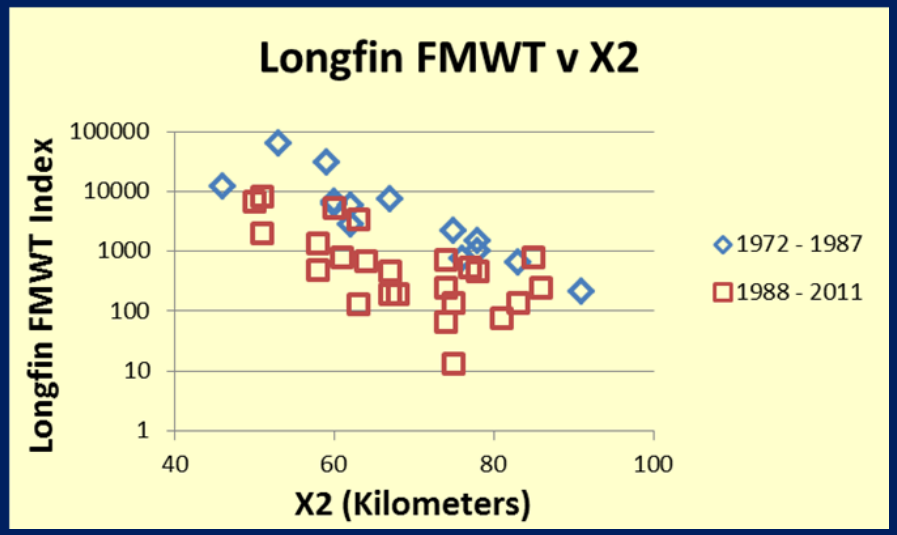
Current FMWT:X2 relationship suggests large outflows achieve only small short-term abundance increases

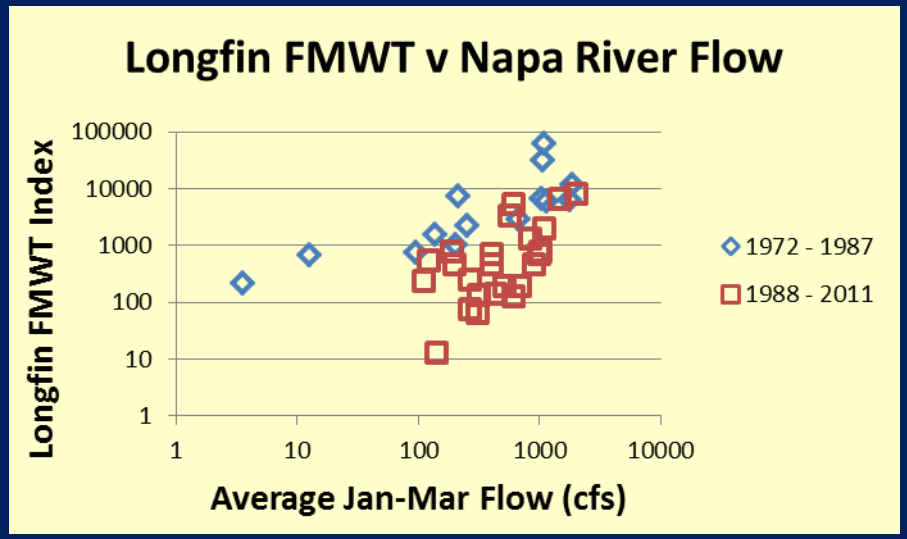


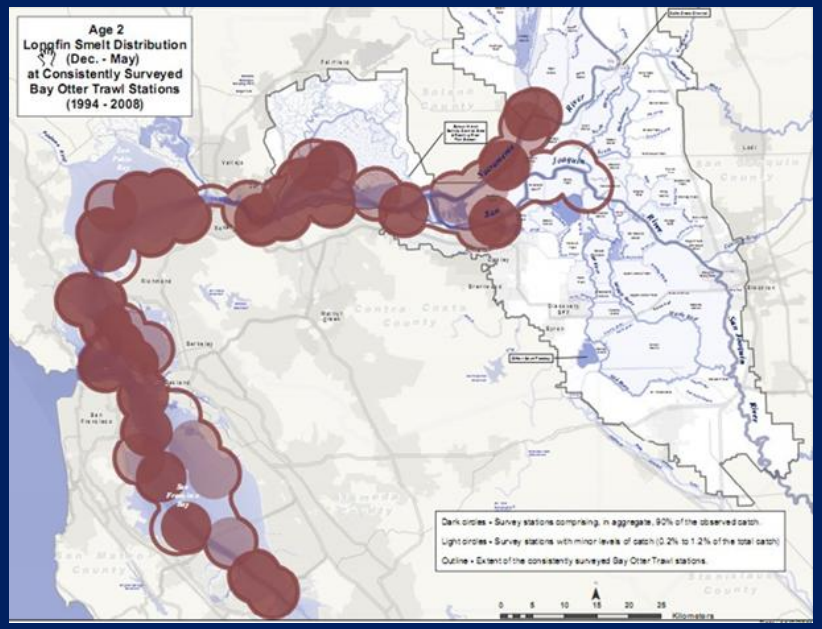


Different sampling surveys suggest different abundance trajectories.

New Analyses Suggest New Perspective (Longfin smelt)





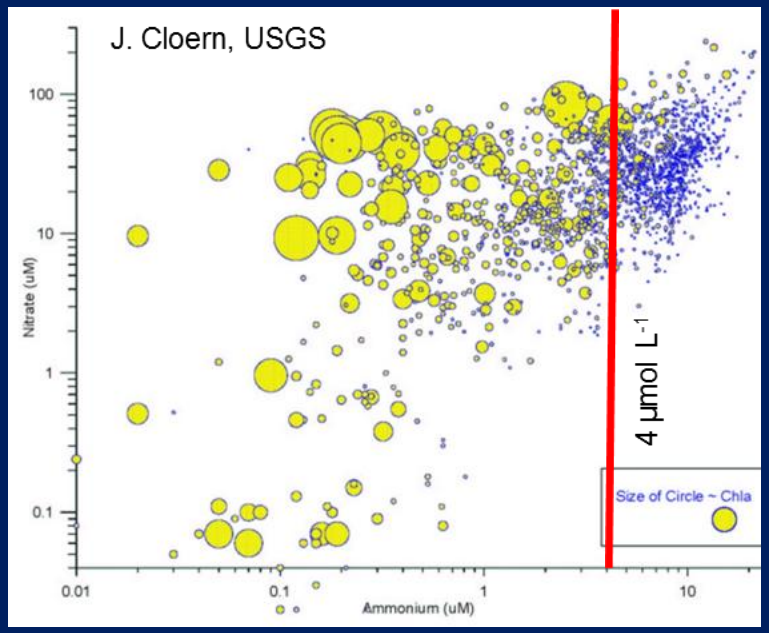


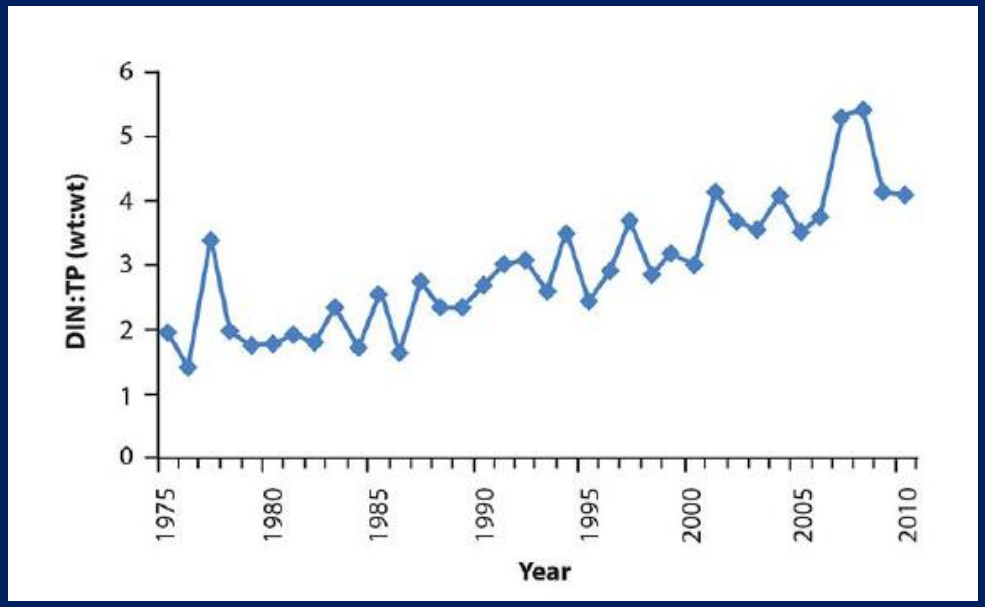
Correlation is not necessarily causation. Informed decision making requires an understanding of the life history and underlying mechanisms.

System Complex: Multiple Hypotheses Regarding System Change

Possible explanation: changes in nutrient ratios and concentrations.

Decreases in productivity. Chl-a associated with high NH_4 and low NO_3.



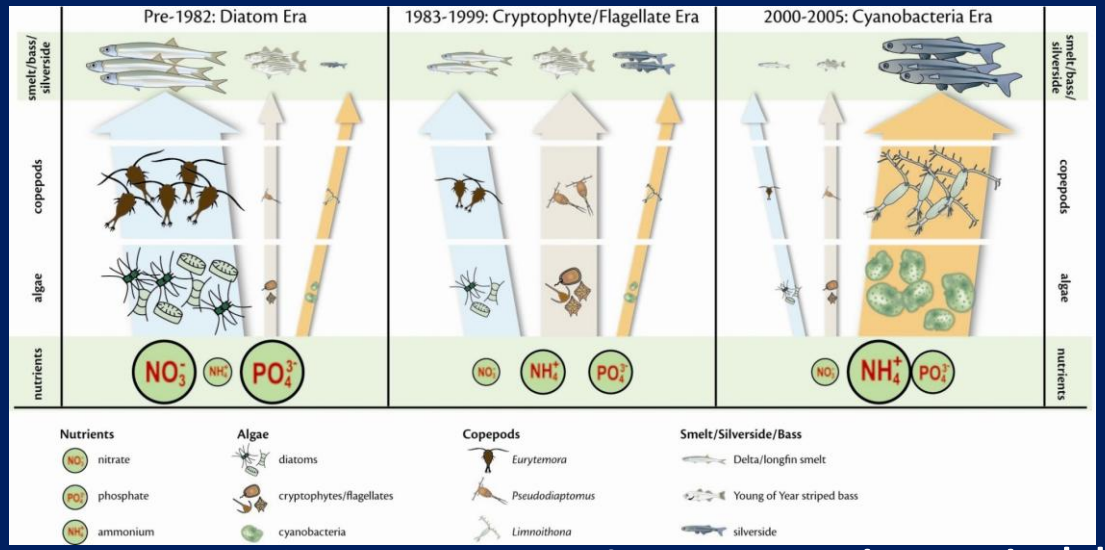


Source control is preferable to dilution using outflow (*See*, Dugdale *et al.* 20XX).

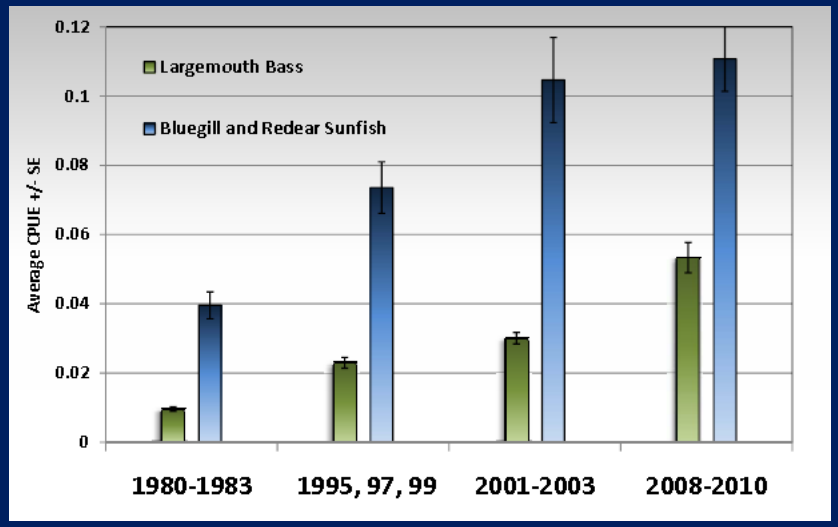
Flow can help with dilution but not ratios.

A Variety of Factors are Changing in the Delta

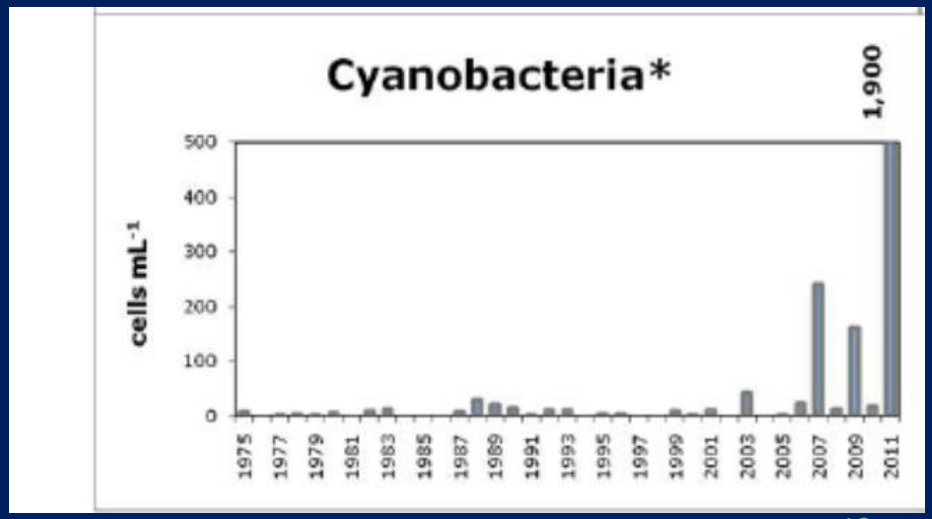
Changes in speciation



Increases in predators



Increases in toxic blue-green algae



Science Investigations To Address Uncertainties

Survey Inefficiencies: FWS initiated process to investigate survey inefficiencies to determine better ways to estimate delta smelt abundance and distribution

Longfin smelt studies: DFW, SWC and other collaborators have identified a suite of studies that will expand current understanding of longfin smelt distribution, abundance, abundance trends, spawning locations, and the relationship between Delta outflow and longfin smelt abundance.

Outflow and salinity trend studies: The PWAs, SFEI, UCD, and CSU San Luis Obispo are evaluating outflow and salinity under "natural" or pre-development conditions.

CSAMP: Collaborative process developing study plans to evaluate the relationship between fall outflow and subsequence abundance of delta smelt and efficacy of Fall X2 action.

Restoration Actions To Improve Ecosystem

Bay Delta Conservation Plan: BDCP will restore thousands of acres of habitat, undertake a suite of measures to address other stressors, and embark on a long-term investigation and adaptive management plan to address issues such as outflow, predation, contaminants, and restoration of natural processes.

SRCSD Wastewater Treatment Plant Upgrade: Nutrient loading and its effect on the food web and the Delta environment being addressed through wastewater treatment plan upgrade.

Conclusion

- Regulation of flow should be considered as part of comprehensive set of actions intended to restore Delta ecosystem function(s);

- Need reasonable certainty that additional flow would provide targeted ecosystem function(s) given highly altered system and limited availability of water resources serving competing beneficial uses;

- Aspects of the science regarding outflow are uncertain and in dispute. Significant resources are being invested in science to reduce uncertainties, resolve disagreements, and identify future conservation measures.

***Supporting materials available Http://www....*

SAN FRANCISCO ESTUARY & WATERSHED SCIENCE
Sponsored by the Delta Science Program and the UC Davis John Muir Institute of the Environment

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Salinity trends, variability, and control in the northern reach of the San Francisco Estuary

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Author:
Enright, Christopher, California Dept. of Water Resources
Culberson, Steven D, Calfed Science Program

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Keywords:
Delta, Suisun Marsh, outflow, salinity, trend, variability

Abstract:
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Salinity trends, variability, and control in the northern reach of the San Francisco Estuary

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Steven D. Culberson, CALFED Science Program

ABSTRACT

The California State Water Project and federal Central Valley Water Project decoupled long-term trends in annual mean outflow and salinity from long-term trends in precipitation. The water projects also dampen seasonal and annual outflow and salinity variability. Despite this, both seasonal and annual timescale outflow and salinity are generally more variable in the water project era concordant with watershed precipitation. We re-constructed monthly time series of precipitation, outflow, and salinity for the northern reach. These include salinity at Port Chicago (since 1947), Beldons Landing (since 1929), and Collinsville (since 1921), Sacramento-San Joaquin Delta outflow (since 1929), and a San Francisco Estuary watershed precipitation index (since 1921). We decomposed data into seasonal, decadal, and trend components to clarify the superposition of variability drivers. With the longest time series over 1,000 months, these are the longest data records in the estuary, save for Golden Gate tide. We used the precipitation index to compare trends and variability in climate forcing to outflow and salinity trends before and after construction of the state and federal water projects and the Suisun Marsh Salinity Control Gate. We test the widely held conceptual model that water project reservoir and delta export operations reduce seasonal and annual outflow variability. We found that the water projects influence the trend of the annual and some monthly means in outflow and salinity, but exert far less influence on variability. We suggest that climate is the primary variability driver at timescales between one-month and ~20 years. We underscore the understanding that identifying trends and mechanisms requires data sets that are longer than the timescale of the lowest frequency forcing mechanism.

KEYWORDS

Sacramento-San Joaquin Delta, outflow, salinity, trend, variability.

INTRODUCTION

State and federal water projects in California modify the magnitude and seasonal timing of San Francisco Estuary watershed river inflows and outflow from the Sacramento-San Joaquin Delta. Water project exports from the Sacramento-San Joaquin Delta reduce river outflow through the estuary more than 20% on average since 1968, primarily for southern state agricultural and municipal water demands. From the inception of the water projects, investigators have warned that these activities change the physical and chemical estuarine environment in ways that are detrimental

to estuary-dependent species (Mall 1969; Hedgepeth 1979; Moyle and others 2004). Outflow reduction and modification of seasonal outflow timing affects biota by changing their transport fate, modifying salinity habitat, and shifting the availability of geomorphic habitat types, especially those associated with or adjacent to salinity habitat (e.g. Kimmerer 2003; Simenstadt 2001).

State and federal water agencies responded to concerns about water project impacts with large-scale and long-term mitigation efforts including the Suisun Marsh Plan of Protection (1977), the CALFED Ecosystem Restoration Program (CALFED 2000), and the Bay-Delta Conservation Plan (BDCP 2009). In the case of Suisun Marsh, over $130 million has been spent on salinity control facilities and local assistance to private landowners. During planning for the State Water Project (SWP) in the 1960s, investigators suggested that waterfowl habitat in the Suisun Marsh could be degraded when lower outflow increased channel water salinity leading to higher soil water salinity and reduction in waterfowl food plant abundance (George 1965; Mall 1969; Rollins 1973).

The northern reach of the San Francisco Estuary (Figure 1) has long been a focus of ecosystem management and attempts to control salinity (Means 1928; California Water Plan 1957; George 1965; Mall 1969; Rollins 1973; Jackson and others 1977). The estuarine salinity gradient is generally steepest and many organisms have abundance maximums in Suisun Bay (Jassby and others 1995). The seasonal magnitude of outflow is positively correlated with abundance of aquatic species across trophic levels (Jassby and others 1995; Kimmerer 2004). Mechanisms for the relationship remain somewhat uncertain and are different from one species and life-stage to the next (Kimmerer 2002). Despite the lack of demonstrated direct or indirect mechanistic linkages, considerable water resources and management effort (via regulatory water quality standards) are dedicated to affecting seasonal outflow conditions to protect salinity habitat (SWRCB 1995). In parallel,

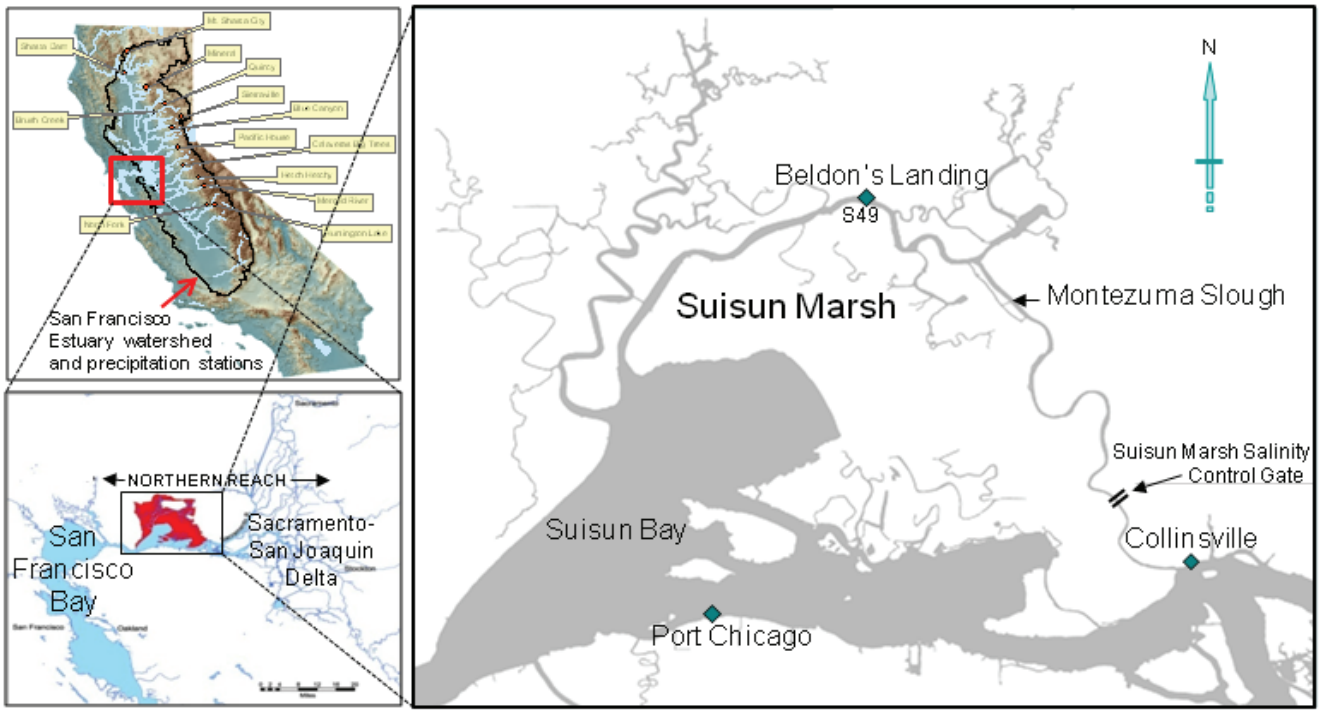

Figure 1 Location of Suisun Marsh, the northern reach of the San Francisco Estuary and historical salinity stations Port Chicago, Beldons Landing, and Collinsville. California map shows location of thirteen foothill precipitation stations within the San Francisco Estuary watershed.

there are ongoing science programs that would identify the process linkages between outflow, and native species abundance, presumably to improve the effectiveness of future water quality standards (e.g. Healy and others 2008).

The purpose of this paper is to describe long-term trends and variability in San Francisco Estuary watershed precipitation, and northern reach outflow and salinity. It is complementary to the work of Knowles (2002) who considered the same problem using a combination of data and modeling to discern the contribution of climate and water project operations on monthly and interannual salinity variability. This analysis also updates of the work of Fox and others (1990) who showed that despite increasing water depletions, outflow had not declined. They cite increasing precipitation, land use induced runoff increase, increased surface flow resulting from groundwater overdraft, and water imports from other drainages.

This work relies on up to 86 years of precipitation, outflow, and salinity data. The length of the data sets allows us to examine trend and variability differences between pre- and post-water project periods (defined later as before and after 1968). These time series offer a unique opportunity to investigate long-term trends because they are long enough to span decadal timescale climate processes. We posit several physical processes that affect long-term salinity trends and variability and compare them to the magnitude of water project induced change.

DATA FOR ANALYSIS OF PRE-PROJECT AND POST- PROJECT TRENDS

A primary aim of this analysis is to detect precipitation, outflow, and salinity trends and modes of variability to discern outflow and salinity response to State and federal water project operation (Figure 2). Monthly average specific conductance (SC), delta outflow, and San Francisco Estuary watershed precipitation were divided into "pre" and "post" water project periods. The federal Central Valley Project began delta water exports in 1950, the State Water Project in 1969 (Figure 2, panel B). Up to 1967, there were no facilities south of the delta to store winter and spring Sierra Nevada runoff through the delta. The water projects began year-round pumping operations in 1968 when San Luis Reservoir was completed. The advent of south-of-delta storage allowed four-season water project export from the delta. For the purposes of this analysis, we define the "pre" water project period as years prior to San Luis Reservoir operation (1929-1967). Accordingly, we define the "post" water project period as 1968 to the present. Since the three salinity stations are also influenced by the Suisun Marsh salinity control gate (SMSCG), the pre- and post-SMSCG periods around 1988 are also delineated.

Precipitation Data

The California Department of Water Resources (DWR) maintains records of monthly average tributary precipitation for the San Joaquin and Sacramento River watersheds as an index of runoff potential to the State and federal water project reservoirs (California Water Supply Outlook). The Sacramento River tributary average includes eight northern Sierra Nevada foothill and northern coast range stations while the San Joaquin river tributary average includes five central and southern Sierra Nevada stations (Figure 1). We aggregated the two indexes into one monthly 13-station average index to represent the 140,000 square kilometer estuary watershed region, an area comprising about 40% of the State (Conomos 1979). We also produced an annual average watershed precipitation time series by summing October through September (water year) monthly averages (Figure 2, panel A). The precipitation records cover the period from October 1920 to September 2006.

For our purpose, the 13-station average represents an index of climate forcing for the San Francisco Estuary watershed. To the extent that trends in 13-station precipitation variability and mean are correlated with delta outflow, the index is a proxy for outflow trends we would expect without water project influence or changes in watershed runoff dynamics. We acknowledge that the index is influenced by antecedent soil moisture, north-to-south Sierra Nevada elevation differences (Dettinger and others 1998), the temporal trend toward earlier Sierra Nevada runoff with time (Roos 1987), and differences

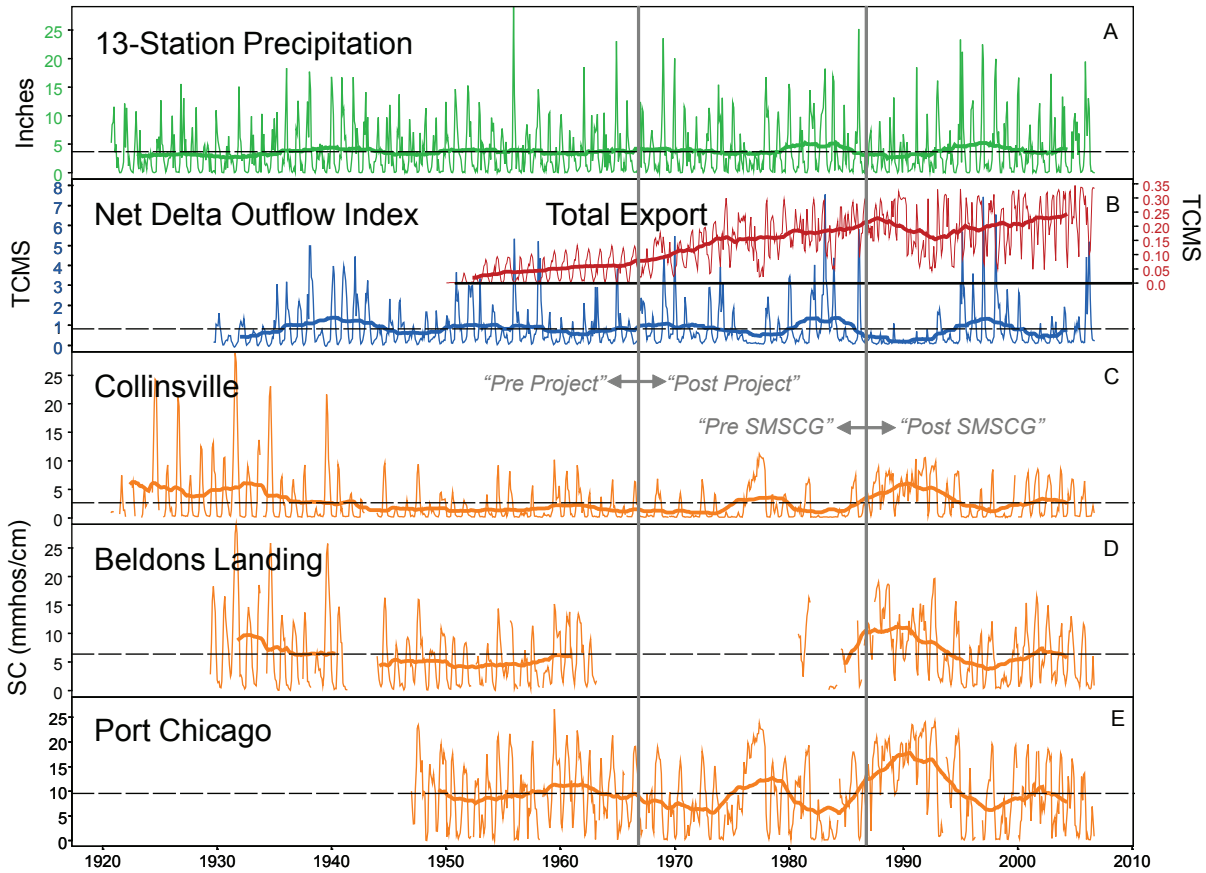

Figure 2 (A): Monthly average of 13 Sierra Nevada foothill precipitation stations on tributaries of the San Francisco Estuary watershed (1920-2006). (B): Monthly Delta outflow index. Right axis is monthly average total water project export. (C,D,E): Monthly average specific conductivity for Collinsville, Beldons Landing, and Port Chicago. Prior to 1966, SC is estimated from approximately four high tide TDS grab samples per week. Heavy solid line is 5-year running average. Dotted line is period of record mean.

in the variability modes between Sacramento and San Joaquin River inflows (Dettinger and Cayan 2003). For our purpose, aggregating tributary watershed precipitation enfolds changing tributary processes to maintain the focus on delta outflow and the coupled salinity response.

Sacramento-San Joaquin River Delta Outflow

Outflow from the Sacramento-San Joaquin Delta is the key physical process of the northern reach of the San Francisco Estuary. On subtidal time scales, outflow is the primary governor of ocean salt transport to the delta (Cheng 1990). While about 80% of outflow is contributed by the Sacramento River watershed, the San Joaquin River watershed accounts for much of the variability in late spring and summer delta salinity (Dettinger and Cayan 2003). We developed monthly and annual outflow estimates from the delta outflow index data set maintained by DWR (DWR Dayflow, 2003). Figure 2 (panel B) shows the monthly average delta outflow index for the period 1929 to 2006.

Suisun Bay and Suisun Marsh Salinity

We assembled long-term salinity time series for three northern reach stations (Figure 2, panels C,D,E). Monthly salinity as specific conductance (SC) was estimated for Port Chicago (Suisun Bay), Collinsville (Sacramento-San Joaquin River confluence), and Beldons Landing (Suisun Marsh) (Figure 1). Data were

gathered and digitized from multiple paper records in DWR hydrologic data bulletins (DWR Bulletin 27, and Bulletin 23, and Bulletin 130 series). Between 1920 and 1971, salinity data was collected as surface zone grab samples by local observers 1.5 hours after high-high tide (nominal high slack) every four days. The monitoring programs were initiated in response to early century drought concerns (Jackson and others 1977). Samples were bottled, time tagged, and mailed to an analysis laboratory where chloride and total dissolved solids (TDS) concentrations were measured. The observers recorded time deviation when samples were not collected at high-high tide. Depending on the station, 25% to 45% of the data was not collected at the prescribed time, though the majority of the deviations were recorded at 1.5 hours after low-high tide. We did not attempt to correct data to 1.5 hour after high-high tide salinity. We averaged grab samples within each month (seven to eight samples per month) to obtain an estimate of monthly average TDS at each station. Monthly average values were set to "missing" if less than four grab samples are available within a given month.

Continuous electrical conductivity (SC) recorders were installed in 1966 at Port Chicago and Collinsville affording approximately five years of overlapped grab sample TDS and continuously recorded SC. Data are available though the Bay/Delta and Tributaries Cooperative Data Management System (DWR/BDAT 2007). We averaged all data within each month to generate monthly average time-series. Monthly average values were set to "missing" if more than one-third of the 15-minute or hourly data is missing.

We converted the TDS data to an estimate of monthly average SC for the historical period with seasonal linear relationships between the overlapping continuous SC and grab sample TDS data. Scatter plots of the overlapping period (1966-70 for Collinsville, 1966-71 for Port Chicago) showed that simple linear models provide unbiased estimators of monthly average SC from TDS and explain 93% to 98% of the variance (Figure 3). Linear models were developed for the nominal wet (October through March) and dry (April through September) periods of the year. There is good agreement between the predicted monthly average SC based on the seasonal linear models versus the measured values. No overlapping SC and TDS data are available for Beldons Landing so the seasonal linear models developed for Collinsville were used to estimate Beldons Landing SC from the historical TDS data.

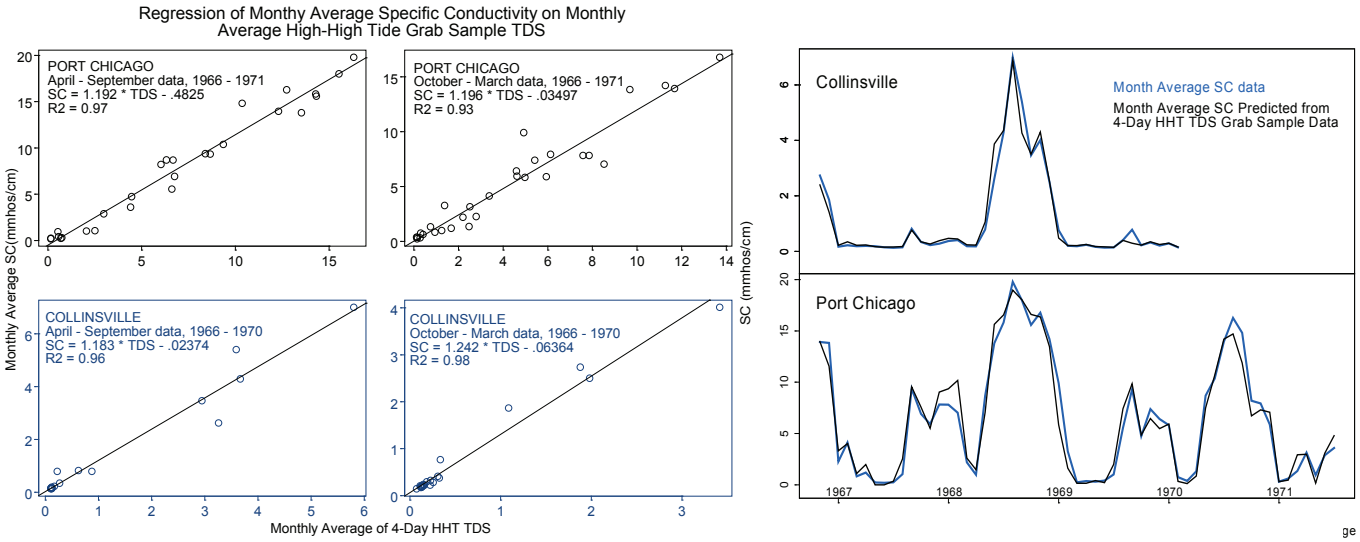

Figure 3 Regression of monthly average specific conductivity on monthly average high-high tide grab sample TDS. Continuous (15-minute) specific conductivity measurements and one per four day HHT TDS grab samples were taken simultaneously between 1966 and 1971. Separate regressions were calculated for approximately wet (Oct-Mar) and dry (Apr-Sep) periods. Right panels show actual monthly average SC for Port Chicago and Collinsville (blue line) versus monthly average SC predicted from regression models of monthly average SC on historical monthly average of 4-day HHT TDS (black).

DATA ANALYSIS METHODS

We used two nonparametric procedures to detect long-term trends and periodic processes. Kendall's tau is a measure of correlation or the strength of the relationship between a variable and, in this case, time (Hirsh 1984). "Seasonal loess time-series decomposition," was also used to differentiate seasonal climate and possible long-term climate teleconnections from long-term trends (Cleveland 1993). This method decomposes the monthly precipitation, outflow, and salinity time-series into frequency components of variation and trend by a sequence of local regression smoothings (Cleveland 2000). The "seasonal" component consists of 12 separate loess fits, one for each month. This feature allows analysis of among-month trends. The procedure does not allow for missing data. Since each of the three salinity data time-series contains missing data, we collapsed the time series and kept track of the missing data periods. We applied the seasonal loess procedure to the collapsed data, acquired a set of smooth decompositions, and then the decompositions were broken apart where data is missing.

RESULTS

In this section, we present and discuss trends in the mean and variability of San Francisco Estuary watershed precipitation, delta outflow, and northern reach salinity at decadal, annual, and seasonal timescales. Table 1 presents all of the summary statistics.

Historical Precipitation, Outflow, and Salinity Time-Series

Figure 2 shows the compiled monthly average time-series for the 13-station precipitation index (1920-2006; panel A), delta outflow (1929-2006; panel B), total export (1951-2006; panel B, expanded right axis), Collinsville (1920-2006; panel C), Beldons Landing (1929-2006; panel D), and Port Chicago (1947-2006; panel E). Each plot also includes the five-year running average the help visualize trends. With over 1,000 months in the time-series, Collinsville salinity is one of the longest records of any parameter in the San Francisco Estuary.

Figure 4 displays summary annual average means and standard deviations for 13-station precipitation, delta outflow, and salinity at the three Suisun Bay and Suisun Marsh stations. The first column covers the full period of record for each data set, while columns two, three, and four divide the data between pre-project, post-project, and post-SMSCG periods, respectively. Despite marginally higher post-project precipitation (47 inches/yr) compared to the pre-project average (43 inches/yr), delta outflow is lower in the post-project period (0.79 TCMS post-project vs. 0.84 TCMS pre-project). Mean salinity is consistent with outflow during pre- and post-project periods. The standard deviation of precipitation increases from 12 inches per year in the pre-project period to 17 inches per year in the post-project period. Similarly, Granger 1979 reported increasing northern California precipitation variability between 1961-1977. Delta outflow and each of the three salinity stations exhibit the same pattern of increased variability in the post-project period. Annual outflow is reduced after 1988 with concomitant increases in Suisun Bay salinity. Table 2 depicts pre- and post-project coefficient of variation as an index of variability on the annual and monthly time-scales. Post-project variability is greater than pre-project variability. In addition, salinity variability decreases from east to west.

Long-term Trend Decomposition: Possible Climate Teleconnections to Watershed Precipitation and Outflow

We applied the seasonal loess trend decomposition procedure to the monthly average data sets. Figure 5 shows each monthly time series decomposed into "seasonal," "decadal," and "trend" fits. Superposition of these signals along with the residual (not shown) returns the original time series (Figure 2). The right column shows the "seasonal" component that we tuned knowing there would be a 12-month frequency mode. The seasonal fit of the precipitation and outflow data well shows the annual pattern of the Mediterranean climate. The seasonal fits also indicate the tendency of wet and dry years to cluster together in nominally decadal pulses, especially in precipitation and outflow. Decadal pulses are somewhat less evident in the salinity data suggesting that additional

Table 1 Summary statistics–period of record for 13-station precipitation, delta outflow, and Collinsville, Beldons Landing, and Port Chicago specific conductivity

	Period	n	Median	Mean	Stnd Dev	CV	Lag-1 correl.	Lag-1 p	Kendall slope	Kendall p
Annual Average	13-STATION PRECIPITATION (inches)									
All data	1921-2006	86	42.4	44.9	14.4	0.32	-0.03	0.68	0.09	0.18
Pre-Water Project	1921-1967	47	42	42.8	11.8	0.27	-0.07	0.45	0.12	0.34
Post-Water Project	1968-2006	39	45.7	47.5	16.8	0.35	0.008	0.94	0.14	0.61
Pre-SMSCG	1921-1987	67	42.5	44.3	14.1	0.32	-0.1	0.22	0.12	0.19
Post-SMSCG	1988-2006	19	45.7	47.3	15.4	0.32	0.09	0.65	0.76	0.16
Monthy Average										
All data	10/21-9/06	1041	2.08	3.74	4.46	1.19	0.39	0		
Pre-Water Project	10/21-9/67	552	2.12	3.57	4.14	1.16	0.38	0		
Post-Water Project	10/67-9/06	480	2.08	3.92	4.77	1.22	0.4	0		
Pre-SMSCG	10/21-9/87	793	2.14	3.70	4.29	1.16	0.4	0		
Post-SMSCG	9/88-9-06	239	1.93	3.86	4.95	1.28	0.37	0		
Annual Delta Outflow	OUTFLOW (CMS)									
All data	1929-2006	86	709	820	530	0.64	0.15	0.06	-1.9	0.45
Pre-Water Project	1929-1967	47	691	837	476	0.57	0.03	0.79	1.8	0.76
Post-Water Project	1968-2006	39	710	795	575	0.72	0.28	0.02	-3.1	0.75
Pre-SMSCG	1929-1987	67	757	853	518	0.61	0	0.95	-6.2	0.98
Post-SMSCG	1988-2006	19	586	700	543	0.68	0.43	0.03	30	0.03
Monthly Delta Outflow										
All data	1929-2006	1041	383	821	1052	1.3	0.59	0		
Pre-Water Project	1929-1967	573	478	906	1076	1.18	0.54	0		
Post-Water Project	1968-2006	468	334	800	1124	1.41	0.65	0		
Pre-SMSCG	1929-1987	814	458	899	1106	1.22	0.58	0		
Post-SMSCG	1988-2006	227	270	706	1076	1.52	0.6	0		
Annual Average	COLLINSVILLE SPECIFIC CONDUCTIVITY (SC umhos/cm)									
All data	1920-2006	86	2057	2570	1988	0.77	0.33	0	-5.8	0.39
Pre-Water Project	1920-1967	47	1999	2537	1960	0.77	0.31	0.005	-72	0
Post-Water Project	1968-2006	39	2116	2605	2041	0.78	0.38	0.001	40	0.082
Pre-SMSCG	1920-1987	67	1951	2335	1954	0.84	0.28	0.002	-32	0.001
Post-SMSCG	1988-2006	19	2573	3326	1953	0.75	0.47	0.02	-200	0.042
Monthly Average										
All data	7/20-9/06	1041	884	2701	3820	1.41	0.64	0		
Pre-Water Project	7/20-9/67	552	809	2847	4493	1.59	0.6	0		
Post-Water Project	10/67-9/06	480	954	2577	2955	1.15	0.68	0		
Pre-SMSCG	7/21-9/87	793	659	2521	4016	1.59	0.63	0		
Post-SMSCG	10/88-9/06	239	2191	3342	3105	0.93	0.64	0		
Annual Average	BELDONS LANDING SPECIFIC CONDUCTIVITY (SC umhos/cm)									
All data	1929-2006	86	5898	6471	2663	0.41	0.4	0	-8.5	0.59
Pre-Water Project	1929-1967	47	5816	5983	2063	0.34	0.28	0.07	-76	0.073
Post-Water Project	1968-2006	39	6546	7097	3224	0.45	0.49	0.011	-290	0.007
Pre-SMSCG	1929-1987	67	5876	6244	2239	0.36	0.28	0.07	-36	0.51
Post-SMSCG	1988-2006	19	5994	6816	3242	0.46	0.48	0.01	-300	0.03
Monthly Average										
All data	6/29-9/06	1041	5033	6227	5347	0.86	0.62	0		
Pre-Water Project	6/29-9/67	552	4240	5878	5577	0.95	0.61	0		
Post-Water Project	10/67-9/06	480	6422	6817	5009	0.73	0.64	0		
Pre-SMSCG	6/29-9/87	793	4276	5830	5480	0.94	0.61	0		
Post-SMSCG	10/88-9/06	239	6797	7085	5039	0.71	0.64	0		
Annual Average	PORT CHICAGO SPECIFIC CONDUCTIVITY (SC umhos/cm)									
All data	1947-2006	86	9537	9595	4150	0.43	0.24	0.01	-8	0.82
Pre-Water Project	1947-1967	47	9955	9500	2396	0.25	0.03	0.84	-44	0.65
Post-Water Project	1968-2006	39	8741	9648	4888	0.51	0.32	0.008	35	0.6
Pre-SMSCG	1947-1987	67	9565	8989	3673	0.41	0.09	0.39	-58	0.25
Post-SMSCG	1988-2006	19	8931	10975	4912	0.51	0.41	0.05	-640	0.006
Monthly Average										
All data	1/47-9/06	1041	9135	9635	6718	0.7	0.64	0		
Pre-Water Project	1/47-9/67	552	9613	9584	6227	0.65	0.56	0		
Post-Water Project	10/67-9/06	480	9182	9786	6925	0.71	0.68	0		
Pre-SMSCG	1/47-9/87	793	8278	8931	6382	0.71	0.62	0		
Post-SMSCG	10/88-9/06	239	11404	11272	7056	0.63	0.66	0		

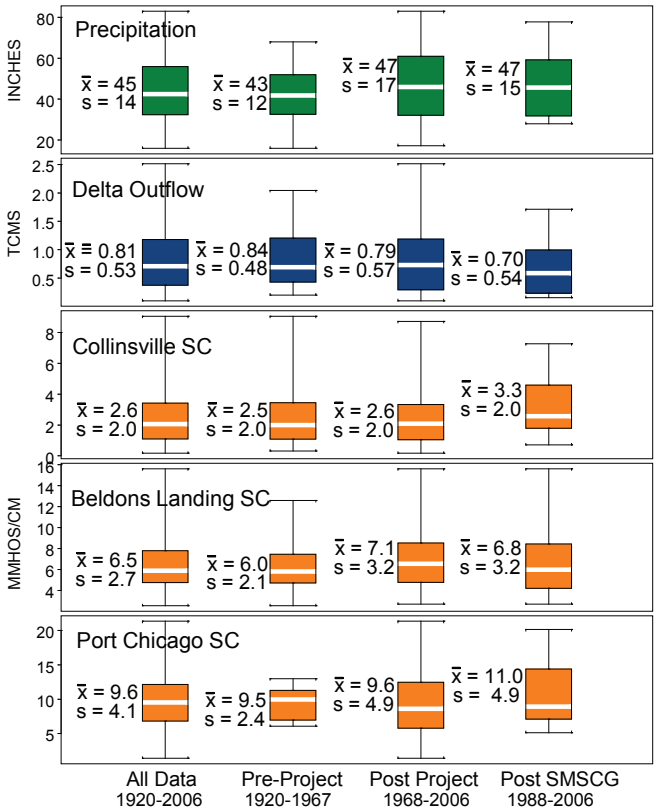

Figure 4 Box and whisker plot of annual average statistics for 13-station precipitation, outflow and SC data. Data is binned as 1) all data, 2) pre-project (prior to 1968), 3) post project (after 1968), and post SMSCG (after 1988) periods. Box is inner quartiles, line is median. The mean and standard deviation are posted aside each box.

factors influence long-term salinity trends. The seasonal loess procedure allows fitting low-frequency processes, in this case possibly associated with decadal scale climate oscillations (Figure 5, middle column). With seasonal and decadal oscillations removed, a robust estimate of the period of record trend is available (Figure 5, right column).

Long-term Trend Decomposition: Climate Teleconnections to Watershed Precipitation and Outflow

The decomposition is useful because we can remove the seasonal signal to reveal lower frequency processes. While the seasonal fits explain most of the variability, the decadal scale fits (Figure 5, middle column) appear to add additional explanatory power. Decadal time-scale north Pacific temperature and pressure anomalies have been observed and correlated with North American climate for some time (e.g. Cayan and Peterson 1989; Schonher and Nicholson 1989; Mantua and others 1997). Zhang and others (1997) developed an index of the sea-surface temperature (SST) anomaly dubbed the Pacific Decadal Oscillation (PDO) and demonstrated reversals in the prevailing polarity of the oscillation, positive and negative, in 1925, 1947, and 1977. Another polarity shift may have occurred in 1998 (Rodionov 2004) though, since 2002, it has turned more positive again. The PDO is correlated with interdecadal fluctuations in north Pacific sea-level pressure and thus integrates interdecadal time-scale, ocean-atmosphere covariability. The monthly PDO from 1921 to 2006 is shown in Figure 7, panel A.

We found no correlation between the monthly PDO and precipitation/outflow indexes. However, the PDO index is correlated with the precipitation and outflow indexes when all are filtered to the decadal scale. We considered loess filter windows between 12 and 300 months to determine the timescale of maximum PDO:precipitation and PDO:outflow correlation (Figure 6). Considering all years (both positive and negative PDO polarity), peak correlation occurs with a loess filter window of about 100-120 months. Figure 7 shows the 120-month fit to monthly average PDO (panel D), precipitation (panel E), and outflow (panel F). In the case of precipitation, the 120-month filter reveals an approximately decadal oscillation. Within an overall period-of-record precipitation mean of 3.7 inches per month, there is a decadal oscillation of about 1 inch. The correlation coefficient is only about 0.1 at 120 months, likely because PDO appears to be positively correlated with precipitation and outflow during positive PDO phase and negatively correlated with precipitation and outflow during negative PDO phase (similar to Gershunov and others 1998). We then separately considered positive and negative PDO polarity years. For positive polarity years, the correlation coefficient peaks at around 180 months at ~0.6 (p=0, Figure 6). With a mean positive PDO year precipitation of 3.8 inches (Figure 8,

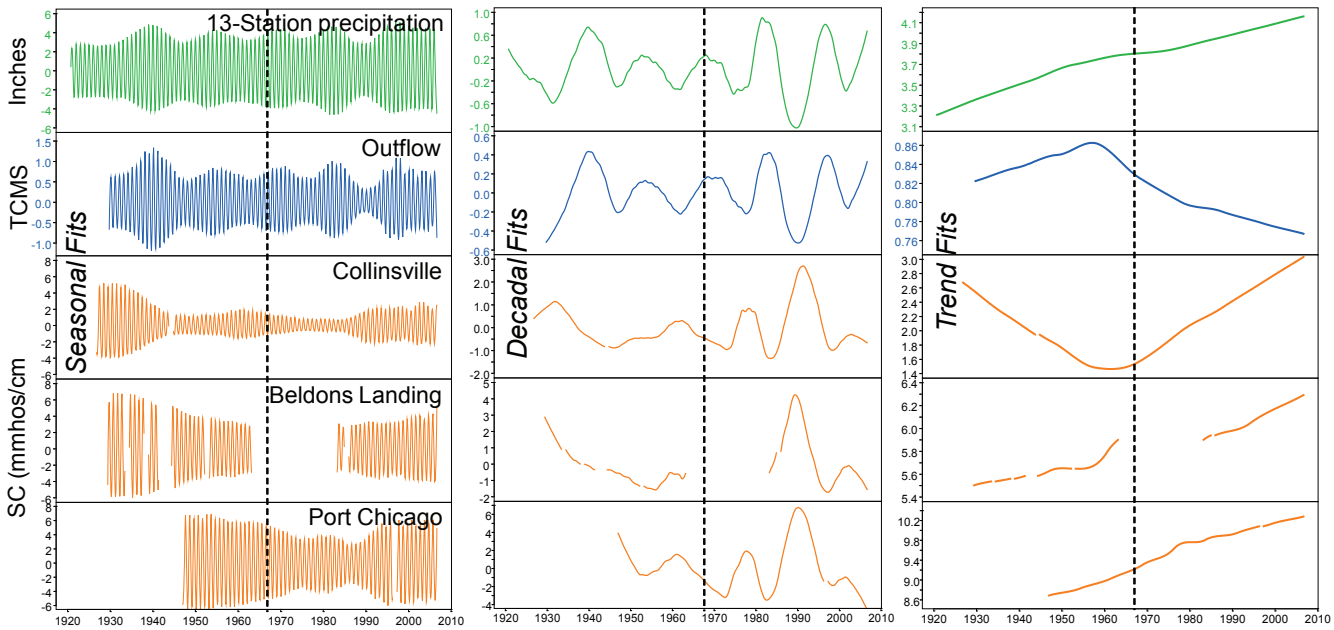

Figure 5 Seasonal loess trend decomposition on monthly average 13-station precipitation, outflow, and salinity data. Right column is the "seasonal" fit based on a 12-month frequency mode. Middle column is the 120 month "decadal" fit of the seasonal fit residuals. Right column is the "trend" fit to the decadal fit residuals. Dotted vertical lines delineate "pre" and "post" project periods.

panel B), the range of the 180 month decadal fit is greater than 2 inches (Figure 8, panel E). Figure 8 also shows the 180-month loess fits to the positive PDO year data (panel D) and corresponding monthly precipitation (panel E) and outflow data (panel F). By contrast, "negative" PDO years produced strong negative correlation peaking between 180 and 240 months (Pearson = ~-0.4 to -0.6, p=0) (Figure 6). The mean negative PDO year precipitation is 3.7 inches and the range of the decadal fit is greater than 2 inches. The 180-month fits are shown in Figure 9.

Table 3 shows a rough estimate of the variance in the original data explained by the decomposition components. Summed R2 is greater than 100 because components are correlated. Therefore, the method is rather conservative (that is, seasonal loess applies iterative component fits to higher frequency component fit residuals), and the estimates of explained variability are inflated somewhat. Bearing this in mind, only the trend components fail to add significant explanatory power by this metric (except for Collinsville salinity). The seasonal component explains 35% to nearly half of the variability of all parameters. Decadal scale vari-

Table 2 Coefficient of variation (standard deviation divided by mean) for annual and monthly average precipitation, outflow, and SC. Data is binned into pre- (prior to 1968) and post- (after 1968) project periods.

Annual Data CV	Pre-Project (prior to 1968)	Post-Project (1968-2006)
Precipitation	0.27	0.37
Outflow	0.57	0.75
Collinsville	0.77	0.82
Beldons Landing	0.34	0.45
Port Chicago	0.25	0.51

Monthly Data CV	Pre-Project (prior to 1968)	Post-Project (1968-2006)
Precipitation	1.16	1.22
Outflow	1.18	1.42
Collinsville	1.17	1.59
Beldons Landing	0.95	0.75
Port Chicago	0.65	0.71

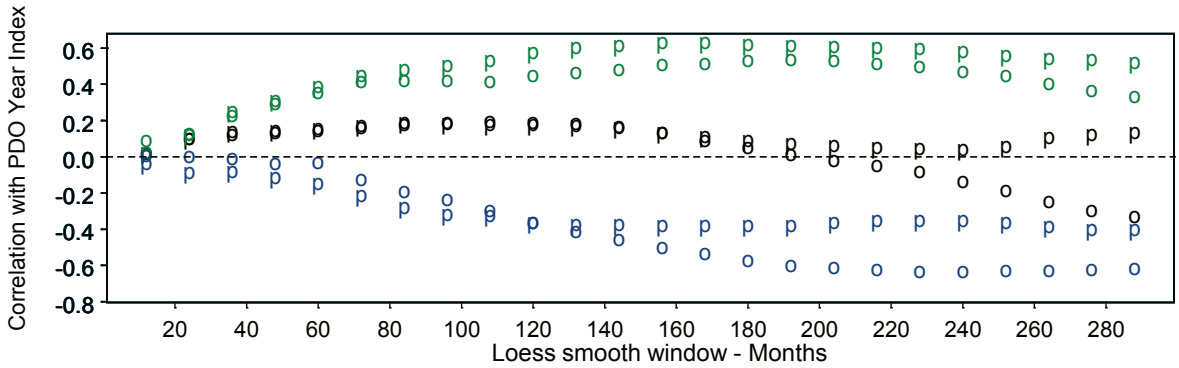

Figure 6 Correlation of monthly PDO with monthly 13-station precipitation and delta outflow. Y-axis is Pearson correlation, x-axis is loess smooth window in months. "p" indicates 13-station precipitation:PDO correlation, "o" indicates outflow:PDO correlation. Black symbols represent correlations with PDO for all months in the record. Green symbols represent correlations only in positive PDO phase months. Blue symbols are correlations in negative PDO months. Maximum correlation in positive PDO months is 160-200 months. Maximum correlation in negative PDO months is 160-240 months.

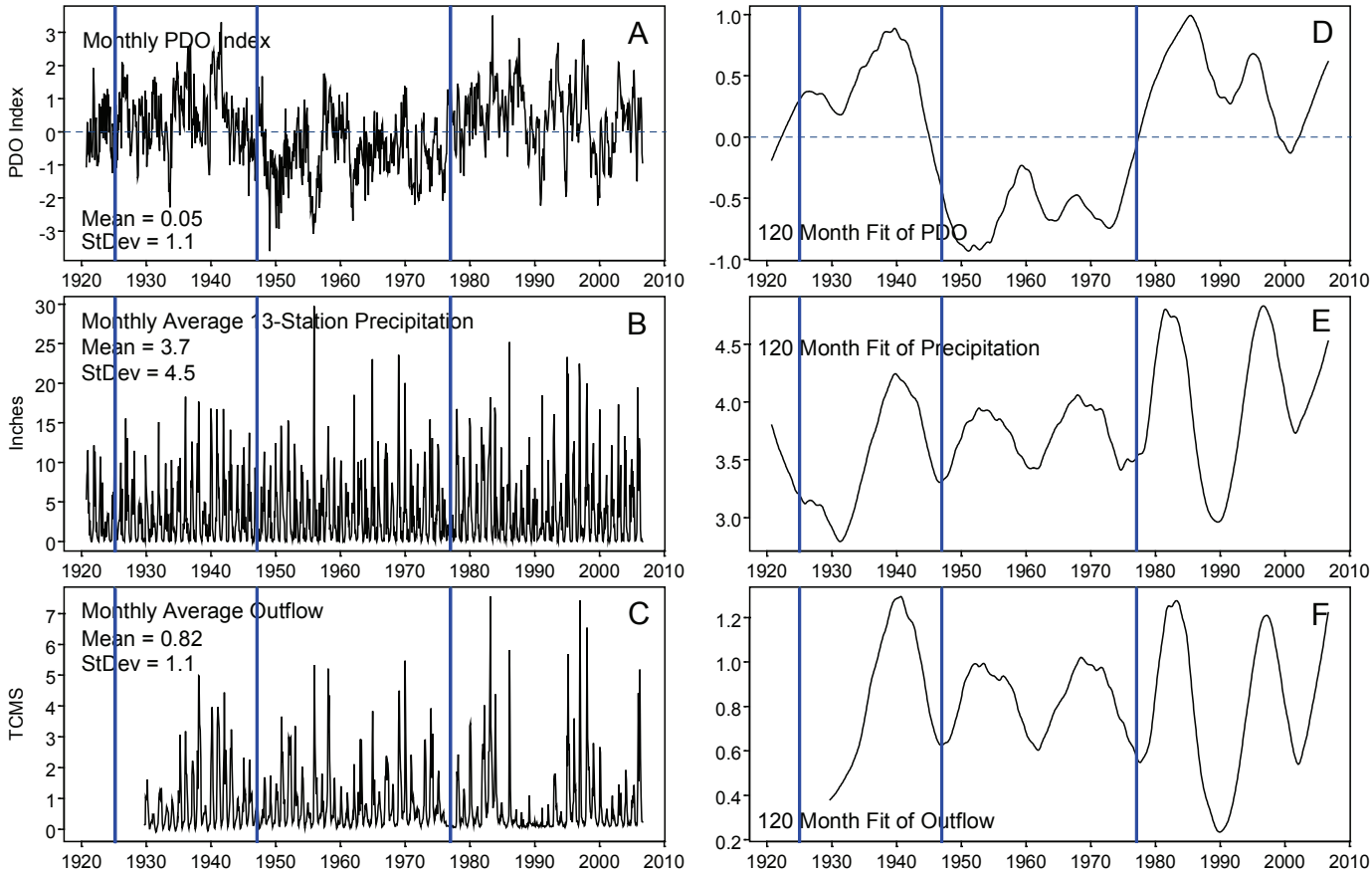

Figure 7 Left column (A, B, C) shows PDO, 13-station precipitation and outflow time-series. Right hand column (D, E, F) shows 120-month loess fits to the data to highlight possible correlation between "decadal" scale variability in PDO and precipitation and outflow. Blue verticals indicate PDO polarity shift.

ability accounts for about 2% of monthly precipitation variability, 10% of monthly outflow and 11% to 15% of salinity data variability.

Long-term (Greater than Decadal) Trends

With loess estimates of the seasonal and decadal oscillations removed, an estimate of the long-term trend emerges. Figure 5 (right column) shows the multi-decade trend fit for each data set. Precipitation exhibits increasing trend from approximately 3.2 to 4.1 inches per month over the period of record. Outflow is concordant up to about 1960, and then decreases from approximately 0.85 TCMS in 1960 to 0.72 TCMS in 2006. As for the salinity station trends, only Collinsville inversely mirrors outflow for the entire record. In contrast, pre-project Beldons Landing and Port Chicago salinity rather unexpectedly trends upward despite rising outflow. In these cases, the rising pre-project salinity trend suggests that other factors, perhaps including changing delta bathymetry, may also play a strong role in salinity transport (see "Discussion").

We also investigated long-term trends using Kendall's nonparametric test of independence. Figure 10 shows the slope of the long-term annual average trend (y-axis) for each of the five data sets. Trends for all data (1920-2006), pre-project (1920-1967), and post-project (1968-2006) periods are represented. P-values are also shown above each bar. Overall, Kendall's tau and seasonal loess methods predict broadly simi-

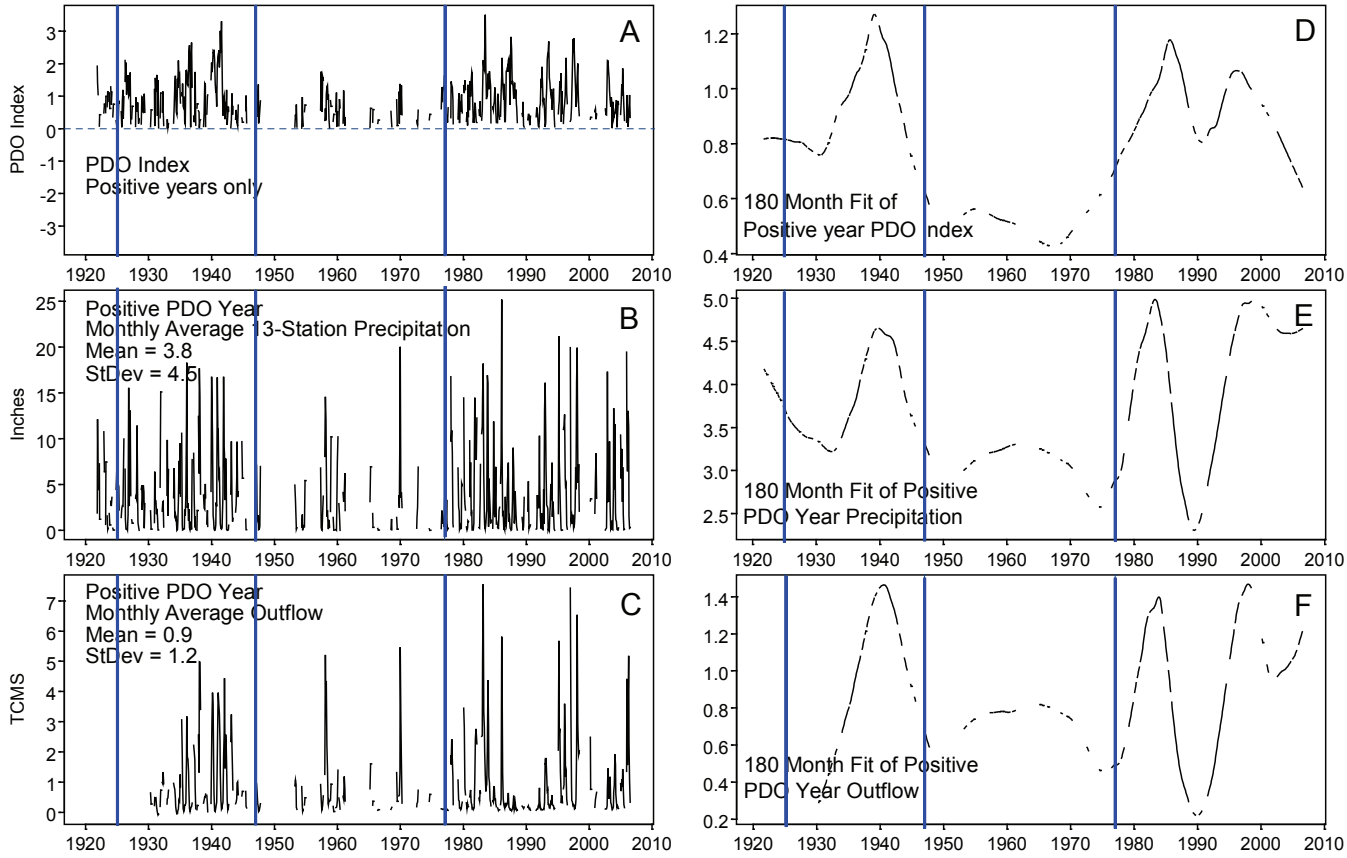

Figure 8 Left column (A, B, C) shows positive polarity PDO years only with corresponding 13-station precipitation and outflow time-series. Right hand column (D, E, F) shows 180 month loess fits to the data to highlight possible correlation between "decadal" scale variability in positive PDO years and same timescale precipitation and outflow. Blue verticals indicate PDO polarity shift.

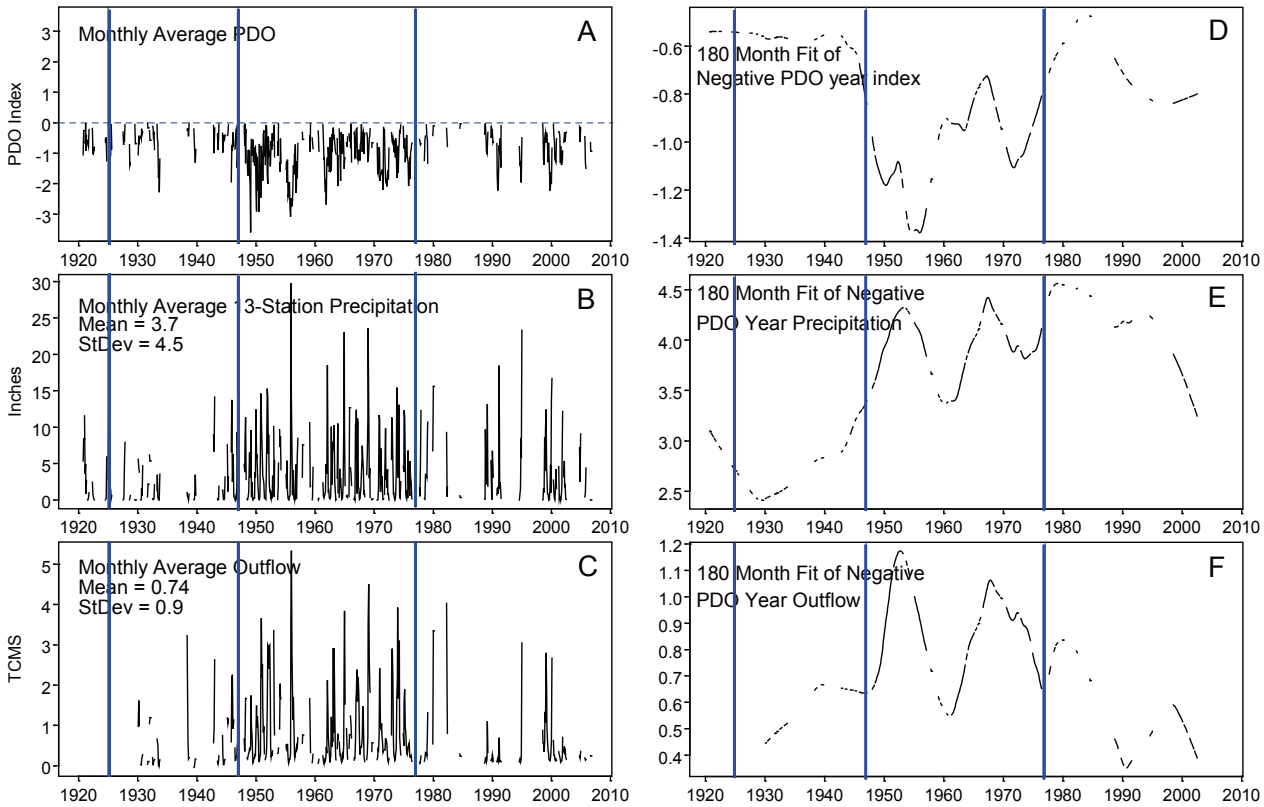

Figure 9 Left column (A, B, C) shows negative polarity PDO years only with corresponding 13-station precipitation and outflow time-series. Right hand column (D, E, F) shows 180 month loess fits to the data to highlight possible correlation between "decadal" scale variability in negative PDO years with same timescale precipitation and outflow. Blue verticals indicate PDO polarity shift.

lar trends. Pre-project outflow and salinity trends are consistent with the suggestion of increased precipitation between 1920-1967 (not significant). Fox and others (1990) similarly found no trend in delta outflow between 1921 and 1986. The pre-project Collinsville salinity trend is significant at approximately -0.07 specific conductivity units per year. In contrast to the suggestion of pre-project salinity trend increase at Beldons Landing and Port Chicago with seasonal loess decomposition, Kendall's tau suggests some (not significant) pre-project salinity trend decrease. Considering the post-project period, there is a non-significant suggestion of precipitation increase in the post-project period as Granger 1979 reported, while, as expected, delta outflow is trending down approximately 5 cms/yr (not significant). Collinsville and Port Chicago specific conductivity are coherent with the outflow trend (p=0.07 and 0.15, respectively). By contrast, Beldons Landing shows significant salinity decrease. Missing data in the early post-project period likely affect the comparability of this estimate to Collinsville and Port Chicago. The sequencing of a six-year drought starting in 1988 followed by several above normal water years further confounds the trend estimate. In addition, note that the SMSCG commenced operation in 1988 reducing Beldons Landing salinity by tidally pumping Sacramento River water into Montezuma Slough (Figure 1) each ebb tide. The seasonal loess trend decomposition untangles some of these confounding influences. The decadal fit (Figure 5) captures the influence of the late 1980s drought and the SMSCG effect beginning about 1989. With the decadal fit removed, the trend fit suggests some salinity increase after 1980.

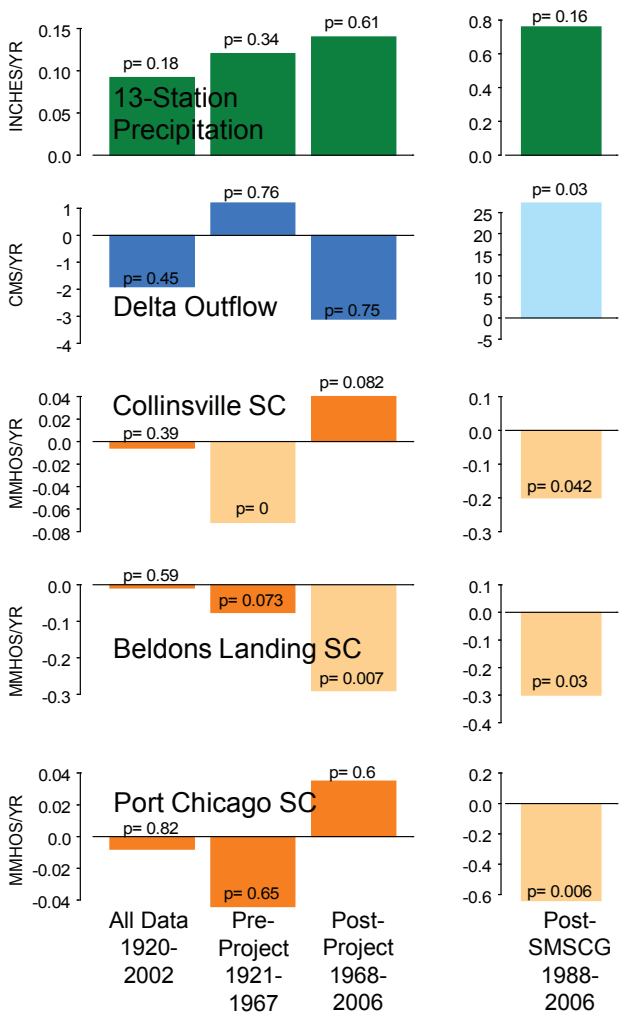

Figure 10 Slope of trend in annual data by Kendall's test. Annual data binned as all data, pre-project, post-project, and post SMSCG. Note SC is plotted on different y-axis scales. All post-SMSCG data is plotted on a different y-axis scale. Pastel bars are significant.

Among-month Trends

A considerable advantage of the seasonal loess procedure is that among-month trend fits are byproducts of the cycle subseries fits. Figure 11 (panels A-E) show among-month loess fits for 13-station precipitation, outflow, and Collinsville, Beldons Landing, and Port Chicago salinity records, respectively. We also applied Kendall's tau to each month series to obtain significance and confidence interval estimates. Trend fits to the log data are shown in blue if not significant, or green if significant ($p<0.05$). There is no significant trend in any month for the precipitation data (Figure 11, panel A). Delta outflow exhibits significant negative trends in April and May, and significant positive trends in July and August consistent with export and reservoir operations beginning in the 1950's (Figure 11, panel B). Also evident are trend inflections upturning between January and June, and down turning August through December. Notwithstanding reservoir effects, the January-February upturn may also reflect snow pack runoff trends noticed first by Roos (1987). The March-April-May upturn likely reflects more recent increased delta outflow requirements in the spring after the 1994 Delta Accord (SWRCB 1995). Down turning outflow trends between August and September likely reflect increased fall pumping after the 1994 Delta Accord.

Salinity trends by month are broadly consistent among stations. Collinsville salinity trends significantly downward in August and September (Figure 11, panel C). However, whether trending up or down over the period of record, Collinsville also shows upward salinity trend inflections in the late 1960's in every month. Beldons Landing salinity trends significantly upward in April, May, and

Table 3 Estimate of the percentage of variability in original data explained by seasonal loess decomposition: Regression of original monthly data on component. Values are R-squared. Note that component R-squares sum to greater than 100.

Component	13-Sta. Precip	Outflow	Collinsville SC	Beldons Lg SC	Pt. Chicago SC
Seasonal	46.0 (p<0.001)	35.0 (p<0.001)	35.0 (p<0.001)	46.0 (p<0.001)	35.0 (p<0.001)
Decadal	2.0 (p<0.01)	10.0 (p<0.001)	14.0 (p<0.001)	15.0 (p<0.001)	11.0 (p<0.001)
Trend	0.2 (p=0.14)	0.2 (p=0.17)	4.6 (p<0.001)	0.04 (p=0.65)	0.6 (p=0.06)
Residual	65.0 (p<0.001)	69.0 (p<0.001)	76.0 (p<0.001)	66.0 (p<0.001)	59.0 (p<0.001)

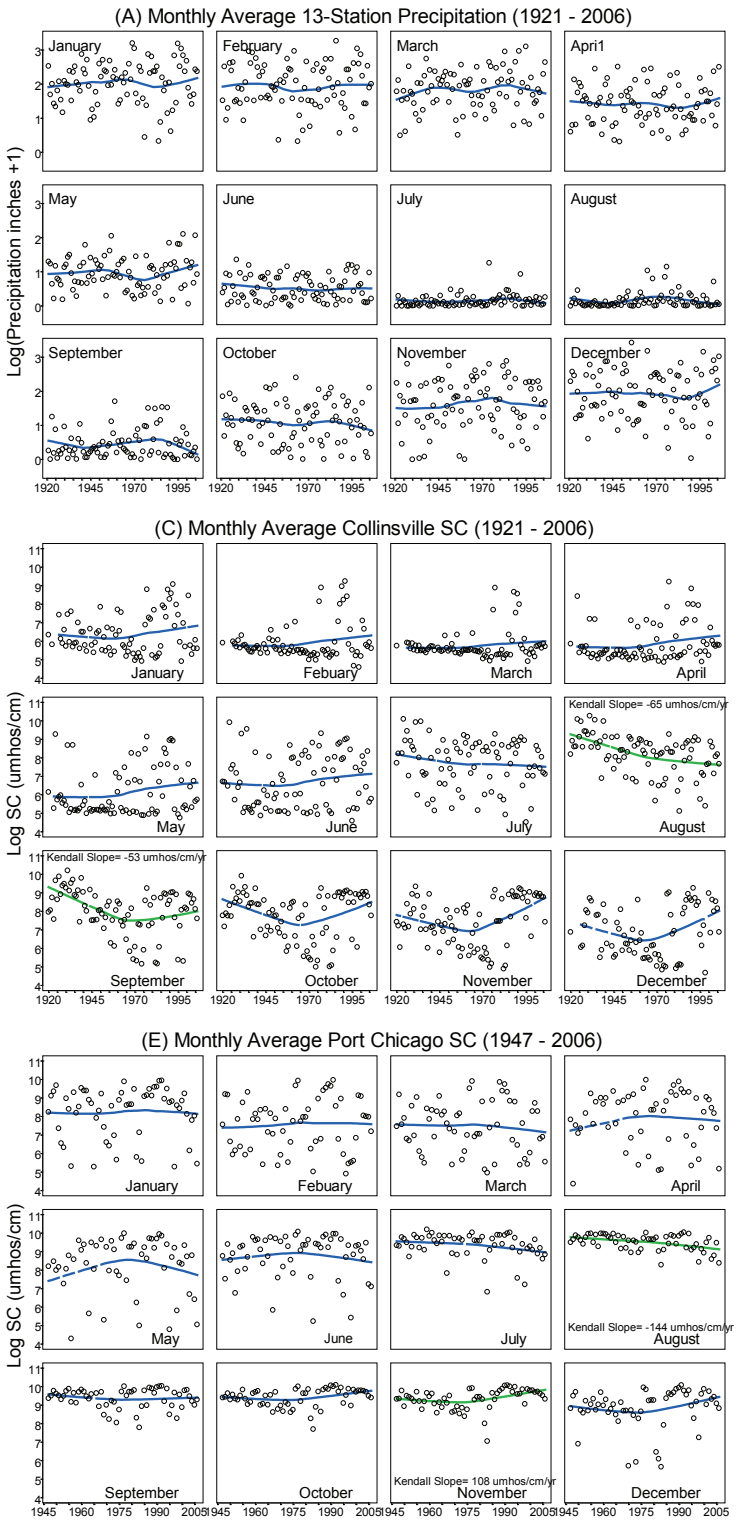

Figure 11 Local regression fits to the log of monthly average data by month. The local regression window spans 60% of the data; the local fitting degree = 1. Local regression fit shown in green if Kendall trend slope is significant at the 95% level.

June, consistent with outflow (Figure 11, panel D). Port Chicago trends downward in spring and summer, significantly downward in August. Salinity trends higher in the fall, significantly in November (Figure 11, panel E). In contrast to Collinsville, but consistent with outflow, Beldons Landing and Port Chicago show slight negative inflections in the post-project period for all months between January and August. All stations have positive post-project inflections between September and December consistent with negative outflow trend.

The slope of the among-month trends as determined from Kendall's Test are shown in Figure 12. Each diamond represents the period of record trend slope for the month. Verticals depict 95% confidence intervals—solid verticals indicate significant trends. For precipitation and outflow, only 4 of 12 months trend in the same direction—due primarily to water project reservoir and export operations. Using data from 1929 to 1986, Fox and others (1990) found significant downward trends in annual outflow in April and May and significant upward trends between July and November. Extending the annual outflow data set now from 1921 to 2006, April and May continues to show significant downward trend while upward trends are now limited to July and August only owing perhaps to greater fall project pumping since the 1994 Delta Accord.

While the three salinity stations are broadly similar, there are notable differences between station salinity trends and trend detection methods. First, Kendall's test suggests a remarkable lack of salinity trend in response to outflow reduction between November and April (Figure 12)—broadly similar to the loess results (Figure 11). The seasonal loess and Kendall trends diverge at Collinsville where, after the late 1960s, loess captures a strong suggestion of positive salinity trend (Figure 11, panel C). We might expect Collinsville salinity to be somewhat more sensitive to delta outflow (while Port Chicago is more ocean influenced). We also note that the Suisun Marsh Salinity Control Gate (SMSCG) began operation in 1988 and tends to increase Collinsville

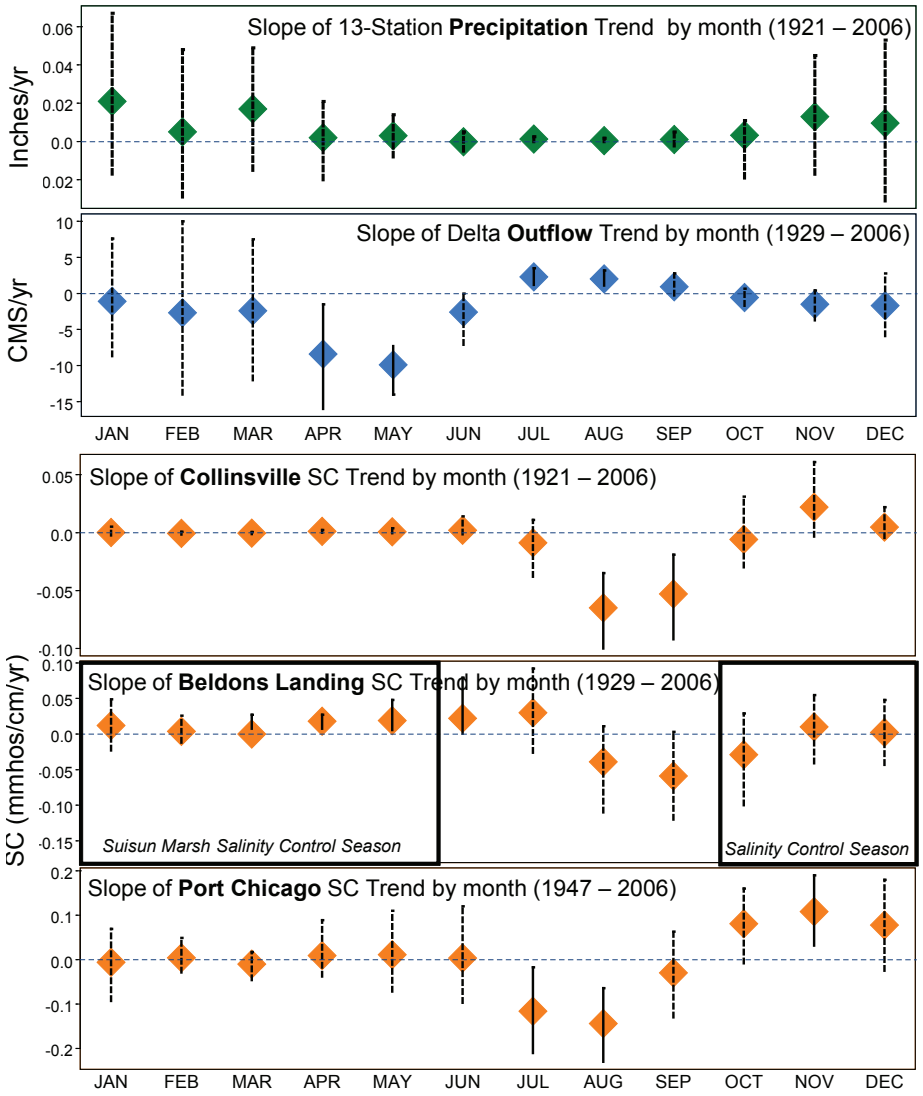

Figure 12 Slope of trends by month using Kendall's test. Confidence limits are 95%. The SMSCG control season is delineated by boxes in the Beldons Landing panel.

salinity between October and May (more below). Despite that, Kendall's test shows Collinsville continuing to resist trending even in May, June, and July despite significant delta outflow reduction in May and June, and significant increase in July. Seasonal loess seems to capture these more subtle nuances of trend. Notably, Beldons Landing broadly tracks the other salinity stations though it alone exhibits significant upward trend in April, May, and June, consistent with the negative trend of outflow in those months.

Long-term Trend of Annual Time-scale Variability

The variability of system drivers—including precipitation and river inflow—are a key physical control on the system. The watershed's Mediterranean climate is characterized by an approximately six-month, wet-dry season cycle. In addition, variability in the general pattern can manifest as clusters of dry (drought) or wet years. A key emerging assumption for ecosystem restoration is that native species evolved to persist under sometimes extreme seasonal, annual and decadal-scale variability of outflow and salinity during the Holocene. On the annual scale, water project reservoir and export operations tend to reduce intra-annual variability by storing winter-spring runoff for summer-fall release and export (Knowles 2000). While watershed land use changes also intervene in multiple ways (Fox 1990), the water projects impose a general homogenizing affect on northern reach salinity by reducing flood peaks and releasing reservoir storage in the dry season. The nascent conceptual model suggests that seasonal variability reduction by water project operations could enhance non-native species opportunities to the detriment of natives that evolved under more variable conditions (e.g., Lund and others 2007).

Table 2 shows a rough test of the water project homogenization conceptual model where annual and monthly data coefficient of variation (CV) is shown for the pre- and post-project periods. Contrary to the conceptual model, there is more variability in the post-project period. Consistent with precipitation CV, post-project CVs are consistently higher than those for the pre-project period. The only exception is Beldons Landing monthly data where CV is lower post-project, likely due at least in part to SMSCG operations by DWR since 1988.

Long-term Trend of Seasonal Scale Variability

We considered trends in seasonal variability by analyzing the residuals of seasonal loess fits by month. We subtracted the local regression fits from the log data and fit simple linear regressions to the absolute value of the residuals (Figure 13, panels A-E). Positive regression line slopes suggest increasing variability—negative slopes suggest declining variability. Green lines indicate significant slope ($p<0.05$), blue is not significant. Only January shows significant positive trend in precipitation variability, though nine of the twelve months at least suggest increasing variability since 1920 (Figure 13, panel A). Outflow variability trends are consistent with precipitation except in April, July, and August. In April neither the precipitation slope (positive) nor the outflow slope (negative) is significant ($p<0.2$ in each case). Outflow variability is trending significantly downward in July and August when precipitation is inconsequential (Figure 13, panel B). This could be due to earlier snow pack melts and increasing reliability of water project reservoir releases to the delta. As for seasonal salinity variability, Collinsville (Figure 13, panel C) exhibits increasing salinity variability in eleven of twelve months—seven months are statistically significant. At Port Chicago (Figure 13, panel E) all twelve months suggest that variability is increasing; March, August, and September are significant. Beldons Landing is somewhat the exception as it exhibits variability increase in six of twelve months, two of those significant (Figure 13, panel D). Notably, salinity variability at Beldons Landing in May is declining ($p=0.15$) in direct opposition to increased outflow variability ($p=0.1$) in May. Keeping in mind that Beldons Landing is missing data between 1964 and 1981, the Suisun Marsh Salinity Control Gate may be compressing variability when it has operated since 1988. The general trend toward increasing salinity variability is only nominally consistent with outflow. Salinity variability in June, July, and August does not well track significant downward trends in outflow variability for the same months. This suggests that other mechanisms are at play including land use

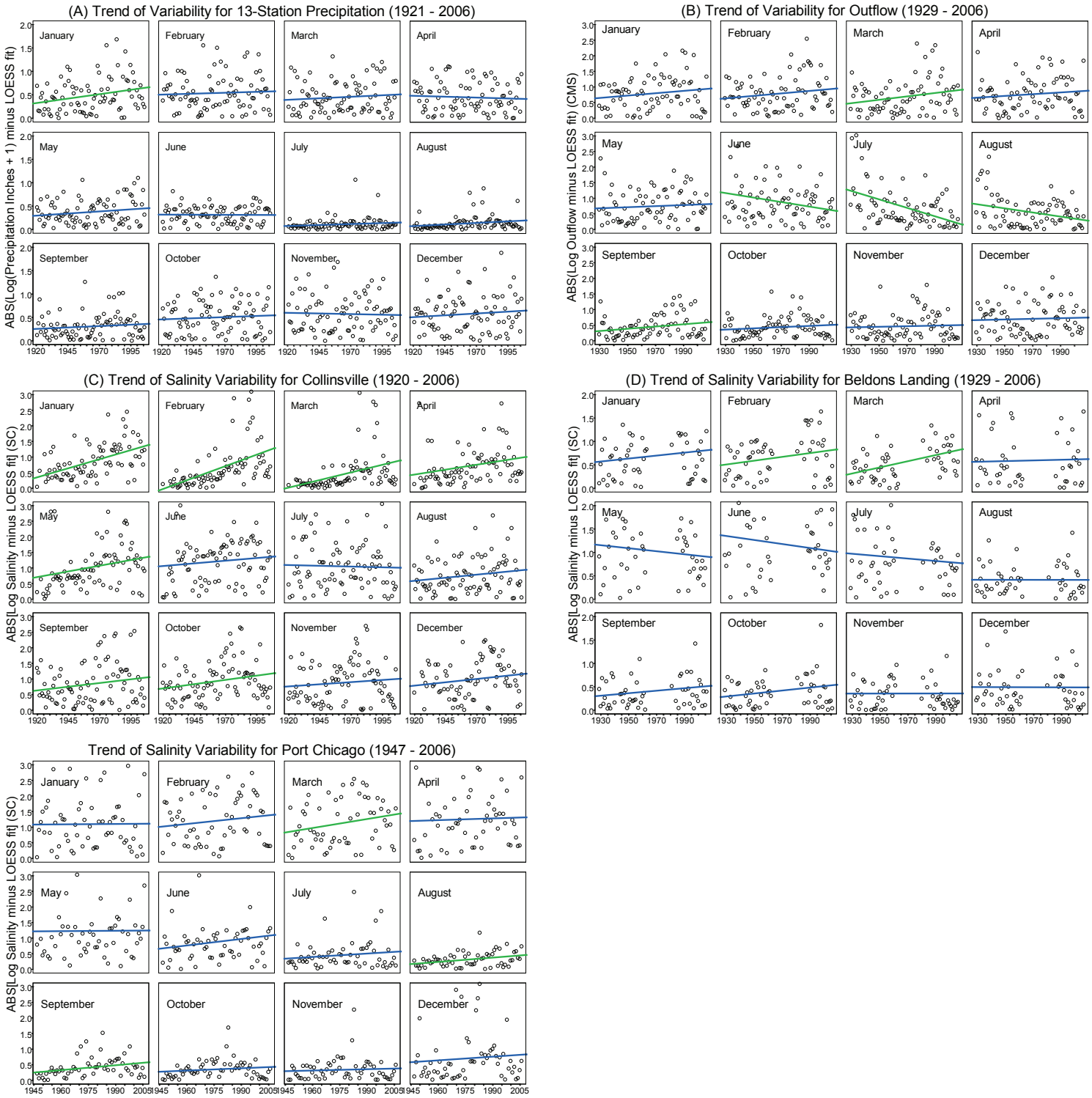

Figure 13 Trend of variability based on local regression fits to the average of 13 Bay-Delta watershed precipitation stations by month. Circles are absolute value of data residuals minus loess fit. Lines are regression fits. Green regression fits indicate significant slopes ($p<0.05$) suggesting trend in variability. Blue is not significant.

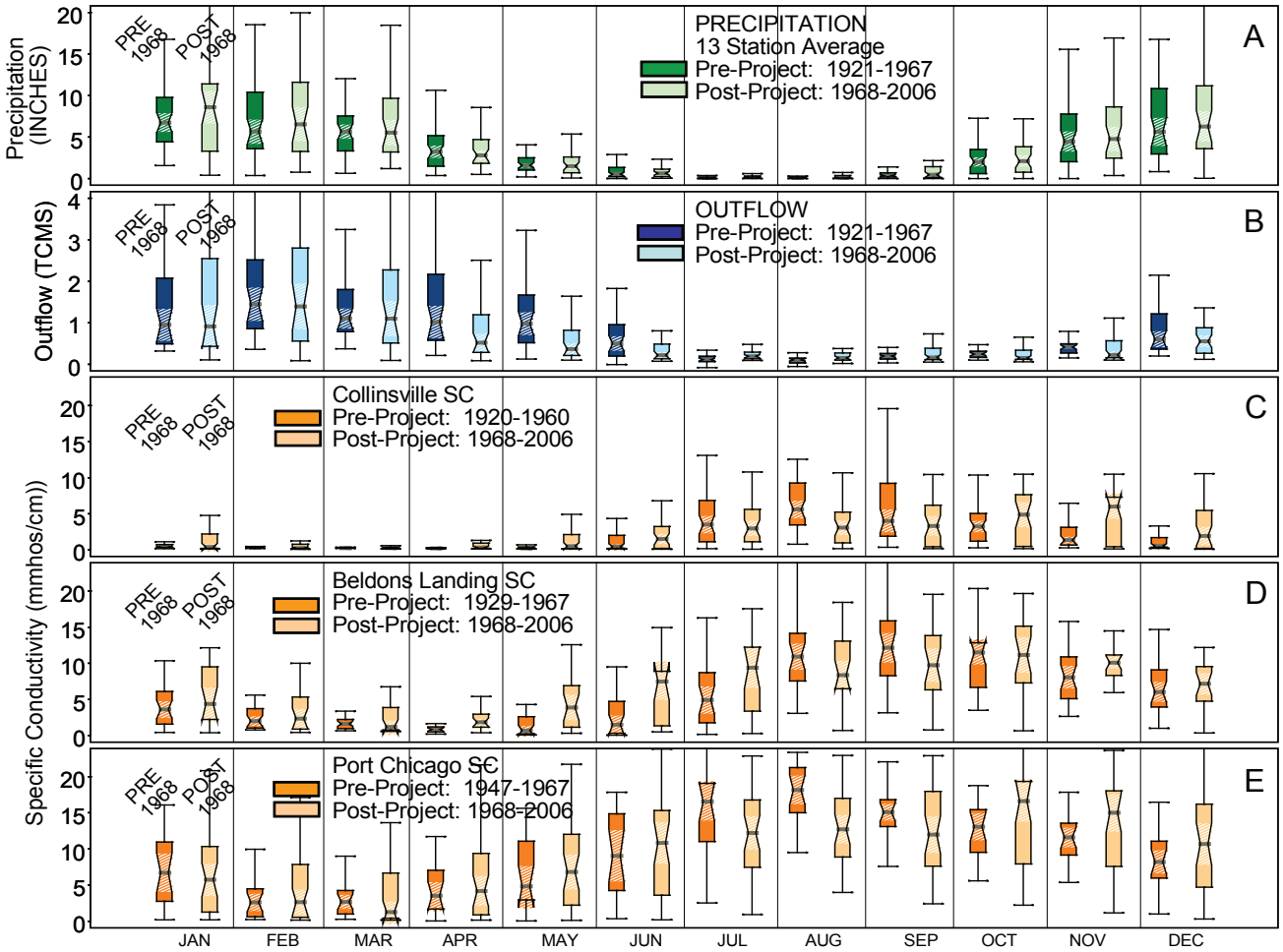

Figure 14 Distribution of pre- and post-project precipitation, outflow, and salinity by month. Box-plot indicates median, 95% confidence interval, inner quartile, and range of data for each month. Pre-project and post-project distributions are shown side-by-side for each month.

and bathymetry changes that could influence tributary and baroclinic flows. Also noteworthy is the apparent reduction in fall outflow and salinity variability in the last decade as the water projects have operated more closely to maximum export-inflow ratios.

Figure 14 compares the pre-project and post-project distributions for precipitation, outflow, and salinity, by month. The five panels show box plots indicating the median, inner quartile, and range of the data for each period and month. If we accept the conceptual model that the water projects reduce month-to-season-scale variability, we would expect Figure 14 to reflect it. In general, the opposite is true. Panel A shows that, excepting April, all wet months (November through May) have wider inner quartile variability and most have greater range in the post-project period. While reservoir and export operations influence outflow medians generally in opposition to precipitation medians, outflow variability matches the precipitation variability pattern in most months (panel B). Salinity is roundly more variable in the post-project period. Port Chicago is more variable in all months, Beldons Landing in ten of twelve months, Collinsville in eight of twelve months. Notably, differences in pre- and post-project salinity variability are often not consistent with

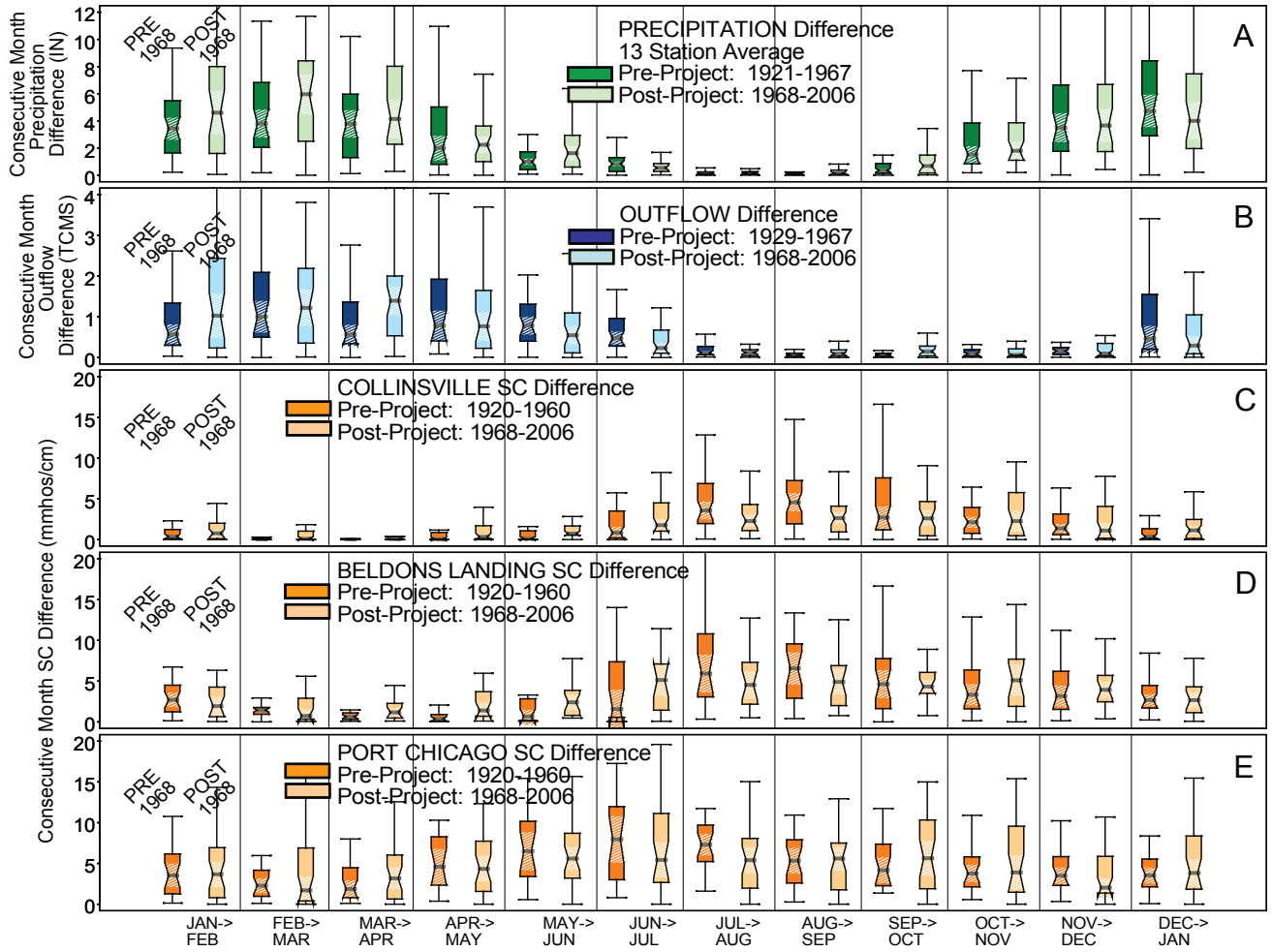

Figure 15 Distribution of consecutive month differences. Box-plot indicates median change, 95% confidence interval, inner quartile, and range of month-to-month difference for each two-month sequence shown on x-axis. Pre-project and post-project difference distributions are shown side-by-side for each month.

outflow variability changes. In general, this occurs in spring and summer months. In April, May, and June, median outflow is lower in the post-project period resulting in higher median salinity that is less often bounded at the low end (by zero) allowing more variability as an artifact of higher salinity despite lower outflow variability. Summer months may be less variable due to earlier snow pack melting and water project efforts to meet delta salinity standards. In general, the water projects influence means, not variability, except when higher means unbound variability.

Another perspective on seasonal scale variability is to examine the pre- and post-project periods for consecutive month-to-month differences in the five data sets. Figure 15 depicts the consecutive month change in precipitation, outflow, and salinity for the periods of record. Again, if water project operations reduce seasonal outflow variability by storing runoff peaks for late spring-summer release that may otherwise have been dryer, then we would expect consecutive month outflow changes to be smaller in the post-project period compared to the pre-project period. The box plots depict the median consecutive month change, 95% confidence interval, inner data quartiles, and range. Figure 15, panel B shows consecutive month change in outflow that, contrary

to the conceptual model, shows a tendency for more consecutive month difference in the post-project period. Consecutive month outflow differences are completely consistent with the same metric for watershed precipitation (Figure 15, panel A). This suggests that climate is a more powerful mechanism controlling seasonal variability than water project operations. This does not negate the conceptual model that water project operations dampen seasonal variability as demonstrated by Knowles (2006). However, it does suggest that seasonal outflow and salinity variability is primarily climate driven. Salinity differences are largely coherent with outflow (Figure 15, panels C, D and E). Port Chicago shows the greatest tendency to deviate from outflow coherence possibly because it is more influenced by bay and ocean conditions.

DISCUSSION

Several themes are cultivated in this work including aspects of trend detection, the relative effect of climate (as watershed precipitation), and influence of water projects on salinity trends and variability at different time scales. We have also considered the effect of northern reach geometry, including the operation of the Suisun Marsh Salinity Control Gate. While other investigators have used models to elucidate trend and variability, we rely on over 80 years of monthly average data and attempt to untangle the superposition of forcing influences. We summarize each of these themes in the following discussion.

Data and Models

This study examines over 1,000 months of data to elucidate the relative influences of climate and water project operations on long-term trends and variability of outflow salinity in the northern reach of the San Francisco Estuary. Our study is complementary to that of Knowles (2002) who used a hybrid of data and modeling to discriminate the individual and combined effect of exports and reservoirs on seasonal and annual outflow. Similar to Fox 1990, we relied only on data allowing examination of the prevailing conventional wisdom about the trajectory of northern reach salinity and associated variability on monthly, annual, and decadal time scales. As shown by others (for example Peterson and others 1995), both data and modeling reveal that natural climate variability often overwhelms water project influence on seasonal and interannual scale salinity.

The advantage of models is that mechanisms included in the formulation can be teased apart for their relative contribution to change. In Knowles' 2002 paper, export and reservoir effects are well scrutinized. A potential limitation of models is that not all mechanisms underlying variability may be represented. In contrast, long-term salinity data implicitly contains all driving mechanisms—though untangling one from another and the interactions between is challenging. For example, during the 86 years of monthly data examined in this study, the hydrologic linkage between watershed precipitation and inflow to the delta has profoundly changed with increasing forest management, valley agriculture, and urban hardscape. Moreover, changes have been incremental, inducing unknown non-stationary influence. That our salinity data and Knowles' modeling agree does not necessarily mean that the same suite and weighting of mechanisms will be identified.

We decomposed data into seasonal, decadal, and trend components. On first glance, Figure 2 shows that the long-term salinity trend is essentially indiscernible within the much larger seasonal, annual, and even decadal scale variability in the record. At the annual timescale, Knowles estimated that reservoir and export operations increase mean annual salinity in the northern reach by 10% to 15% (Knowles 2002, Figure 8). While we could not produce a comparable estimate, the loess trend decomposition explains some of the subtle points. First, both nonparametric trend detection methods (loess and Kendall's tau) clearly show that outflow and Collinsville salinity trends are consistent with the precipitation trend in the pre-project period (1921-1967). Precipitation increased about one-tenth of an inch per year with concomitant increase in outflow of about one CMS/year up to 1967 (Figures 5 and 10). After 1968, the outflow trend turns negative (approximately -3 CMS/yr) in opposition to the continuing upward trend in precipitation (nearly 0.15 in per year) (Figures 5 and 10). In the post-project period both Port Chicago

and Collinsville have slightly higher annual mean salinity while Beldons Landing is up more than 10% (Figure 4). During the post-SMSCG period (after 1988), all three salinity stations increase in the range that Knowles predicts. Outflow is about 15% less since 1988 than the pre-project period (Figure 4).

Importance of Long Time Series for Trend Detection

We found that trend detection is challenging for several reasons. For example, there is disagreement between the trend detection methods for salinity at Beldons Landing and Port Chicago in the pre-project period. The decadal component of the loess salinity decomposition appears to absorb much of the downward trend at each of the stations. The remaining long-term trend component is positive (Figure 5). In contrast, the Kendall's tau method suggests that pre-project salinity is decreasing. All else equal, with the early century passing of hydraulic mining sediments Suisun Bay likely experienced a long-term positive salinity intrusion trend as its bathymetry eroded and baroclinic circulation increased. Overall, Suisun Bay has eroded approximately 1 m since 1920 (Cappiella and others 1999). When Suisun Bay was shallower during the early part of the century, tidal range, current speed, tidal excursion, and salinity dispersion were likely reduced east of Carquinez Strait (Enright and Miller 2004). The disagreement between trend detection methods suggests that the Kendall method is influenced by sub-trend scale power. This indicates an advantage of the seasonal loess method that it can discern robust long-term trends from shorter timescale influences.

Another example of the importance of separating out decadal-scale influences from long-term trend can be seen by comparing salinity means and trends (Figures 4 and 10). Figure 4 shows that mean salinity at Collinsville and Port Chicago is higher in the post-SMSCG period. At the same time, Figure 10 shows that post-SMSCG salinity is trending significantly lower. The peculiar sequence of hydrology since 1988 accounts for the declining salinity trend as the early years of the period (1988-1992 and 1994) were considered "below normal" or "critically dry" years. Since 1994, nine of twelve years have been classified as "wet" or "above normal" water years (DWR 2007). Despite the declining trend, the 1988 to 2006 salinity mean is higher than any other subset examined in this paper. The 18-year "trend" as determined by the Kendall method is well captured by seasonal loess (Figure 5, "decadal fits"). Once the decadal trend is removed, a rather monotonic upward trend fit emerges at all three salinity stations (Figure 5, "Trend Fits").

This is an important distinction since the forcing mechanisms behind the decadal fit may be entirely different from the trend fit. On the one hand, we suggested above that decadal scale ocean/atmosphere climate teleconnections explain about 10% of the total outflow and salinity variability. On the other hand, slowly changing watershed runoff characteristics, northern reach bathymetry deepening, and expanding water project operations together explain long-term (greater than decadal) trends. This underlines the importance of using data sets longer than the scale of the lowest frequency forcing mechanism. In this case, decadal timescale variability is approximately 20-25 years. There is a risk of misidentifying the forcing mechanisms when trend identification is attempted using shorter data sets. The seasonal loess method effectively sequesters the decadal variability in the decadal fit. It thereby better accounts for drought and ocean/climate teleconnection-scale variability and provides a more robust estimate of the long-term (multi-decadal) trend.

Drivers of Long-term Trends and Variability

All else equal, we would expect outflow and salinity to be well correlated with San Francisco Estuary watershed precipitation trends and variability. Two primary findings of this work are: (a) the water projects have decoupled long-term trends in annual mean outflow and salinity from long-term trends in climate forcing, and (b) climate has primary control over monthly to decadal scale outflow and salinity variability. The conceptual model of variability reduction by water project operation turns out to be only a secondary driver of variability.

a. **Water projects have decoupled the long-term delta outflow trend from the long-term precipitation**

trend. Outflow trend downward in opposition to the precipitation trend in the post-project period (Figure 5, "Decadal Fits"). While there have been significant changes in the watershed affecting soil permeability and water retention in the post-project period, on the annual time-scale, water project export is the primary driver of outflow reduction. Despite precipitation trending upward, Port Chicago and Collinsville respond to outflow reduction with annual salinity increases of about 1% and 4%, respectively, and positive trends each around 0.04 mmhos/cm per year (Figure 5, "Decadal Fits"). Beldons Landing curiously shows an 18% increase in the annual mean, but significant negative salinity trends in the post-project period. The apparent mean increase owes partly to the large section of missing data in the early post-project period (Figure 5), while the sequence of drought to wet years from 1988 to 2006 along with SMSCG operations accounts for the downward salinity trend.

The water projects also modify annual averages of outflow and salinity and generate year-to-year serial correlation. The summary statistics in Appendix 1 show that lag-1 annual outflow is not correlated in the pre-project period, however it becomes significantly correlated (0.28, $p<0.05$) in the post-project period. The monthly lag-1 correlation is always significant but the correlation is somewhat higher post-project (0.54 pre-project; 0.65 post-project). The annual 13-station precipitation index is not lag-1 correlated in either period.

We also suspect that the northern reach salinity regime was significantly influenced by bathymetry changes in the Suisun Bay due to land use and changing sediment supply. Erosion of Suisun Bay since about 1920 (Cappiella 1999), along with about 10 cm of sea-level rise, likely eased dispersive transport of ocean salt up estuary. All else equal, we would expect the trend toward increased depth in Suisun Bay to generate an upward salinity trend over time. It could be that the long term, positive salinity trend at Beldons Landing and Port Chicago in opposition to increasing watershed rainfall reflects unrelated serial processes: First, after 1920, the gradual erosion of Suisun Bay with concomitant increases in baroclinicity and shear flow dispersion generated greater salinity intrusion than increasing precipitation and outflow could repel. Second, just as Suisun Bay had passed most of the mining sediments, the water projects began reducing outflow thus keeping Suisun Bay salinity on a steady long-term positive trend (Figure 5, "Trend Fits").

b. Revising the conceptual model about water project effect on salinity variability. Water project operations reduce seasonal salinity variability by storing winter runoff and releasing it for dry season demands. Over-year storage further reduces annual variability by storing more during wet years and releasing it in dry years. A prevailing ecosystem conceptual model holds that flow and salinity variability represents a key physical-chemical process underpinning ecosystem resilience (for example, Lund 2007). A corollary is that native species coevolved with variable seasonal-to-decadal salinity and may therefore lose competitive advantage by temporal homogenization of the flow/salinity regime. A conceivable irony is that these trends, while indicative of the previous 86 years of development, may imitate the buffering capacity of the historical landscape with its vast wet season floodplain storage and slow surface and groundwater drainage into the dry season. In any case, Table 1 indeed shows that annual outflow is serially correlated in the post-project period while precipitation is not. Moreover, Figure 12 shows spring outflow decreasing while summer outflow is increasing. Knowles' findings support the conceptual model. He estimates that annual salinity variability along the northern reach is reduced by water project operations about 10% (Knowles 2002, Figure 8). However, despite the soundness of the conceptual model, and the magnitude of the effect estimated by Knowles, the data do not verify variability reduction. Our results suggest that annual average salinity variability (Figure 4, Table 1, and Table 2) and by-month salinity variability (Figure 13, Table 1, and Table 2) is generally greater than

the pre-project period. This is not because the prevailing conceptual model is incorrect. On the contrary, more post-project variability strongly suggests that there are other powerful mechanisms at play including climate and land use changes that overpower the homogenizing influence of project operations. There is however, emerging evidence to suggest that water project operations are making incursions into salinity variability in the fall since the late 1990's when export/inflow ratio limits have been approached more consistently.

The Influence of Climate

Large-scale Pacific Ocean and atmosphere interactions profoundly influence the climate of the San Francisco Estuary watershed. In general, the gradient between Pacific Ocean pressure systems determines storm system tracks through the seasons. At the inter-annual timescale, the El Niño-Southern Oscillation (ENSO) influences the pressure system gradient with opposite polarity effects on the Pacific Northwest and Southern California. The San Francisco Estuary is positioned near the fulcrum of the latitude polarity and ENSO influence is sensitive to the longitudinal position of the Aleutian low. ENSO status influences estuary salinity in rather complex ways, including north to south snowpack variability, leading to variability of intra-annual runoff patterns (Schonher and Nicholson 1989; Dettinger and Cayan 1995; Knowles 2000). We enfolded the complexity of these climate forcings by lumping runoff from the vast San Francisco Estuary watershed in to one precipitation index—the average of 13 monthly average Sierra foothill precipitation gauges (Figure 1). The 13-station precipitation index is well correlated with monthly average delta outflow (0.67, p=0), even though the linkage between them is influenced by reservoir operations, antecedent soil moisture, and whether precipitation falls as rain or snow. The 13-station precipitation index is thus an effective proxy for the outflow trends we would expect without water project influence or changes in watershed runoff dynamics. With it, we were able to investigate the relative influence of seasonal and annual water project effects on delta outflow compared to watershed scale climate forcing. In addition, with 86 years (1,032 months) in the record, we investigated the influence of decadal-scale Pacific Ocean and atmosphere variability on San Francisco Estuary precipitation and outflow.

Decomposing precipitation data into various timescale components revealed a considerable periodic oscillation at the decadal timescale. We investigated these low-frequency oscillations and possible teleconnections between Pacific Ocean/atmosphere variability. We found: (1) strong correlation between PDO and precipitation/outflow indexes when all are filtered to the decadal scale; (2) about 10% of monthly precipitation and outflow variability is explained by decadal scale oscillations in the PDO index; and (3) decadal scale variability in the monthly outflow and salinity data explains 10% to 15% of their total variability. Collinsville (western delta) salinity is somewhat better explained by decadal scale variability than Port Chicago (Suisun Bay). This suggests that climate teleconnection to northern reach salinity may also have differential effect depending on proximity to coastal ocean salinity influence. By virtue of their positions in the northern reach, delta salinity is more influenced by watershed precipitation, while Suisun Bay salinity is marginally more influenced by other coastal ocean processes like the California current and upwelling.

Other Salinity Trend and Variability Drivers

This paper focuses on first and second moment trends in outflow and salinity due to the influence of climate and water project operations. Over the 86-year period of the data, several other physical processes have influenced salinity trends and variability that are beyond the scope of this paper. When we examine any long time-series for the estuary, we must be mindful that the trends and variance result from a complex superposition of process influences and feedbacks. Some of the other salinity mixing mechanisms and timescales of influence include:

- ENSO scale fluctuations of the California current and associated upwelling modify San Francisco Bay/ocean water exchange and influence San Francisco Bay salinity available for tidal dis-

persive transport upstream (Walters and Gartner 1985; Peterson and others 1989).

- Salt dispersion by the northern reach channel network greatly increased during period of rapid delta reclamation. This tidal timescale process efficiently mixes salinity upstream as the characteristic length between channel bifurcations is reduced. Linear channel "cuts" and meander cutoffs in Suisun Bay and the delta along with ship channel dredging and ongoing channel island erosion is increasing the ratio between tidal excursion and channel reach length. As the ratio increases, salinity is mixed by bifurcation flow asymmetries (Burau and others 2008).
- Tidal energy dissipation in the northern reach has diminished over time as the land-water interface was sharpened and simplified by levees. The presettlement physiography of the northern reach exhibited more complex land-water interfaces and biogeomorphic processes that absorbed tidal energy. Complex landscape allometry attenuates tidal range, tidal currents, and shear dispersion of salinity gradients (Simenstad and others 2000). Modification of the northern reach geometry may be the single most important long-term driver of salinity regime change since European settlement.
- Sea-level rise is occurring at almost 2 mm per year accumulating perhaps 10 cm since 1921. This is a slow but significant impact on northern reach salinity regime by marginally increasing wave speeds, tidal velocity, baroclinicity, shear dispersion, and tidal flow asymmetries (tidal trapping). Each process tends to increase upstream salinity mixing.
- Permanent island flooding since 1921, including Mildred Island, Little Mandeville Island, and Sherman Lake, increase salinity mixing by tidal trapping. Other islands, including Liberty Island, may reduce ocean salt transport to the delta by absorbing tidal energy. The importance of this physical salinity driver may increase in the future.
- Drastic changes in watershed land use especially in the first half of the century modified soil permeability and runoff characteristics. The well-known alterations include levees, bypasses, soil compaction, forest modification, groundwater overdraft, imports from other watersheds, conversion of emergent marshes, and surface hardening (Fox and others 1990).

CONCLUSION

We re-constructed monthly time series of San Francisco Estuary watershed precipitation (since 1921), delta outflow (since 1929), and northern reach salinity at Port Chicago (since 1947), Beldons Landing (since 1929), and Collinsville (since 1921). We decomposed the data into seasonal, decadal, and trend components to clarify the superposition of variability drivers. With the longest time series over 1,000 months, these are the longest data records in the estuary save for Golden Gate tide. We used the precipitation index to compare trends and variability in climate forcing to outflow and salinity trends before and after construction of the water projects and the Suisun Marsh Salinity Control Gate. Our primary conclusions extend and clarify the work of other investigators:

- The state and federal water projects decoupled long-term trends in annual mean outflow and salinity from long-term trends in precipitation.
- The water projects dampen seasonal and annual outflow and salinity variability.
- Despite this, both seasonal and annual timescale outflow and salinity are generally more variable in the water project era concordant with watershed precipitation.
- Annual average precipitation is not serially correlated. Annual average outflow is likewise not serially correlated until water project influence intensifies in the late 1960s.
- We suggest a revision of the widely held conceptual model that the water projects have reduced flow and salinity variability in the northern reach. While water project operations act to reduce flow and salinity variability, actual sea-

sonal and annual variability has increased since the late 1960's. Therefore, water projects induce secondary influence on annual and seasonal outflow and salinity variability. Climate is a more powerful long–term variability driver at the seasonal and annual scale.

- About 10% of monthly precipitation and outflow variability is explained by decadal scale oscillations in the PDO index. Further, decadal scale variability in the monthly outflow and salinity data explains 10% to 15% of their total variability.
- We underscored the value of long data records for discerning trend and variability drivers. On the one hand, ocean/atmosphere climate teleconnections explained significant decadal scale (20-year to 25-year) variability. On the other hand, slowly changing watershed runoff characteristics, northern reach bathymetry deepening, and expanding water project operations together explain long-term (greater than decadal) trends. Therefore, identifying trends and mechanisms requires data sets that are longer than the scale of the lowest frequency forcing mechanism.
- The seasonal loess method effectively sequesters the decadal variability in the decadal fit. It thereby better accounts for drought and PDO-scale variability and provides a more robust estimate of the long-term (multi-decadal) trend.

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TRENDS IN FRESHWATER INFLOW TO SAN FRANCISCO BAY FROM THE SACRAMENTO-SAN JOAQUIN DELTA[1]

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ABSTRACT: Outflow from the Sacramento-San Joaquin river system (Delta outflow) provides about 90 percent of the freshwater flow to San Francisco Bay. Because this river system also supplies most of the water used in California, some believed that annual freshwater flow to the Bay had declined by as much as 50 to 60 percent as water use increased. Consequently, we studied trends in actual Delta outflow and precipitation for the period 1921 to 1986, which is when Delta outflow data are available. We found that there has been no decrease in the annual Delta outflow over this period. In fact, a statistically significant increase in annual Delta outflow of 87 cfs/yr has occurred during the period 1921 to 1986. One reason that Delta outflow has increased is because precipitation has increased faster than water use. Other contributing factors include increased runoff from land use changes, water imports from other areas, and the redistribution of ground water. In addition, statistically significant seasonal trends in Delta outflow were found. Over the period 1921-1986 Delta outflow decreased in April and May and increased from July through November. Changes in other months were not statistically significant. These seasonal changes result primarily from the operation of upstream flood control and water development projects, which store water in the spring and release it in the summer and fall. These seasonal changes are also influenced by a climatic shift that has decreased spring snowmelt runoff and increased late summer through winter precipitation.
(KEY TERMS: San Francisco Bay; Delta outflow; nonparametric trend analysis; precipitation.)

INTRODUCTION

San Francisco Bay is the largest estuary along the Pacific coast of the United States (Conomos *et al.*, 1985). Ninety percent of the Bay's freshwater inflow comes from the Sacramento-San Joaquin Delta and its tributary river system, which drains the area enclosed within the dashed line on Figure 1. This watershed includes the Central Valley, one of the richest agricultural regions in the world. The Sacramento-San Joaquin drainage supplied about 55 percent of the freshwater used in California in 1985, or some 2.2 billion cubic feet per day (19 million acre-feet per year), including about 60 percent of the irrigation water and 40 percent of the drinking water (CDWR, 1988). This water is moved throughout the state in complex man-made water systems, with 1.2 trillion cubic feet (27 million acre feet) of reservoir storage and some 1300 miles of aqueduct (described in Kahrl, 1979; CDWR, 1983). Water consumptively used within or exported out of this region would otherwise flow into San Francisco Bay.

Some have claimed that this upstream development reduced the total amount of freshwater reaching the Bay by 50 to 60 percent (Meyer and Davoren, 1981; Nichols *et al.*, 1986; Rozengurt *et al.*, 1987). These alleged reductions in freshwater flow have been blamed for adverse affects on Bay fisheries and water quality (Kjelson *et al.*, 1982; Herrgesell *et al.*, 1983). However, these claims of flow reduction are not based on analyses of the amount of freshwater actually reaching the Bay. Instead, they arise from an inappropriate use of hypothetical flows developed for planning purposes by the California Department of Water Resources (CDWR).

In this paper, we analyze actual freshwater inflow to the San Francisco Bay to quantify annual and seasonal changes. Our study was designed to answer three questions: (1) Has there been a large decline in the annual amount of freshwater reaching San Francisco Bay? (2) Have there been changes in the seasonal patterns of freshwater flow to the Bay? and (3) What are the principal causes of any noted changes?

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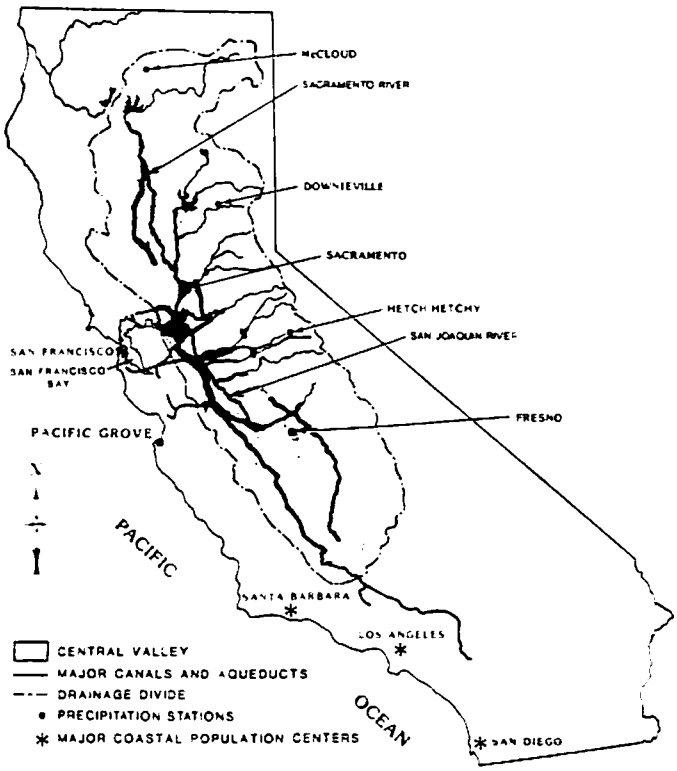

Figure 1. Major Features of California's Central Valley That Influence Freshwater Flow to San Francisco Bay.

THE DATA

Descriptive information on the flow and precipitation data that we analyzed is summarized in Table 1. The starting point for our work was monthly flow and precipitation time series for the period from October 1920 through September 1986 (water years 1921 to 1986). All references to years in this work are to water years unless otherwise noted. The monthly time series were used to compute annual and seasonal time series. Annual water-year precipitation series were formed by summing the total monthly precipitation from October through September for each year. Annual water-year flow series were formed by computing the monthly average flow in cfs for each year. Seasonal time series were formed by separating the monthly time series into 12 monthly data sets where successive values are one year apart (e.g., a January series, a February series, etc.). All three of these time series – monthly, annual, and seasonal – were analyzed in this work.

Actual Delta Outflow

To identify and describe trends in freshwater flow into San Francisco Bay, we analyzed California Department of Water Resources (CDWR) monthly Delta outflow data (Table 1). Delta outflow is the estimated net freshwater flow at Chipps Island at the western edge of the Delta (Figure 2). It is calculated from a water balance around the Delta (Figure 2a) because strong tidal fluctuations preclude direct measurement (CDWR, 1987a, plus updates). It is computed from gauged streamflows and estimated net consumptive use within the Delta resulting from about 1800 agricultural diversions.

We used the available record, which spans the period from October 1920 through September 1986. These data should reflect historic changes in freshwater flow from upstream development because the record covers the period when most of the development occurred. For example, about 95 percent of the total upstream reservoir storage capacity has been built since 1921, exports out of the drainage commenced in 1929, and major features of the Federal Central Valley Project and the California State Water Project were completed in the 1950s and 1960s, respectively (CDWR, 1983).

Precipitation

Because Delta outflow results from precipitation on upstream drainages, we also analyzed precipitation records over the same period (Table 1) at five locations to determine if climatic changes had occurred (CDWR, 1980; NOAA, 1981-1986). These locations, shown in Figure 1, are: McCloud and Downieville in the mountains of the northern part of the drainage; Sacramento in the northern lowlands; Hetch Hetchy in the mountains of the southern part of the drainage; and Fresno in the southern lowlands (Table 1). We selected these stations because they provide good geographic coverage of the upstream watersheds that drain into the Bay, they are among the few that have nearly continuous records for the period from 1921 to 1986, and they have not been affected by major station moves or instrumentation changes.

Unimpaired Delta Outflow

CDWR also estimates the total river flow available for present use, and this is called unimpaired flow (CDWR, 1987b). We analyzed unimpaired flows to help explain trends in actual Delta outflow since trends in unimpaired flows are principally due to

TABLE 1. Descriptive Information on the Flow and Precipitation Data Analyzed in This Study.

Type of Data	Period of Record	No. Values	Median	Mean	Standard Deviation	Range	Lag-1 ACC*	Durbin Watson d**
				FLOW DATA (average flow in cfs***)				
Actual Delta Outflow								
Annual Time Series	1921–1986	66	28,486	30,240	17,743	3,513 – 89,452	0.074	1.84
Monthly Time Series	10/20–9/86	792	15,729	30,441	36,678	–3,578 – 270,412	0.69	0.61
Unimpaired Delta Outflow								
Annual Time Series	1921–1983	63	34,991	39,213	19,598	7,603 – 99,514	–0.01	1.88
Monthly Time Series	10/20–9/83	756	24,008	39,378	40,521	2,472 – 258,426	0.68	0.65
Depletions								
Annual Time Series	1921–1983	63	8,180	9,052	4,924	2,038 – 28,514	–0.23	2.34
Monthly Time Series	10/20–9/83	756	4,464	9,023	15,756	–39,055 – 82,342	0.46	1.13
				PRECIPITATION DATA (total precipitation in inches***)				
McCloud								
Annual Time Series	1921–1986	66	47.67	49.71	15.90	14.11 – 90.68	–0.07	2.12
Monthly Time Series	10/20–9/86	790	2.37	4.15	4.89	0.00 – 23.79	0.44	1.13
Downieville								
Annual Time Series	1921–1986	63	62.41	62.57	18.78	22.00 – 102.65	0.02	1.93
Monthly Time Series	10/20–9/86	773	2.97	5.24	6.24	0.00 – 40.01	0.47	1.07
Sacramento								
Annual Time Series	1921–1986	66	17.00	17.85	6.81	6.71 – 36.57	0.07	1.83
Monthly Time Series	10/20–9/86	792	0.63	1.49	2.01	0.00 – 12.20	0.48	1.06
Hetch Hetchy								
Annual Time Series	1921–1986	66	33.94	35.51	11.41	14.73 – 72.40	–0.17	2.32
Monthly Time Series	10/20–9/86	792	1.77	2.96	3.47	0.00 – 26.23	0.44	1.12
Fresno								
Annual Time Series	1921–1986	66	9.28	10.18	4.00	4.44 – 23.59	–0.17	2.34
Monthly Time Series	10/20–9/86	792	0.31	0.85	1.18	0.00 – 8.56	0.41	1.18

*For the annual time series, this is the one-year lagged autocorrelation coefficient. For the monthly time series, this is the one-month lagged autocorrelation coefficient. The statistical significance of the lag-1 ACC was evaluated in a two-sided t-test of the null hypothesis of no autocorrelation against the alternate hypothesis of autocorrelation (Pancratz, 1983, p. 68). None of the annual lag-1 ACCs are statistically significant at the 5 percent level. All of the monthly lag-1 ACCs are statistically significant at the 5 percent level.

**The Durbin-Watson d statistic is computed for the linear model $y=c_0+c_1T$ where y is flow or precipitation, T is time, and the c_n's are regression coefficients. The statistical significance of this statistic was evaluated in a two-sided test of the null hypothesis of no autocorrelation against the alternate hypothesis of autocorrelation (Draper and Smith, 1981, p. 163). For the annual series, none of the d's are statistically significant at the 5 percent level. For the monthly series, all of the d's are statistically significant at the 5 percent level.

***For the annual series, flow is reported as the annual average in cfs and precipitation as the total annual precipitation in in/yr computed by summing monthly values. For the monthly series, flow is reported as the monthly average in cfs and precipitation as the total monthly precipitation in in/mo computed by summing daily values.

changes in precipitation. Unimpaired flow estimates are available from October 1920 to September 1983 (Table 1).

Unimpaired flow is a computed estimate of the total water supply in areas tributary to the Delta. Unimpaired outflow is not "actual" nor "natural" outflow, but rather it is a hypothetical flow that never occurred at any time. It is computed from a water balance around the valley (shaded area in Figure 1) by summing rim inflows at the periphery of the shaded area in Figure 1 and the valley floor runoff and subtracting the consumptive use of native vegetation in the Delta (CDWR, 1987b). These computations use gauged streamflows adjusted by CDWR to remove the influence of physical facilities (i.e., upstream reservoir storage, exports, etc). Thus, unimpaired flows are a measure of runoff from precipitation in upstream drainages with current land use and the vast network

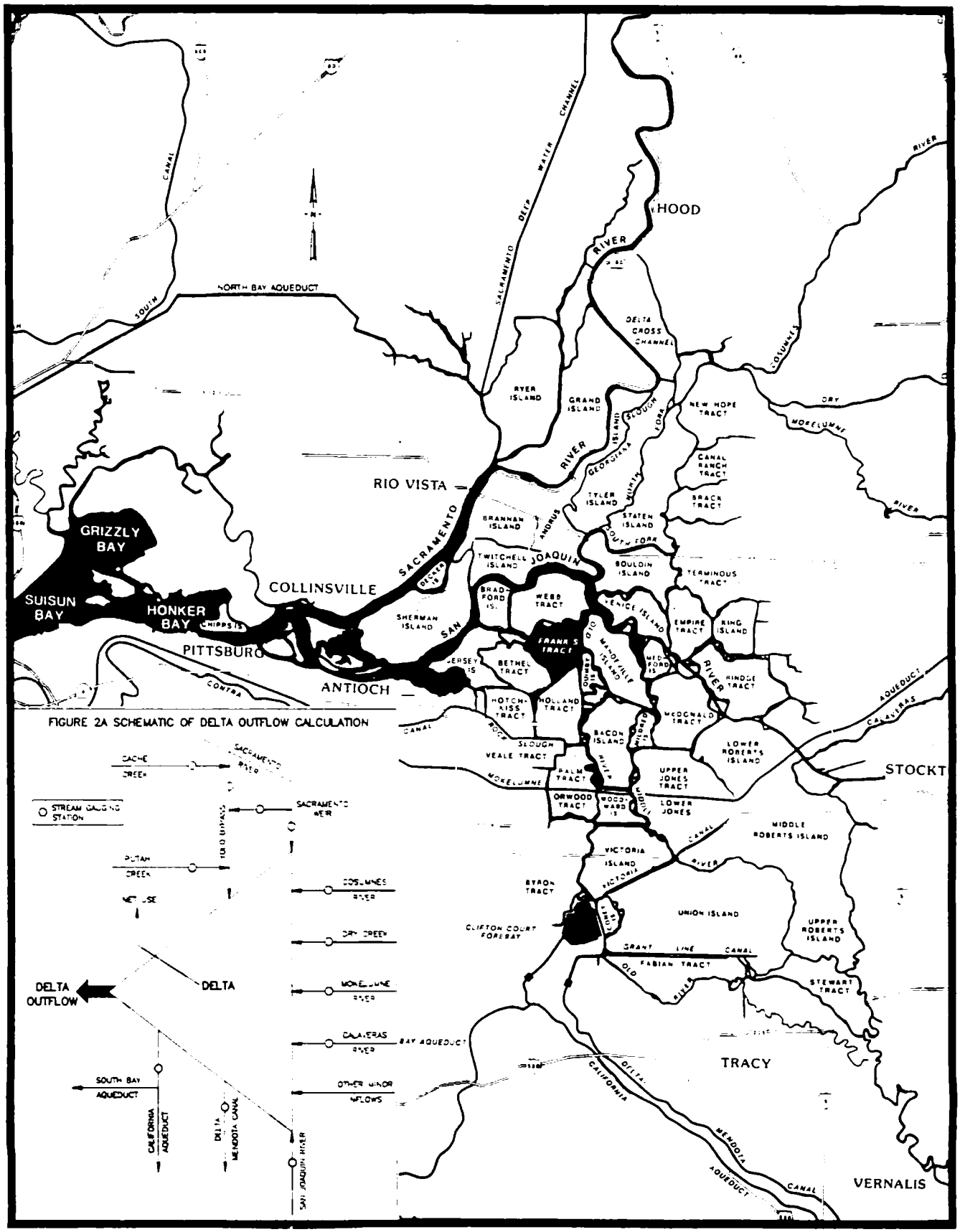

Figure 2. The Sacramento-San Joaquin Delta, the Major Outlet for Freshwater Into San Francisco Bay.

of man-made channels in place (e.g., an extensive system of levees, dredged deep-water channels, flood bypass channels, overflow weirs, etc.). These channels and levees substantially increase flows over levels that would occur under "natural" conditions, because they prevent flooding into adjacent swamps and increase stream velocities, reducing the amount of evaporation and transpiration that would otherwise occur (Fox, 1987).

Depletions

The difference between unimpaired and actual Delta outflow is a measure of the amount of water removed from upstream drainages for export and consumptive use. We calculated annual and monthly "depletion" time series by subtracting actual Delta outflow from unimpaired Delta outflow. Depletions represent the amount of freshwater removed from the basin that otherwise would have flowed into San Francisco Bay with present levees and channels.

DATA ANALYSIS

The data described above were analyzed for trends using classical parametric techniques from hydrology (Chow, 1964; Yevjevich, 1972) and nonparametric methods that have become popular in the past decade (Hirsch *et al.*, 1982; Hirsch and Slack, 1984; Gilbert, 1987; Berryman *et al.*, 1988). We emphasize the results from the nonparametric procedures because the data sets violate some of the assumptions underlying the parametric methods. All of the methods used are amply described in the literature. Therefore, we only briefly outline the steps we followed in this work. All of the techniques described here were applied to all three series – annual, seasonal, and monthly – unless specifically excepted.

Smoothing

Each time series was smoothed to portray the essential features of the data. We used a 10-year moving average (Chow, 1964) and LOWESS, which stands for "LOcally WEighted regression Scatter plot Smoothing" (Cleveland, 1979; Chambers *et al.*, 1983). LOWESS was chosen because outliers do not distort the smoothing and it accommodates missing values. We used the version of LOWESS implemented on Systat (Wilkinson, 1986).

Parametric Trend Estimation

First, we estimated the trend in each data set using ordinary least-squares regression (Chow, 1964; Draper and Smith, 1981). We used this procedure, even though it is not optimal for our data, because it is simple and widely understood. A trend was estimated by fitting a straight line to the data with time as the independent variable. For the monthly time series, the month was included as a dummy variable to account for seasonal variability (Draper and Smith, 1981, p. 241; Bowerman and O'Connell, 1987). We do not report the statistical significance of trends calculated in this manner because the data violate some of the underlying assumptions required for such tests (Smith, 1986; Helsel and Hirsch, 1988).

Nonparametric Trend Estimation

Trends were also estimated and their statistical significance assessed using nonparametric procedures because the data sets contained outliers and were not normally distributed. In all cases, we tested the null hypothesis of no trend against the alternate hypothesis of either an upward or downward trend using a two-tailed test. We selected a significance level (α) of 10 percent as commonly used by the U.S. Geological Survey in similar work (Smith *et al.*, 1987). However, most of the trends we report as statistically significant at the 10 percent level are also significant at the 5 percent level. Because the trend procedures used were different for annual and seasonal series, as opposed to monthly series, each type is discussed separately.

Annual and Seasonal Time Series

Successive values in these series are separated by one year, and seasonal cycles are not present. A trend was quantified using Sen's slope estimator (Sen, 1968) as implemented in a Fortran program developed by Battelle Pacific Northwest Laboratory (Gilbert, 1987). In the Sen method, the data are ranked in the order in which they are collected over time, and the slopes of the straight line segments linking all possible pairs of data points are computed. These slopes are ranked, and the Sen slope is the median value. This method is preferred to least-squares for our data because it is not biased by the major floods and droughts at the beginning and end of the data sets.

The statistical significance of trend in these series was tested used the Mann-Kendall test (Mann, 1945;

Kendall, 1975) as implemented in a Fortran Program developed by Battelle (Gilbert, 1987). In this test, the data are time ranked as in the Sen method and assigned the value +1, −1, or 0 according to the sign of the calculated differences of all possible time-ranked pairs. The Mann-Kendall S statistic is then computed as the number of positive differences minus the number of negative differences. Since the distribution of S is nearly normal for the sample sizes evaluated here (Table 1), we used the standard normal deviate Z (computed from S and the variance of S) referred to the cumulative normal distribution to evaluate significance (Gilbert, 1987, p. 211).

Serial correlation between successive values in a data set (i.e., autocorrelation) can result in overestimation of the true statistical significance of trend. Consequently, we checked each annual and seasonal time series for serial correlation using the one-year lagged (lag-1) autocorrelation coefficient (Pancratz, 1983) and the Durbin-Watson d statistic (Draper and Smith, 1981, p. 162). Since these statistics are not defined when missing values are present (Table 1), we estimated missing values in the McCloud and Downieville precipitation records by regressing these two records with one another. The statistical significance of the annual (lag-1) autocorrelation coefficient was tested using Bartlett's approximation for the standard error with the t-distribution (Pankratz, 1983, p. 68). All of the annual (Table 1) and seasonal series were independent at the 5 percent level except the August and September seasonal series. Others have also reported that annual data are either independent or very nearly so (Yevjevich, 1964; Potter, 1979, 1981).

Monthly Time Series

These series comprise monthly data over the period of record, and successive values are separated by one month. The monthly series have strong seasonal cycles and series correlation. Consequently, we used modifications of the Sen slope estimator and Mann-Kendall test that account for the seasonal effects and serial correlation.

A trend was quantified using the seasonal Kendall slope estimator (Hirsch *et al.*, 1982) as implemented in a Fortran program developed by the U.S. Geological Survey (USGS). This is a generalization of Sen's slope estimator. The Sen slope is computed for all data pairs for the same month from the entire data set, the Sen slopes are ranked, and the median of the ranked values is the seasonal Kendall slope.

The statistical significance of a trend in a monthly time series was evaluated with the seasonal Kendall test (Hirsch *et al.*, 1982) corrected for serial correlation (Hirsch and Slack, 1984) as implemented in a Fortran program developed by the USGS. The seasonal Kendall test is an adaptation of the Mann-Kendall test for a trend, in which each month is treated as an independent variable. The Mann-Kendall S statistic and the variance of S are computed separately for each month over all years and the grand test statistic S* is computed as the sum of individual monthly Mann-Kendall S statistics. Serial correlation is accounted for by estimating the covariance between successive months within the same year and including it in the computation of the variance of S*. Since the distribution of S* is nearly normal for the sample sizes evaluated here (Table 1), we used the standard normal deviate Z (computed from S* and the variance of S*) referred to the cumulative normal distribution to evaluate significance (Hirsch *et al.*, 1982).

Calculation of Percent Change

Throughout this paper, we use "total percent change" or simply "percent change" to quantify the magnitude of the trend over the period of record referenced to the beginning of the record. This quantity is always calculated as follows:

$$\text{percent change} = 100\text{x}(\text{trendxN}) / [\text{median} +/- 1/2(\text{trendxN})] \qquad (1)$$

where N is the number of years in the record (66), the plus (+) sign is used for a decreasing trend and the minus (−) sign for an increasing trend.

ANNUAL TRENDS

Actual Delta Outflow

Annual flow data are plotted in Figures 3a-3c, superimposed over LOWESS smoothed curves. The LOWESS curves indicate that the actual Delta outflow (Figure 3a) has slightly increased even though depletions (Figure 3c), or net water use, have increased markedly. Plots of 10-year moving averages (not shown here) display the same trends and relationships among the three sets of flow data. Similar trend curves published by the U.S. Geological Survey (USGS, 1986, p. 163) show an increasing trend in the two major components of Delta outflow, the Sacramento River and the San Joaquin River (Figure 1). These simple graphical displays clearly indicate that Delta outflow, which is over 90 percent of the

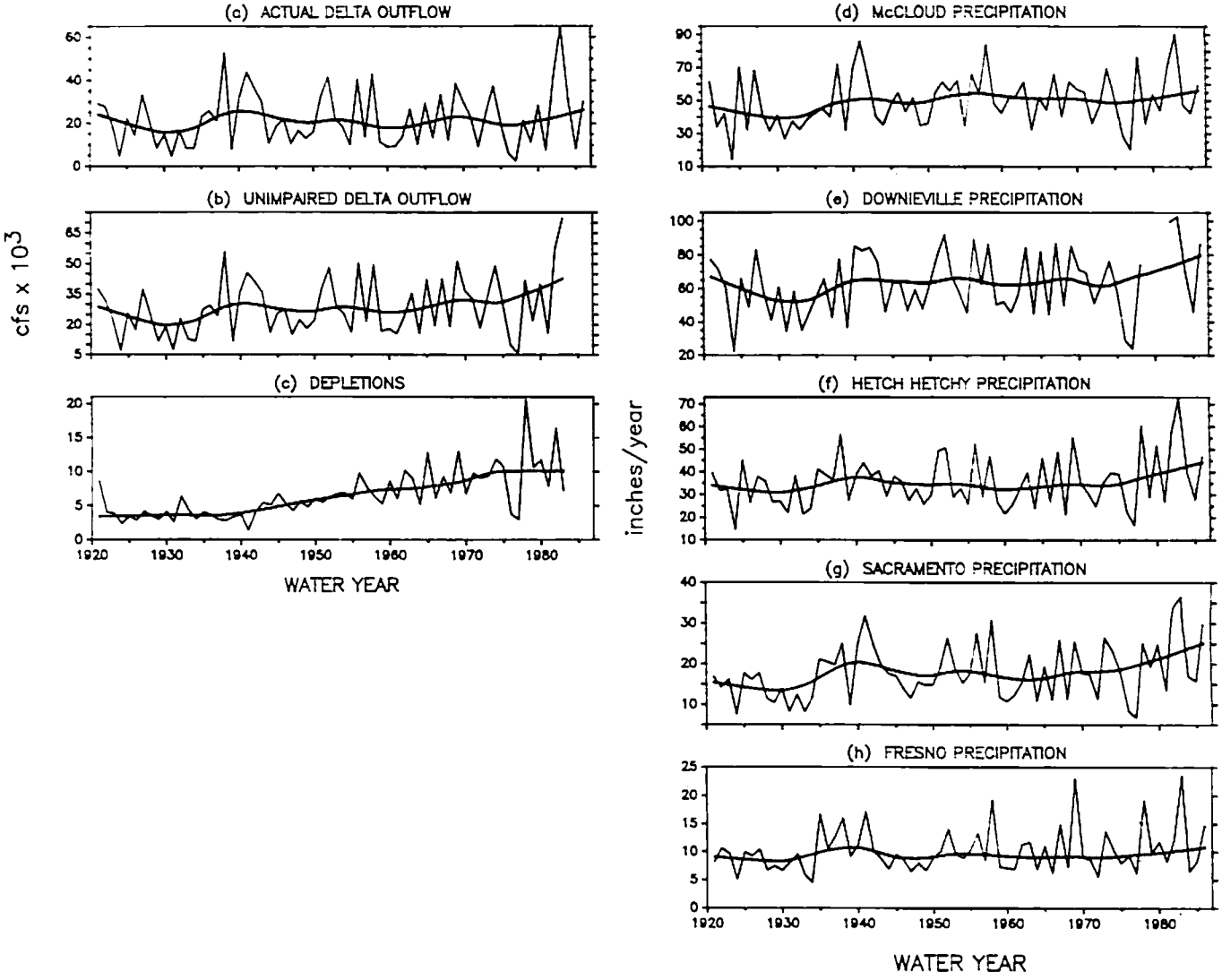

Figure 3. Annual Flow and Precipitation Data. The jagged lines plot the annual average flows and total annual precipitation. The smoothed line is the LOWESS trend curve, computed for f=0.30, where f is the fraction of the points included in the smoothing routine (Cleveland, 1979). Different y-scales are used for each plot.

freshwater flow into San Francisco Bay, has not declined over the period from 1921 to 1986.

The trend analysis (Table 2) confirms that Delta outflow has not decreased. Table 2 compares the "trend" or average rate of change in both annual and monthly time series estimated by two separate methods: least-squares and Sen's slope. Both trend methods indicate that actual Delta outflow has slightly increased over the period 1921 to 1986, in agreement with the LOWESS trend curve (Figure 3a). The nonparametric procedure provides a more accurate estimate of the true, long-term trend in our data sets because it is not biased by outliers. Most of the least-squares trends are higher than their Sen counterparts due to outliers.

The Sen analysis for the annual series indicates that Delta outflow has increased at 41 cfs/yr or by about 9 percent since 1921. Because the two-tailed p-value (0.72) is greater than the significance level of 0.10, the null hypothesis of no trend is accepted and the alternate hypothesis of a trend is rejected. This means that the trend in annual Delta outflow over the period 1921 to 1986 is not inconsistent with the hypothesis of no trend.

The seasonal Kendall results for the monthly series indicate that Delta outflow has increased by 87 cfs/yr or by about 45 percent since 1921. Since the two-tailed p-value (0.032) is less than the significance level of 0.10, the null hypothesis of no trend is rejected and the alternate hypothesis of a trend is accepted.

TABLE 2. Trend Analysis of Annual and Monthly Flow and Precipitation Data.

	Annual Time Series			Monthly Time Series		
	Least-Squares Trend[1]	Sen's Trend[2]	Two-Tailed p-Value[3]	Least-Squares Trend[1]	Seasonal Kendall Trend[2,4]	Two-Tailed p-Value[3]
FLOW DATA	(cfs/yr)	(cfs/yr)		(cfs/yr)	(cfs/yr)	
Actual Delta Outflow	+ 95	+ 41	0.72	+102	+87*	0.03
Unimpaired Delta Outflow	+285	+244	0.12	+285	+89*	0.01
Depletions	+182	+171*	<0.01	+177	+58*	<0.01
PRECIPITATION DATA	(in/yr)	(in/yr)		(in/yr)	(in/yr)	
McCloud	+0.18	+0.20*	0.05	+0.20	+0.29*	0.05
Downieville	+0.20	+0.18	0.18	+0.20	+0.16*	<0.01
Sacramento	+0.10	+0.08*	0.06	+0.11	>+0.00*	<0.01
Hetch Hetchy	+0.13	+0.06	0.31	+0.12	+0.05*	0.07
Fresno	+0.03	+0.02	0.29	+0.046	>+0.00*	0.06

[1]Computed as the slope of the straight line fit to the data using linear least-squares regression. For monthly series, a dummy month variable (Draper and Smith, 1981) was included to account for seasonal variability. The test statistic is not reported because the data violate underlying assumptions of the t-test (Helsel and Hirsch, 1988).

[2]The asterisk (*) indicates that the Sen trend is statistically significant at the α=0.10 level in a two-tailed test of the null hypothesis of no trend against the alternate hypothesis of either an upward or downward trend.

[3]This is the attained significance level from the two-tailed hypothesis test described in note No. 2. It is the probability (p) of exceeding the absolute value of the Z-statistic in a two-tailed test. When the p-value is less than the significance level of 0.10, the nonparametric trend is statistically significant.

[4]The seasonal Kendall trend is computed only for monthly series and is a generalization of the Sen trend used for the annual time series.

Since the Z-statistic is positive (Z=+2.15), the trend is upward. This means that a statistically significant increase in monthly Delta outflow has occurred over the period from 1921 to 1986.

The reason that the monthly series yields a statistically significant trend, while the annual series does not, is in part due to the much larger sample size for the monthly series (792 observations versus 66). Further, the monthly series is dominated by strongly increasing trends in the summer and fall months, as discussed in the next section on seasonal trends. These seasonal trends have little influence on the trends in the annual series.

Precipitation

The annual Delta outflow has not declined since 1921, even though depletions have increased (Figure 3c). This could result from some combination of the following four factors: (a) an increase in precipitation in the Sacramento-San Joaquin drainage between 1921 and 1986; (b) an increase in the fraction of precipitation that runs off and contributes to outflow, as a result of changes in land use; (c) increased surface flow resulting from the known ground water overdraft in the San Joaquin Valley; and (d) water imports into the area from other drainages.

We checked the possibility of increased precipitation in the Sacramento-San Joaquin drainage by analyzing precipitation data from five representative locations, as well as unimpaired flow data, to see if they exhibited an increasing trend.

We first regressed the annual Delta outflow on the annual precipitation and unimpaired outflow to determine if there was any relationship between the series. As expected, there was a statistically significant relationship between actual outflow and precipitation at all five of the stations (r^2=0.89 to 0.95, p<0.01) as well as between actual outflow and unimpaired outflow (r^2=0.98, p<0.01).

We then evaluated the trend in the five precipitation time series (Table 1). The annual precipitation data are plotted in Figures 3d-3h, superimposed over LOWESS smoothed curves. The LOWESS curves suggest that precipitation has increased at all five stations over the period of record. Similar plots of 10-year moving averages show the same trends at each station. Unimpaired flow (Figure 3b) is the total runoff from upstream drainages. The upward trend in unimpaired flow agrees with the upward trend in precipitation, suggesting that the increasing trend is a

basin-wide phenomenon. The unimpaired flow data show that more water has been available for consumptive use in recent years than earlier in the century.

The trend analysis (Table 2) confirms a basin-wide increase in precipitation and runoff upstream from San Francisco Bay. Both the annual and monthly series indicate that precipitation increased over the period 1921 to 1986 at the five stations we studied. All of the increasing trends for the monthly series are statistically significant at the 10 percent level. To assure that we had not fortuitously selected five stations with an increasing trend, we selected five additional stations – Portola, Colfax, and Auburn in the northern mountains and Huntington Lake and Yosemite in the southern mountains – and tested those annual series for trends. All five of these stations also displayed increasing Sen trends that ranged from 0.10 to 0.26 in/yr, comparable to the five original stations (Table 2). The Sen trends at Huntington Lake (0.26 in/yr; $p<0.01$) and at Portola (0.12 in/yr; $p=0.025$) were statistically significant at the 5 percent level. Most of the increase in precipitation seems to have occurred in the mountainous parts of the Sacramento-San Joaquin drainage, which produces the majority of the runoff that ultimately reaches San Francisco Bay.

We do not have time series data on the fraction of annual precipitation that runs off and contributes to outflow. This fraction could have increased due to changes in land use. Land use changes that could increase runoff include replacing high water-using inland marshes with lower water-using irrigated lands (Fox, 1987), replacing native vegetation with paved areas, buildings and other urban land uses (CDWR, 1983, p. 176), and clearing heavily forested areas. These land use changes increase the water supply by reducing consumptive use and by increasing runoff.

We checked for evidence of an increasing fraction of precipitation, increasing ground water overdraft, and imported water appearing as outflow in the following way. First, we regressed the logarithm of actual Delta outflow on monthly precipitation. Then we looked at the trend in the regression residuals. If the relationship between outflow and precipitation is constant in time, the residual should show no trend. If, however, the residuals do show a trend in time, this indicates that the relationship between precipitation and outflow has changed in time (as a result of ground water overdraft, water imports, or a change in the fraction of precipitation that runs off and contributes to outflow).

To check if the relation between actual outflow and precipitation is constant in time, we regressed the logarithm of monthly actual Delta outflow (logQ) on the total monthly precipitation (P) calculated by summing the five individual monthly time series. The residuals were then tested for a trend to determine if a change in the precipitation-runoff relationship could have contributed to the increase in Delta outflow. LogQ was used because the logarithms of monthly outflow are approximately normally distributed, as is common for monthly flow data (Delleur *et al.*, 1976), the resulting regression relationships were approximately linear, and the residuals were approximately normally distributed. Seasonal variability was accounted for by including the month in the regression as a dummy variable (Draper and Smith, 1981, p. 241).

The resulting flow-precipitation relationship and all regression constants were statistically significant (two-tailed $p<0.01$), and the model accounted for 60 percent of the variability in the flow data. The trend in the residuals was evaluated using the seasonal Kendall test corrected for serial correlation (Hirsch and Slack, 1984). The two-tailed p-value for this trend test was 0.091, which is less than the significance level of 0.10. Thus, the null hypothesis of no trend is rejected and the alternate hypothesis of a trend is accepted. Since the Z-statistic is positive ($Z=+1.69$), the trend is upward. This indicates that the increase in the monthly Delta outflow (Table 1; 87 cfs/yr) over the period from 1921 to 1986 is caused in part by a change in the precipitation-runoff relationship.

Unimpaired outflow has increased (Table 2), confirming the increase in precipitation (although unimpaired outflow trends could also be influenced by changes in land use and water imports). The water supply (i.e., unimpaired flow) increased at a faster rate than water was removed from the system (i.e., depletions) over the period from 1921 to 1986, which is why the annual Delta outflow has not decreased. The two-tailed p-values indicate that the monthly trends in unimpaired flow ($p=0.012$) and depletions ($p<0.01$) are statistically significant at the 5 percent level.

To confirm that the trend in precipitation was large enough to account for the observed increase in unimpaired outflow, we made a very rough estimate of the amount of additional runoff that would be generated by the precipitation increase. The calculations are summarized in Table 3. The increase in Delta outflow due to precipitation increases was estimated by multilying the drainage-area-weighted annual Sen trend (Table 2) by a regional area and a regional runoff factor. This rough estimate indicates that the precipitation increase is equivalent to an increase in flow of about 180 cfs/yr.

This rough estimate (Table 3) indicates that the precipitation increase might account for about 70 percent of the increase in annual unimpaired outflow (Table 2; 244 cfs/yr). Thus, one of the main reasons

TABLE 3. An Estimate of the Contribution of the Increasing Trend in Precipitation to the Increasing Trend in Delta Outflow.

Regional Area	Stations Used to Compute Increase in Precipitation	Land Area[1] (mi^2)	Average Annual Increase in Precipitation[2] (in/yr)	Runoff Factor[3]	Increase in Runoff Due to Increase in Precipitation[4] (cfs/yr)
Sacramento Valley Floor	Sacramento	4,946	0.084	0.11	3.4
Sacramento Mountains	Auburn Colfax Downieville McCloud Portola	21,602	0.16	0.46	120
San Joaquin Valley Floor	Fresno	5,434	0.024	0.065	0.62
San Joaquin Mountains	Hetch Hetchy Huntington Lake Yosemite	10,512	0.16	0.41	51
TOTALS		42,494			180

[1]The areas are taken from Bulletin 1, Table 53, pp. 309-310 (SWRCB, 1951).

[2]The annual increase in precipitation is the Sen trend for the annual time series for the five stations in Table 2 plus five additional stations added for this computation (Auburn, Huntington Lake, Colfax, Portola, and Yosemite). Each regional trend (e.g., 0.16 in/yr for the Sacramento Mountains) is a drainage area-weighted average for the region.

[3]The runoff factor was computed as the ratio of average annual unimpaired outflow from each regional area in column (1) as reported in CDWR (1987b) to the total annual precipitation for each area from Rantz's (1969) isohyetal map for the Central Valley, where flow and precipitation are expressed in the same units.

[4]Computed as [areal] x [precipitation increase] x [runoff factor] x [0.0737 ft^3yr/in mi^2 sec]. All values, including the total, are reported to two significant figures.

that freshwater flow into San Francisco Bay has not declined is because precipitation has increased enough to offset increases in water use. Additional data, particularly a more recent isohyetal map and trend estimates for additional precipitation stations, would be required to refine this estimate.

Other Factors

Factors other than an increase in precipitation also have contributed to the upward trend in water supply to the Bay. The calculations presented above indicate that roughly 30 percent of the increasing outflow trend is caused by factors other than precipitation increases. These other factors include imports, redistribution of ground water, and land use changes.

Water has been imported into upstream drainages from the Trinity River and Tule Lake since the mid-sixties. These imports averaged about 1100 cfs in 1980. This amounts to an increase of about 17 cfs/yr, if averaged over the period from 1921 to 1986. Return flows from ground water pumped for agricultural and municipal uses may also have increased surface flows, particularly during droughts when users turn to ground water to augment dwindling surface supplies. About 3800 cfs of ground water were pumped in 1980 in the Delta watershed (CDWR, 1983). If only 10 percent of this water were to appear as surface flow, this would represent an increase of about 6 cfs/yr if averaged over the period from 1921 to 1986. Finally, as noted above, land use changes may have increased the fraction of precipitation that runs off and ultimately appears as Delta outflow. This final factor cannot be quantified directly with available information.

SEASONAL TRENDS

We also analyzed monthly Delta outflow and precipitation data to determine whether changes had occurred in individual months. Each monthly flow and precipitation time series was subdivided into 12 independent monthly data sets, referred to as "seasonal" time series. The resulting 96 individual seasonal series were separately analyzed for trend. This work indicates that the statistically significant annual trends found in the monthly time series (Table 2) are due to strong seasonal trends, which differ in both magnitude and direction from month to month.

Actual Delta outflow is plotted for each month in Figure 4, superimposed over LOWESS smoothed curves. The LOWESS curves suggest that outflow has decreased in April, May, and June and increased in all other months over the period from 1921 to 1986. It is interesting to note that the spring declines level out in the post-1960 period after the major facilities shown in Figure 1 were on line. Similar plots of 10-year moving averages show the same trends.

The LOWESS results are confirmed by the trend analysis (Table 4), which shows that declines have taken place in April, May, and June and increases in all other months. Although the two trend methods yield equivalent trend directions (i.e., increasing, or decreasing), trend magnitudes differ between the two procedures due to outliers. The Sen slope is a better representation of the true trend in these data because least-squares unduly weights the outliers, which overestimates the magnitude of trends.

Statistically significant increases in outflow have occurred in summer and fall months. The Sen analysis indicates that July through September flows have significantly increased over the period from 1921 to 1986. Statistically significant decreases in outflow

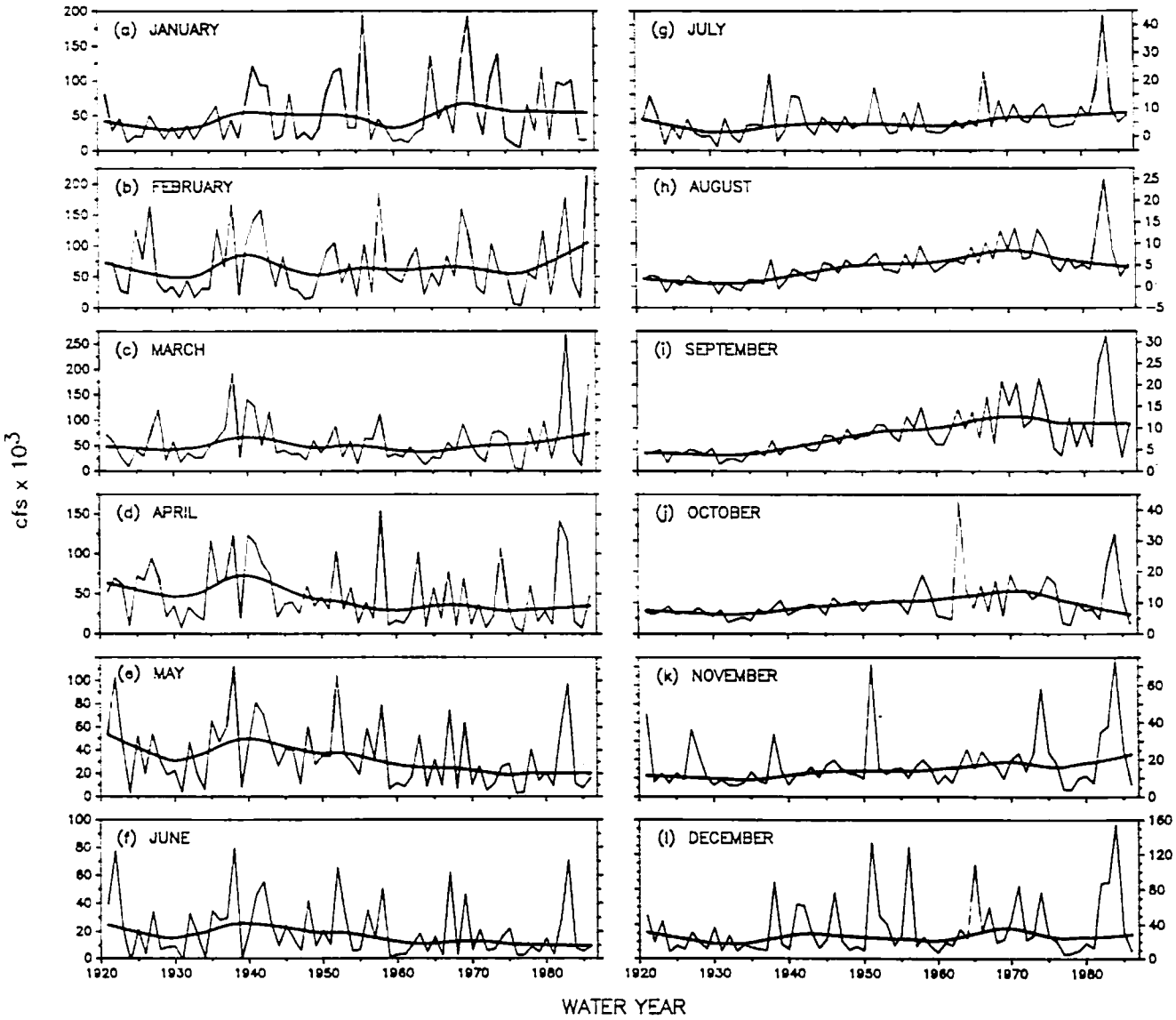

Figure 4. Monthly Average Actual Delta Outflow Computed at Chipps Island. The jagged lines plot the monthly average flows in cfs for each month. The heavier, smoothed line is the LOWESS trend curve, computed for f=0.30, where f is the fraction of the points included in the smoothing routine (Cleveland, 1979). Different y-scales are used for each plot.

have occurred in April and May. The Sen analysis indicates that since 1921, outflow has declined in April by 56 percent and in May by 64 percent (Table 4). Thus, the major change that has occurred since 1921 is a redistribution of flow from April, May, and June to all other months.

The seasonal trends shown in Table 4 are probably due to two factors – upstream reservoir operation/consumptive use and an apparent shift in climatic conditions. We studied the effect of each of these factors on Delta outflow by comparing monthly trends in the precipitation data with those for the flow data (Figure 5).

Water projects upstream from the Bay are operated to control floods, to supply downstream water users, and to meet in-stream needs, including salinity control, fisheries, recreation, and navigation. Flood control is required because the entire valley was historically subject to almost annual flooding (Thompson, 1960). Reservoir capacity is set aside from mid-October through March for flood control. The increase in actual Delta outflow in these months (Figure 5a) is apparently due to increases in the amount of precipitation and in the fraction of precipitation that contributes to outflow. The monthly unimpaired outflow (Figure 5b) and precipitation data (Figures 5d-5h) indicate that statistically significant increases in runoff and precipitation have occurred throughout the flood season, but predominantly in November, January, and March. The increased amounts of rainfall usually are not captured for use in the present system due to the need to reserve space for flood control. Thus, they have contributed to the annual increase in Delta outflow discussed previously.

Flood control requires that most water storage to satisfy year-round uses must occur primarily from April to June. This use pattern is reflected in the monthly Delta outflow trends (Figure 5a). Statistically significant decreases have occurred in April and May outflow (Table 4), when water is stored. However, not all of the late spring decrease is due to water project operation. Precipitation has

TABLE 4. Trend Analysis of Seasonal Delta Outflow Time Series.[1]

Month	Least-Squares Trend[2] (cfs/yr)	Sen's Trend[3] (cfs/yr)	Total Percent Change[4] (percent)	Two-Tailed p-Value[5]	Lag-1 ACC[6]	Durbin Watson d[7]
October	+123	+108*	+148	<0.01	0.19	1.84
November	+163	+148*	+111	0.013	0.22	1.59
December	+369	+169	+69	0.21	0.12	1.84
January	+489	+134	+38	0.48	0.16	1.75
February	+176	+94	+12	0.75	–0.01	1.89
March	+227	+16	+3	0.91	0.02	1.89
April	–322	–424*	–56	0.025	–0.01	2.08
May	–365	–416*	–64	0.018	0.02	2.07
June	–192	–141	–48	0.14	–0.02	2.08
July	+122	+90*	+405	<0.01	0.16	1.87
August	+152	+133*	+349	<0.01	0.55†	1.59†
September	+187	+172*	+867	<0.01	0.49†	1.64

[1]The seasonal time series in this table were formed by separating the monthly time series (Table 1) into 12 monthly data sets where successive values are one year apart.

[2]Computed as the slope of the straight line fit to the data using linear least-squares regression. Test statistics are not reported because the data violate underlying assumptions of the t-test (Helsel and Hirsch, 1988).

[3]The asterisk (*) indicates that the trend is statistically significant at the α=0.10 level in a two-tailed test of the null hypothesis of no trend against the alternate hypothesis of either an upward or downward trend.

[4]The total percent change is computed for the Sen trend from: 100x(trendxN) / [median +/– 1/2(trendxN)] where N = number of years in the record = 66. The plus (+) sign is used for a decreasing trend and the minus (–) sign for an increasing change because the trend is computed with respect to the beginning of the record.

[5]This is the attained significance level from the two-tailed hypothesis test described in note No. 3. It is the probability (p) of exceeding the absolute value of the Z-statistic in a two-tailed test. When the p-value is less than the significance level of 0.10, the nonparametric Sen trend is statistically significant.

[6]The dagger (†) indicates that the one-year lagged autocorrelation coefficient (lag-1 ACC) is statistically significant at the 5 percent level in a two-tailed t-test (Pancratz, 1983). Because the August and September lag-1 ACCs are statistically significant, the two-tailed p-values may overstate the true significance of the Sen trend (i.e., the p-values may be smaller than warranted).

[7]The Durban-Watson d statistic is computed for the linear model $Q=c_0+c_1T$ where Q is the flow, T is time, and the c_ns are regression coefficients. The statistical significance of this statistic was evaluated in a two-sided test of the null hypothesis of no autocorrelation against the alternate hypothesis of autocorrelation (Draper and Smith, 1981, p. 163). The dagger indicates that d is statistically significant at the 5 per cent level.

decreased during late spring at all five stations (Figures 5d-5h). Others have reported that April to July unimpaired runoff (i.e., snowmelt runoff) has declined over the period 1921 to 1983 (Roos, 1988).

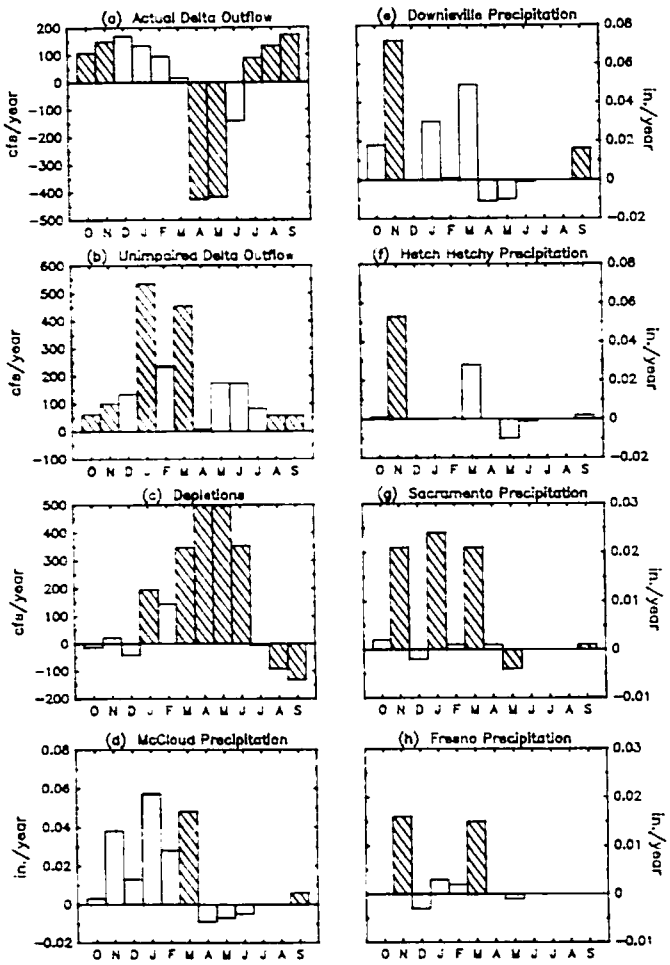

Figure 5. Monthly Trends in Flow and Precipitation. Shaded bars indicate the trend is statistically significant at the 10 percent level in a two-tailed Z test. Unshaded bars indicate the trend is not statistically significant. Different y-scales are used for each plot.

The water stored in April to June is released in the summer and early fall for consumptive and various in-stream uses including salinity control, fish and wildlife, and navigation. This is reflected in the July to November outflow (Figure 5a), which has increased over the period 1921 to 1986 (Table 4). Part of this increase is due to increases in precipitation from September through November (Figures 5d-5h).

These analyses suggest that a climatic shift has occurred in upstream drainages that has redistributed monthly precipitation. Because most of the rainfall increase has occurred during the flood season when it cannot be captured for future use, it has augmented Delta outflow. Spring precipitation has decreased and late summer through winter precipitation has increased. Similar results have also been reported by the CDWR. Roos (1988) analyzed a number of indices of water supply in areas tributary to the Bay. He found that April through July runoff into the Central Valley (Figure 1) declined since 1921 and markedly since 1950 (Roos, 1988), while the annual volume of runoff increased (Roos, 1988). Because April to July is snowmelt season, this suggests a shift in the fraction of flow resulting from rain instead of snowmelt.

If this climatic/hydrologic shift were to continue, it could have significant adverse effects on California's present water delivery system. The increased winter runoff (Figure 5b) and early snowmelt (Roos, 1988) would be spilled from the reservoirs because of the flood control requirement, instead of going into storage for later use. Carry-over storage of the late spring snowpack would be reduced, decreasing the quantity of water reliably stored for later use.

DISCUSSION

Our analyses demonstrate that there has been no reduction in annual freshwater inflow to San Francisco Bay from the Sacramento-San Joaquin Delta over the period from 1921 to 1986, although seasonal shifts in Delta outflow have occurred. Thus, there is no basis for any contention that long-term average annual reductions in freshwater inflow to San Francisco Bay have occurred. Spring decreases result from exports and the need to store water for later use and to protect the valley from flooding. Changes in this pattern would require changes in reservoir operating rules as well as additional off-stream storage. The increased summer and fall outflows prevent salinity intrusion into the Delta and provide important benefits that must be balanced against any adverse effects that may result from reduced April and May flows.

Previous estimates of reductions in freshwater flow into San Francisco Bay (Meyer and Davoren, 1981; Nichols *et al.*, 1986; Rozengurt *et al.*, 1987) were not based on analyses of actual outflow. Instead, these other estimates are hypothetical because they are based on planning estimates of Delta outflow that never occurred historically. The hypothetical outflow reductions are computed from CDWR's "level-of-development" and "unimpaired" outflows by assuming that "level-of-development" flows are equivalent to "actual" flows and that "unimpaired" flows are equivalent to "natural" flows or those that occurred in

1850. Neither assumption is accurate. The relevant outflows and the computation used to estimate the hypothetical 50 to 60 decline are summarized in Table 5.

The CDWR uses various computer models (e.g., reservoir operations, consumptive use, water balance) to estimate flows that would have been observed with different system configurations, if historic precipitation were repeated. These models are used to calculate two types of flows, "level-of-development" and "unimpaired" Delta outflows. The level-of-development flows are those that would occur if the physical facilities and upstream land use at a given point in time (e.g., 1990) were fixed and the climate since 1921 were repeated (CDWR, 1987a, #28-30). Level-of-development outflows have never occurred historically and are not equal to actual outflow, as shown in Table 5.

Unimpaired outflows, as discussed previously, are those that would have occurred if the climate of 1921 to 1983 were repeated, with no reservoirs, exports, and in-basin water use, but with all existing land uses, channels, and levees in place (CDWR, 1987b). Unimpaired flows are not the same as "natural" flows (Table 5) as CDWR has clearly stated (CDWR, 1987b, p. 1) and as demonstrated by Fox (1987). Further, the unimpaired flows are not equal to the average flow in 1850, as assumed by Nichols *et al.* (1986).

The 1990 level-of-development flows are about 46 percent of the unimpaired flows (Table 5), which represents a reduction of 54 percent (see note to Table 5). Previous estimates of level-of-development flows for 1980 and other years correspond to a reduction of 50 to 60 percent from unimpaired flows. This is the basis of the claim that freshwater flow to the Bay has been reduced. This claim is incorrect because unimpaired and level-of-development flows are hypothetical and never occurred historically. Reductions based on these flows are likewise hypothetical.

Actual Delta outflow analyzed in this work is an estimate of the amount of water that historically reached the Bay from 1921 to 1986 when most of the development of California's large-scale water system had occurred (CDWR, 1983, 1988). Our analyses of actual Delta outflow clearly demonstrate that annual freshwater inflow to the Bay from the Sacramento-San Joaquin Delta has not declined. The actual outflow has averaged 30,240 cfs annually (21.9 million acre feet) over the period from 1921 to 1986 and 33,980 cfs (24.6 million acre feet) over the period 1976 to 1986.

CONCLUSIONS

Two independent trend tests (least-squares regression and Sen's slope) on monthly and annual series indicate that actual Delta outflow has not declined over the period from 1921 to 1986. The monthly Delta outflow time series indicates that a statistically significant increase in actual Delta outflow of 87 cfs/yr, or about 45 percent, has occurred since 1921.

The principal reason that Delta outflow has not decreased is because the water supply has increased faster than water use. The annual unimpaired runoff has increased at 244 cfs/yr, primarily as a result of increases in precipitation (0.02 to 0.26 in/yr) at the stations studied. Other factors, including imports, the redistribution of ground water, and an increase in the fraction of the precipitation that runs off, may also have contributed to the increase in actual Delta outflow.

There have been statistically significant seasonal changes in Delta outflow. Flows have decreased in April and May and increased from July through November. Changes in other months are not statistically significant. This primarily results from the

TABLE 5. Comparison of Actual Delta Outflow With Various Planning Estimates.

Representation of Delta Outflow*	Period of Record	Average Annual Outflow (cfs)	Authority
Actual**	10/20-9/86	30,240	CDWR (1987a, #27 and updates)
Unimpaired**	10/20-9/83	39,210	CDWR (1987b)
Natural	10/20-9/83	18,510	Fox (1987)
1980 Level of Development	10/20-9/78	19,300	CDWR (1983, p. 184)
1990 Level of Development	10/20-9/78	17,950	CDWR (1987, #30d)
2000 Level of Development	10/20-9/78	17,440	CDWR (1987, #30d Rev.)

*The alleged 50 to 60 percent reduction in freshwater flow to San Francisco Bay is computed from:
100x[unimpaired flow – level-of-development flow] / unimpaired flow.
**Analyzed in this work.

operation of upstream flood control and water development projects that store water in the spring and release it in the summer and fall. This seasonal pattern is also affected by a decrease in spring snowmelt runoff and an increase in summer through winter precipitation.

If the seasonal shift in precipitation and runoff continues, additional reservoir storage capacity will be required to maintain present firm yield of California's water system. Decreased flows have occurred during spring when water is stored. Increases have occurred during the winter, when the flows usually cannot be captured for subsequent use because of the flood control reservation.

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ranching and the first commercial production of grain in the valley. Campo de los Franceses, within which Stockton now stands, was deeded to Guillermo Gulnac in 1844, and later obtained by Captain Weber. Additional land grants were made along the periphery of the Delta until California became a state (Thompson 1957). Also, with the increasing attention to the valley, several exploring expeditions entered the Delta, notably Captain Belcher's trip up the Sacramento in 1837 and the Captain Wilkes U.S. Exploring Expedition in 1841.

1847: TRANSPORTATION VIA STEAMBOAT

The first steamboat, the *Sitka*, traveled to Sacramento from San Francisco in 1847 (Hutchings 1859). Regular steamboat travel along the San Joaquin River began in 1849. Steamboats became the primary mode of transportation within the Delta, shipping products to market in San Francisco and later bringing miners part way to their diggings in the Sierra Nevada. The steamboat era came to an end around 1878, as hydraulic mining debris reduced channel depths and railroads became the more economical means of transportation.

1848: GOLD DISCOVERED

The discovery of gold marked the beginning of a flood of settlement in the Delta region. Settlements and small gardens and orchards quickly sprang up along the Sacramento River, and the wood cleared from the land was used to fuel steamboats (Fig. 1.11). Riparian forests were affected early. Homesteads were established along the high lands of the natural levees, while the wetter land behind was used as pasture in the summer (Van Löben Sels 1902, Hoppe pers. comm.). The Delta had relatively little human modification until this time.

1850: FEDERAL SWAMP AND OVERFLOWED LAND ACT

The Swamp and Overflowed Land Act was passed in 1849 and extended to California in 1850, when it became a state. The Act transferred "swamp and

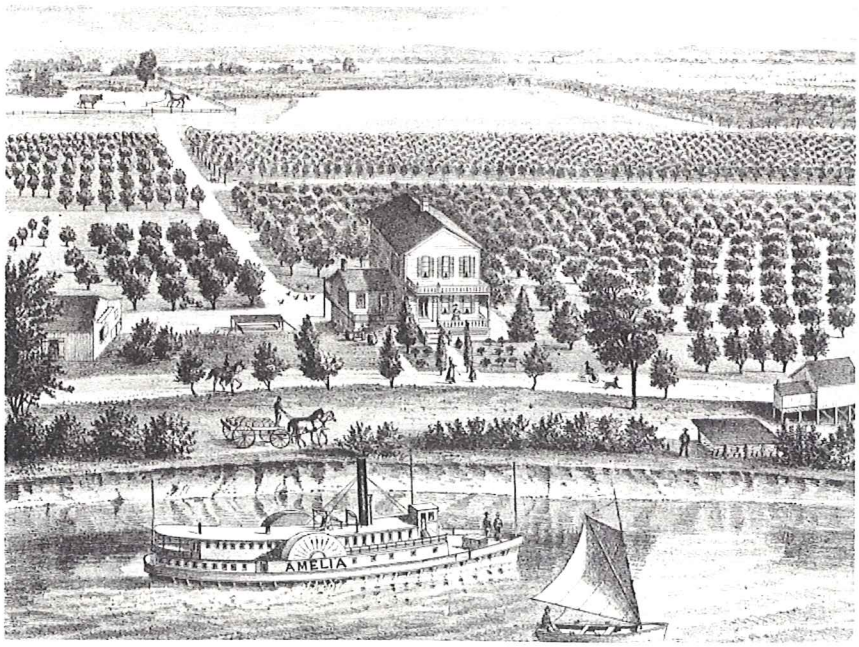


Figure 1.11. Orchards on Grand Island, along Steamboat Slough. The natural levee lands along the river were some of the first areas to be cultivated in the Delta and were prime sites for orchard crops. (Thompson and West 1880, courtesy of SharingHistory.com)

overflowed" lands from the federal government to the state for sale to the public (see Box 2.3). This was intended to incentivize drainage of wetlands.

1850: LEVEE BUILDING BEGINS

The first levees constructed in the Delta were to protect the City of Sacramento after the 1850 flood. Levee building in the tidal wetlands began, among other places, on upper Grand Island in 1853, Andrus Island in 1855, Roberts Island in 1856, Union Island in 1857, and Brannan Island in 1859 (Tucker 1879a-f, Rose et al. 1895). These initial efforts involved the damming of many small sloughs that branched and headed within the wetlands (Fig. 1.12). Such actions modified hydrologic conditions by reducing tidal prism, tidal channel length, and tidal wetland area. Also, as levees were raised steadily higher to keep floodwaters from spilling into the wetlands, this effectively raised flood levels, such that unprotected lands were flooded to a greater extent than before (Gilbert 1917).

1851: SWAMP AND OVERFLOWED LAND FIRST SOLD

The state passed its first law to grant swamp and overflowed land to individuals. Later, the California Reclamation District Act of 1855 governed the sale of these lands for $1 per acre, with a limit of 320 acres (Thompson 1957). The limit was increased to 640 acres in 1859. The early period of reclamation was fraught with battles between private control and state and federal assistance. Some argued that reclamation should be left to private interests to guarantee that the land would be used, while others challenged that projects were too large to be coordinated and implemented effectively by private landholders.

1855: RAILROADS INTRODUCED

The Sacramento Valley Railroad was established in 1855. It wasn't until 1871, however, that the California Pacific Railroad Company, Central Pacific Railroad Company, and Western Pacific began expanding through the valley.

Figure 1.12. Damming sloughs. In the early years of reclamation, most of the smaller sloughs that brought tides to the interior of Delta islands were dammed either with tide gates or by building a levee across them. (Unknown ca. 1900, MS 229, Dyer Photograph Album, courtesy of Holt-Atherton Special Collections, University of the Pacific Library)

1856: HYDRAULIC MINING EFFECTS FELT

Hydraulic mining for gold began in the Sierra Nevada in 1853 and over the next several decades washed entire hillsides into the streams and rivers (Fig. 1.13). Sediment inflow increased more than nine times over historical levels, from about 1.5 million cubic meters (2.0 million yd^3) annually to about 14 (31.4 million yd^3; Gilbert 1917, Atwater and Belknap 1980). Suisun Bay accumulated about 115 million cubic meters (150 million yd^3) between 1867 and 1887 (Cappiella et al. 1999). Effects were felt in the Sacramento Valley as early as 1856 (Bailey [1919]1927), but were particularly apparent in the Delta after the 1862 flood. The sediment raised the beds of streams which exacerbated the effects of floods, dramatically decreased tidal range, and hampered navigation, eliminated important spawning grounds for fish, and increased river turbidity (Box 1.2; Gilbert 1917). In some cases (mostly upstream of the Delta) the sediment covered valuable agricultural land (Nesbit 1885). It was also contaminated with mercury used in the mining operations, which (along with mercury from the Coast Range) continues to affect downstream ecosystems today. This was outlawed in the 1884 *People v. Gold Run Ditch and Mining Company* case, whch ended with the Supreme Court decision, *Woodruff v. North Bloomfield et al*, in 1892. The apex of debris from the American River is estimated to have passed Sacramento in 1896, though waves from other rivers passed through later (Gilbert 1917). Over the past century, sediment supply has diminished substantially, with a 50% reduction in the Sacramento River's sediment supply between 1957 and 2001 (Wright and Schoellhamer 2004) and significant erosion in Suisun Bay (Cappiella et al. 1999).

1861: RECLAMATION DISTRICT ACT PASSED

The California Legislature created the State Board of Swamp Land Commissioners to encourage the establishment of reclamation districts to levee the Delta. These districts would join land together within natural boundaries to facilitate reclamation. The first districts to be created were District #1, the American Basin; District #2, the Sacramento Basin; and District #3, Grand Island.

1862: FLOOD

The largest flood in recorded history passed through the Central Valley in the winter of 1861-1862. Accounts describe the Sacramento Valley as almost entirely flooded. It washed away the town of Rio Vista and blocked flood tide currents at the water surface. Mining debris from the Sierra Nevada contributed to the damages caused by the flood.

1862: AMERICAN RIVER MOUTH REALIGNED

In order to relieve pressure on the levees protecting the City of Sacramento from flooding by the American River, efforts were initiated in 1862 to realign the American River at its mouth. It was diverted from its channel curving to the south and made to enter the Sacramento about a half a mile upstream.

1863: SEVERE DROUGHT

The large floods of 1862 were followed by several years of severe drought. As cattle and sheep died of starvation, ranchers sought new grazing land, including the Delta.

Figure 1.13. Hydraulic mining. The caption of this photograph, which is shown as Plate I of Grove Karl Gilbert's treatise on hydraulic mining debris (1917), reads: "A hydraulic gold mine. The water is conveyed by pipe, under a head of several hundred feet, and delivered through a nozzle that can be turned in any direction. The jet washes the auriferous earth from the cliff and thence to a sluice, seen at the left. The sluice is several hundred feet long and contains pockets of mercury by which the gold is caught. (photo by Gilbert 1908, from Gilbert 1917)

BOX 1.2. CHANNELS FILL WITH HYDRAULIC MINING DEBRIS

Hydraulic mining debris, particularly in the Sacramento River, dramatically raised the river's bed. As the debris accumulated, tidal range that had once been two feet at Sacramento in 1847 became negligible by the 1880s. By the early 1900s, the rise and fall of tides was reduced even further to be imperceptible nine miles downstream of Sacramento (Mendell 1881, Hall 1880). The increasing bed levels caused low water levels to increase close to six feet between 1849 and 1879, a year where a tide range of two inches was recorded at Sacramento (Fig. 1.14; Taylor 1913, Gilbert 1917). An 1895 report found that "the bottom of the river bed is now higher than the old low-water surface of the river (Rose et al. 1895). Tidal action was partially restored by 1913, subsequent to the 1892 *Bloomfield v. Woodruff* decision that outlawed hydraulic mining. Today, tide ranges at Sacramento are largely restored to their 1849 two foot (0.6 m) range, though the changes to channel geometry that occurred alongside the rising bed levels challenges interpretation. It is unknown what the tide range would be at Sacramento today were there still several hundred thousand acres of tidal marsh and over one thousand miles of tidal channel in the Delta.

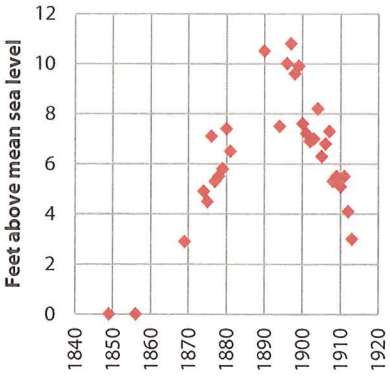


Figure 1.14. Rising bed levels through the hydraulic mining period, indicated by low-water stages of the Sacramento River at Sacramento. This graph is adapted from Table 2 (pp. 29-30) in Gilbert (1917).

1866: CONTROL OVER SWAMP AND OVERFLOWED LAND GIVEN TO COUNTIES

The Board of Swamp Land Commissioners was dissolved and control over surveying and selling the State's swamp and overflowed land was given to the counties.

1868: ACREAGE LIMITS FOR SWAMP AND OVERFLOWED LAND REMOVED

The Green Act removed acreage limitations for individuals to purchase swamp and overflowed land. Other incentives were also given for large-scale reclamation efforts. The 640-acre limit was restored in 1874.

1869: COORDINATED LEVEE BUILDING AND RECLAMATION

With the reclamation of Sherman Island in 1869 by the Tide Land Reclamation Company, a new era began. At one time, the Tide Land Reclamation Company held 120,000 acres of land in the Delta (Paterson et al. 1978). The majority of the work in the initial decades was performed by hand by Chinese laborers. In the 1870s, steam-powered dredges were used to rebuild and raise levees (Fig. 1.15). During this period, many channel meanders were cut off, particularly on the San Joaquin River, to lessen levee miles (reduce cost) and shorten travel distance. It was understood that reclamation was generally easier within the central Delta, because these peat lands could be easily cleared with fire (the land along the Sacramento River flood basins did not burn deeply because they were not deep peat soils) and levees did not have to be built to withstand the flood heights of the Sacramento River (Tide Land Reclamation Company 1872, Naglee 1879). In general, the levees within the central Delta were built to prevent tidal inundation of the land, whereas the levees to the north and south were largely to prevent overflow by major river floods. By 1900 more than half of the Delta had been leveed and an even greater area had experienced reclamation attempts (Fig. 1.16; Thompson 1957). The Delta was almost entirely reclaimed by 1930, although levees continue to break, requiring significant expenses in drainage and repair.

Figure 1.15. Clam-shell dredge building levees. The clam-shell dredge, Vulcan, is shown building the height of an artificial levee along an unknown waterway. After initial reclamation efforts, where levees were built primarily by Chinese laborers, dredges were used to build higher levees to keep out the tides and floods. (McCurry Foto Co. ca. 1910, courtesy of the California History Room, California Sate Library, Sacramento)

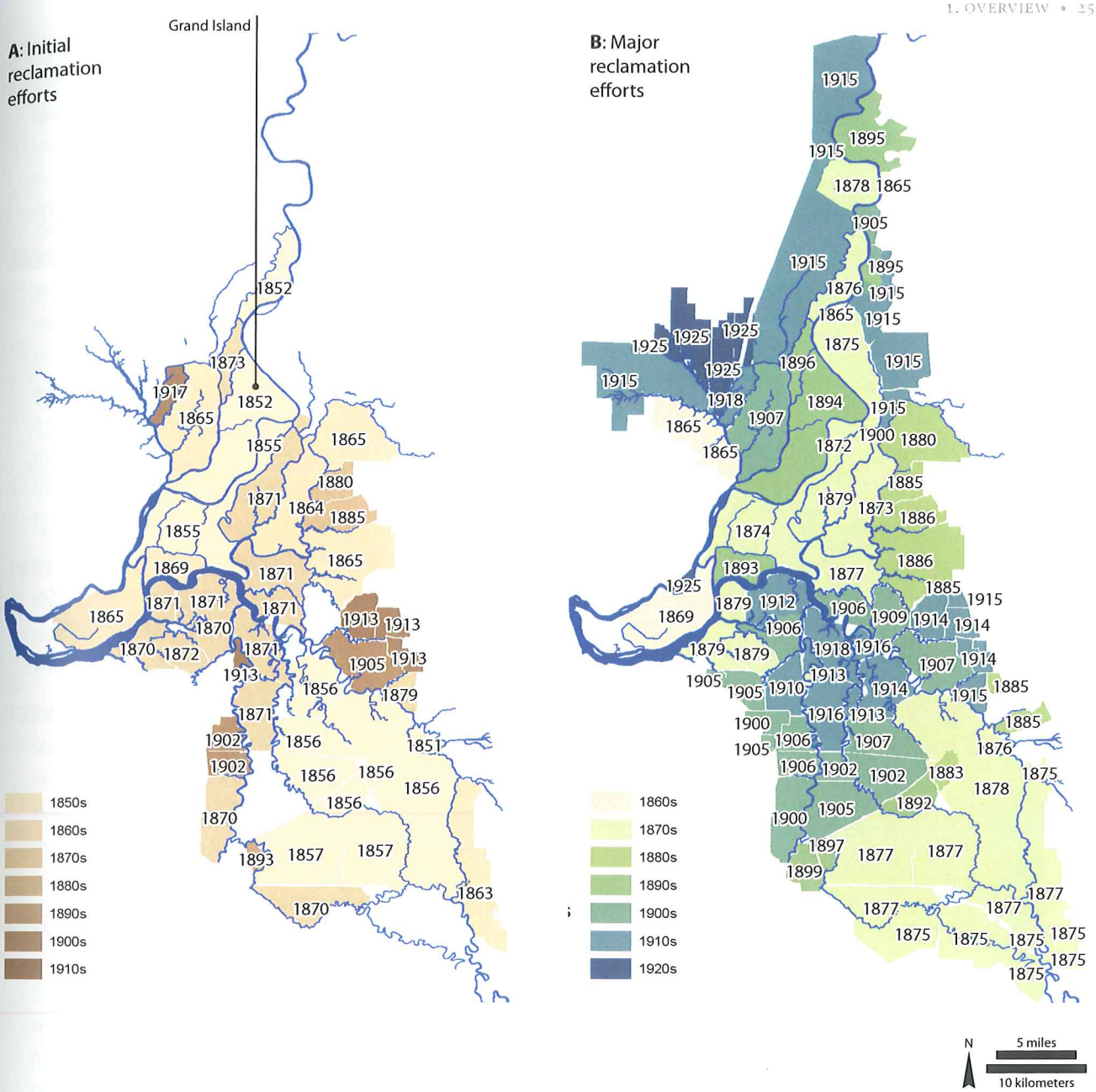


Figure 1.16. Reclamation sequence in the Delta. In A, the earliest date of known reclamation efforts is shown if this is different from the main date of reclamation given in historical records (B). For instance, small levees and damming of sloughs began as early as 1852 on Grand Island, but the island was not officially reclaimed until 1894. The dates given for the initial reclamation efforts do not indicate that the entire islands were reclaimed, simply that work had begun on that island or tract of land. Also, dates for major reclamation are those given for levee completion and do not necessarily indicate that the entire area was under agricultural production by that time. Information was compiled from numerous sources, including reclamation notes by the State Engineering Department (Tucker 1879a-f), John Thompson's (1957) reconstructions of reclamation sequence, those of the California State Lands Commission, and the Department of Water Resources.

1860: LARGE MAMMAL POPULATIONS ON THE DECLINE

Most large mammal populations significantly reduced or eliminated. Beaver and otter had become scarce several decades earlier due to intensive trapping.

1879: STRIPED BASS INTRODUCED INTO THE DELTA

This marked a period of other introductions in the rivers and streams of California. It also was a period when salmon hatcheries were established, in an attempt to recover already declining populations. This has led to the situation today, where the majority of salmon migrating through the Central Valley are of hatchery origin, without the unique endemism to individual rivers and streams that is found in wild populations.

1880: SALMON FISHING AND WATERFOWL HUNTING INTENSIFIES

Commercial fishing began in the 1850s and canneries were established in the 1860s (the first in 1864). A recorded 10.8 million pounds of salmon were caught in 1880, with the peak catch in 1909 at 12 million pounds (Yoshiyama et al. 1998). The last cannery on the Sacramento River went out of business in 1919. Hunting for ducks, geese, and other waterfowl for market increased in the decades after the Gold Rush. It became a significant business in the late 1800s, with markets in Sacramento and San Francisco for both the meat and eggs.

1886: RIPARIAN RIGHTS UPHELD

In *Lux v. Miller* and *Lux v. Haggin,* riparian water rights were upheld over appropriative rights.

1887: THE WRIGHT ACT PASSED

The Wright Act authorized the formation of irrigation districts, allowing and fostering the irrigation of lands not lying adjacent to rivers or streams.

1890: FISHERY AND WATER DIVERSION REGULATIONS

The State Board of Fish Commissioners began regulating fisheries and water diversions (Jacobs 1993).

1893: DEBRIS COMMISSION CREATED

With the Caminetti Act, the California Debris Commission was tasked with solving the mining debris problem. The first state appropriation for river improvement was in 1897. Detailed surveys and maps were made of the major rivers in the valley. The Dabney Commission report of 1904 presented flood control policy. The Debris Commission posed a number of solutions, including the "Minor Project" of 1907 and the "Major Project" of 1910, which involved dredging operations and included modifications such as the cutoff of Horseshoe Bend on the lower Sacramento River in 1914. This significantly increased the width and depth of the lower Sacramento River.

1902: FEDERAL RECLAMATION ACT

The passage of the Federal Reclamation Act created the U.S. Bureau of Reclamation which subsequently granted $500,000 to address hydraulic mining debris in California.

1914: WATER COMMISSION ACT

The current system of surface water rights was established with the passage of the Water Commission Act.

1920: SALINITY INTRUSION STUDIED

Salinity intrusion became significant in the 1920s, promting monitoring and a lawsuit. The intrusion caused the cities of Antioch and Pittsburg to seek new water sources in 1926. An investigation was initiated, and a report produced in 1931 on the control of salinity in the Delta, which proposed several options (CDPW 1931).

1931: STATE WATER PLAN PROPOSED

The State Water Plan, by State Engineer Edward Hyatt, laid out the system that was to transfer water from the north to the southern part of the state, though it had been proposed by others in various forms earlier. It was authorized in 1933 and was later undertaken by the Federal Government as a public works project, named the Central Valley Project. Today, it is one of the largest water infrastructure projects in the world and forms the core of the network of reservoirs, canals, and pumps that store and transport water throughout California.

1933: STOCKTON CHANNEL DREDGED

The Stockton Deep Water Ship Channel was dredged, deepening the channel substantially. This reach had been modified substantially by earlier leveeing and dredging efforts.

1938: O'SHAUGHNESSY DAM HERALDS AN ERA OF DAM BUILDING

Major changes in the hydrographs of rivers feeding into the Central Valley are brought about by an era of dam building that resulted in the damming of every major river in the Sierra Nevada, except for the Cosumnes River. One of the first major dams, the Mendota Dam on the San Joaquin, was constructed in 1881.

1940: DELTA WATER EXPORTS BEGIN

The completed Contra Costa Canal initiated water exports from the Delta. The Tracy (C.W. "Bill" Jones) Pumping Plant was completed in 1951, which brings water the Delta-Mendota Canal, all part of the Central Valley Project. Exports have continued to grow. Part of this increase is attributable to the completion of the California Aqueduct in 1973. Exports to the Bay Area and Southern California now exceed 6 million acre-feet.

1944: DELTA CROSS CHANNEL CONSTRUCTED

This channel, which connects the Sacramento River to the Mokelumne just upstream of Walnut Grove, facilitates water transfers through the Delta to the Tracy Pumping Plants. It has contributed to altering the magnitude and direction of flows in the Delta.

1955: SACRAMENTO DEEP WATER SHIPPING CANAL

Construction for the Sacramento Deep Water Shipping Channal began in 1955. The canal extends from West Sacramento southward through the Yolo Bypass to the outlet at Cache Slough. It was completed in 1963.

1966: THE FEDERAL ENDANGERED SPECIES PRESERVATION ACT

The Federal Endangered Species Preservation Act in 1966 established the protection of endangered species.

1969: ASSESSMENT OF ENVIRONMENTAL IMPACTS REQUIRED

The National Environmental Policy Act (NEPA) was passed in 1969, along with the state's Porter-Cologne Water Quality Act, which granted authority to the State Water Resources Control Board (SWRCB) regarding water quality. In 1970, the California Environmental Quality Act (CEQA) was passed, similar to NEPA.

1982: PERIPHERAL CANAL PROPOSAL REJECTED

A proposal to build a peripheral canal to divert water exports around the Delta to southern California was rejected by voters in 1982. It had been recommended by the Delta Environmental Advisory Committee in 1973.

1987: BAY-DELTA HEARINGS BEGIN

The Bay-Delta hearings were in response to the SWRCB failing to establish adequate water quality standards.

1993: LISTING OF ENDANGERED SPECIES

The Delta smelt (*Hypomesus transpacificus*), endemic to California, was listed as a threatened species in 1993 and it is now endangered. In 1999, spring-run Chinook salmon (*Oncorhynchus tshawytscha*) and Sacramento splittail (*Pogonichthys macrolepidotus*) also were added to the list of endangered species. The southern green sturgeon was listed as threatened in 2006.

1994: AGREEMENT ON WATER QUALITY STANDARDS

California and the EPA signed the Bay-Delta Accord in 1994, which formed CALFED. The California Bay-Delta Authority was created in 2002 to provide oversight for CALFED. Its authority and the Delta Science Program were later transferred to the Delta Stewardship Council.

2002: PELAGIC ORGANISM DECLINE

By 2004, researchers recognized long-term declines in abundance of important Delta fish species, including delta smelt, longfin smelt, threadfin shad, and juvenile striped bass, despite relatively good water years. The Interagency Ecological Program (IEP) has been monitoring and studying these declines since 2005 (Baxter et al. 2010).

Public Comment
Bay Delta Plan Workshop 3
Deadline: 10/26/12 by 12:00 noon

State Water Resources Control Board
1001 I Street
Sacramento, California 95814

Via email: commentletters@waterboards.ca.gov

RECEIVED
10-26-12
SWRCB Clerk

SUBJECT: Bay-Delta Workshop 3 – Analytical Tools for Evaluating Water Supply, Hydrodynamic and Hydropower Effects

Dear Chairman Hoppin and Members of the Board:

The Department of Water Resources (DWR) appreciates the opportunity to participate in the ongoing process for Phase 2 of the Bay-Delta Water Quality Control Plan (WQCP) update. In the attached submission, DWR presents a discussion of the computer simulation models that could be used to analyze water supply and hydrodynamic effects of a proposed update to the WQCP, and the development of a multi-dimensional model called SELFE. We also address climate change analysis, as well as elaborate on the differences between "Natural" versus "Unimpaired" flow. Our submittal includes excerpts from the draft Bay Delta Conservation Plan (BDCP) Environmental Impact Report (EIR) which contains a complete list of models used to evaluate alternatives related to the BDCP and the BDCP Effects Analysis.

As part of our submittal, we present an assessment based on model output of potential impacts associated with the implementation of the Fall X2 action set forth in the 2008 U.S. Fish and Wildlife Service (USFWS) Biological Opinion. This analysis uses the CalSim-II model, and describes the possible impacts to combined State Water Project (SWP) and Central Valley Project (CVP) exports as well as combined storage in Shasta and Oroville reservoirs. This analysis is intended to present a more complete picture of the impact of the Fall X2 action on the CVP and SWP.

As discussed in the submittal, in addition to the potential impacts to water supply, the imposition of a Fall X2 standard that significantly draws down reservoir levels can have a significant impact on water temperature management at the reservoirs. In the case of Oroville Reservoir, the cold water pool is critical for providing protection to listed species such as spring-run Chinook salmon and Central Valley steelhead. Access to the cold water pool at Oroville is limited. If the water level in the reservoir drops below a certain point, the project's ability to provide the amount of cold water necessary to support the Feather River Hatchery, as well as to maintain suitable temperatures in the lower Feather River for spawning and egg incubation, becomes compromised and can lead to adverse impacts to the species.

Also discussed in the attached submission are the various models available to analyze impacts to the Bay-Delta hydrology and ecosystem. Below is a summary of the models discussed in the submittal:

CalSim-II

CalSim-II is used to simulate much of the water resources infrastructure in the Central Valley and Delta Regions, and is the best available planning model for SWP and CVP operations. Inputs to the model include water diversion requirements, stream accretions and depletions, return flows and groundwater operations. The model is capable of investigating the impacts resulting from unimpaired flow requirements, as well as incorporating the storage to temperature relationship. It can also incorporate the effects of climate change.

CalLite

CalLite is a rapid and interactive screening model best used to screen various Central Valley water management alternatives, and for developing improved understanding of operational decisions during consensus-based decision making.

DSM2

The Delta Simulation Model 2 (DSM2) is a one-dimensional open channel flow and water quality simulation model, which can capture processes influenced by tidal dynamics. Applications of DSM2 include simulating historical conditions, forecasting future conditions, and planning studies using input from CalSim-II. It can help assess the incremental impacts caused by future facilities and operations, as well to determine the impacts of potential changes in the Delta associated with changes in flow patterns.

DSM2 does not adequately represent the complex behaviors of juvenile and adult migrating fish. Attempts to incorporate fish behavior have not been validated by field observations due to the lack of Delta-wide data availability. However, continued development of the model may allow limited representation of delta smelt, Chinook salmon and steelhead behavioral characteristics. Thus, currently there is no widely accepted model which represents fish behavior.

Bay-Delta SELFE

SELFE is an open source, three-dimensional computational model which can depict the major flow characteristics of the Delta. It features a variety of transport, sediment and biological processes. DWR has incorporated into SELFE practical details such as agricultural sources and sinks, gates and barriers. It is best used for a three-dimensional hydrodynamic and salinity transport model of the full Bay-Delta system, and is also well suited to model the

effects of sea level rise. A full Delta calibration is planned for release in Spring 2013 and, shortly after that, training is to be offered within the modeling community.

In addition to the models presented, the submittal includes as an attachment an excerpt from the draft Appendix 5A of the BDCP EIR. DWR has been, and continues to be, very active in developing methodologies for projecting future hydrologic conditions that take into account climate change trends. While BDCP Appendix 5A details an approach for evaluating climate change effects that works well for the BDCP, we recommend your staff evaluate the relevant information contained in the appendix as it may not be appropriate for the purposes in updating the WQCP. For instance, the BDCP approach looks at two distinct future periods centered around 2025 and 2060. Other types of approaches provide a continuous projection of climatology and hydrology spanning from current conditions out to the future, rather than focusing on a specific future period or periods. This distinction along with others are important to consider to when choosing a climate change analysis approach. DWR invites your staff to meet with the DWR Climate Change Technical Advisory Group for additional focused discussions and more detailed guidance and recommendations on qualitative and quantitative analytical approaches.

Finally, the submittal includes a discussion of the differences between the terms "Natural Flow" and "Unimpaired Flow." It is being included to illustrate the factors that should be considered when applying these specific terms correctly. Natural flow and unimpaired flow may be the same when applied to an upstream location, such as the Sacramento River at Shasta Dam; but, they would definitely not be the same when applied to the Sacramento River at Freeport. The included example illustrates why.

Thank you for your consideration of the comments and the attached report. If you have any questions, feel free to contact me at (916) 653-8045

Sincerely,

Katherine Kelly for

Russ Stein
Acting Deputy Director

Attachment

SWRCB Workshop 3

Analytical Tools for Evaluating Water Supply, Hydrodynamic and Hydropower Effects

DWR Contribution
October 26, 2012

The following discussion focuses on the computer simulation models used by the Department of Water Resources (DWR) that could be used by the State Water Resources Control Board (SWRCB) to analyze water supply and hydrodynamic effects of a proposed update to the Bay-Delta Plan. The models are CalSim-II, the related CalLite model, the Delta Simulation Model (DSM2) and its modules simulating hydrodynamics, water quality, and particle movement. This submittal also describes the development of a multi-dimensional model called SELFE. SELFE is capable of simulating the hydrodynamics and water quality at both the Sacramento San Joaquin Delta and the San Francisco Bay. A short discussion on incorporating climate change into analyses of future conditions is included as well as one on the distinction between "Natural" versus "Unimpaired" Flow.

Included as an attachment are excerpts from Appendices 4 and 5 of the draft Environmental Impact Report/Statement for the Bay-Delta Conservation Plan (BDCP). Appendix 5A illustrates how CalSim-II and DSM2 can be used in assessing potential impacts. It gives a complete description of all the modeling tools used to study the effects of the alternatives related to the BDCP. We have also included excerpts from draft Chapter 4 of the BDCP EIR/S which include a complete list of models used to analyze the BDCP alternatives (Section 4.3); an illustration of the sequence of the application of the modeling tools required to complete the analysis (Figure 4.1) and a table describing the utilization of the models in the BDCP Effects Analysis (Table 4.1).

1- CalSim-II

DWR and the U.S. Bureau of Reclamation Mid-Pacific Region (Reclamation) have jointly developed CalSim-II, which simulates much of the water resources infrastructure in the Central Valley of California and Delta region. CalSim-II is a generalized reservoir-river basin simulation model that allows for water allocation targets or goals (Draper et al. 2002) to be specified by the user. CalSim-II represents the best available planning model for the SWP and CVP system operations and has been used in previous system-wide evaluations of SWP and CVP operations (USBR, 1994, 2004, 2008). CalSim-II simulates an 82-year period using monthly time increments.

CalSim-II models all areas that contribute flow to the Delta. The geographical coverage includes: the Sacramento River Valley; the San Joaquin River Valley; the Sacramento-San Joaquin Delta; the Upper Trinity River; the CVP and SWP deliveries to the Tulare Basin; and the SWP deliveries to the central and south coast regions. CalSim-II

includes major reservoirs in the Central Valley of California including Trinity, Lewiston, Whiskeytown, Shasta, Keswick, Folsom, Oroville, San Luis, New Melones and Millerton reservoirs. CalSim-II also includes all the major CVP and SWP facilities including the Clear Creek Tunnel, Tehama Colusa Canal, Corning Canal, Jones Pumping Plant, Delta Mendota Canal, Mendota Pool, Banks Pumping Plant, California Aqueduct, South Bay Aqueduct, North Bay Aqueduct, Coastal Aqueduct and East Branch Extension. In addition, it includes some locally managed facilities such as the Glenn Colusa Canal, Contra Costa Canal and the Los Vaqueros Reservoir.

Inputs to CalSim-II include water diversion requirements (demands), stream accretions and depletions, rim basin inflows, irrigation efficiencies, return flows, non-recoverable losses, and groundwater operations. Sacramento Valley and tributary rim basin hydrologies are developed using a process designed to adjust the historical sequence of monthly stream flows over an 82–year period (1922 to 2003) to represent a sequence of flows at a future level of development. Adjustments to historic water supplies are determined by imposing defined level of land use on historical meteorologic and hydrologic conditions. The resulting hydrology represents the water supply available from Central Valley streams to the CVP and SWP at the current or future level of development.

A CalSim-II simulation provides sequential monthly values for river flows and diversions, reservoir storage, Delta flows and exports, Delta inflow and outflow, deliveries to project and non-project users, reservoir operations controlling variables (e.g. in-stream flow, water quality standards, flood control, Delta exports, etc.). Reclamation's 2008 Operations Criteria and Plan (OCAP) Biological Assessment (BA) Appendix D provides more information about CalSim-II (USBR, 2008a). CalSim-II output provides the basis for multiple other hydrologic, hydrodynamic, and biological models and analyses. CalSim-II results are used to determine water quality, hydrodynamics, and particle tracking in the DSM2 model. The outputs feed into temperature models including the Upper Sacramento River Water Quality Model (USRWQM), the Reclamation Temperature Model, and other habitat and biological models.

CalSim–II model can be re-formulated to investigate impacts resulting from a new flow requirement at a location based on a certain percentage of unimpaired flows. DWR has conducted analyses of the effects of potential flow requirements based upon an assumed percentage of unimpaired flow.

CalSim-II is also amenable to incorporating the effects of climate change. This is accomplished by changing the streamflow values and incorporating sea level rise. Changes in runoff and streamflows are simulated through VIC modeling under representative climate scenarios. These simulated changes in runoff are applied to the CalSim-II inflows as a fractional change from the observed inflow patterns (simulated future runoff divided by historical runoff). Sea level rise in CalSim-II is incorporated through development of a new flow-salinity response relationship.

It is noted that CalSim-II is structured to meet current water right priorities in the Sacramento and San Joaquin valleys as well as Delta in-basin use and regulatory requirements. If any new flow requirements necessitate reduction of applied water demands in Sacramento valley, CalSim-II model will need to be modified accordingly.

Case-Study of the Potential Impact of Fall X2

CalSim-II is best used in a comparative mode or comparative analysis that compares a No Action Alternative to a With Action Alternative. System performance metrics are then compared and analyzed to determine levels of impacts to the No Action condition that occur because of the With Action condition. Some typical system performance metrics include reservoir storage, river flows, Delta outflow, deliveries, exports, and water quality. These performance metrics can be quantitatively analyzed in many ways such as evaluating long-term average impacts, worst case impacts, best case impacts, dry period impacts, frequency of impacts, etc. The quantitative analysis is then often enhanced or supported with qualitative analyses.

An example analysis that compared a future condition with and without 2008 USFWS Biological Opinion Reasonable and Prudent Action 4, more commonly referred to as the Fall X2 Standard, is presented below.

Major Assumptions

No Action Alternative Simulation (With Fall X2)

- 1922 – 2003 Simulation Period
- Future Level of Development Land-Use and Demands (2030)
- Future Level of Climate Change (2025)
- Future Level of Sea Level Rise (15 cm)
- Water Rights Decision 1641 regulations
- 2008 USFWS Biological Opinion Reasonable and Prudent Actions including Fall X2 requirements which occur only in years following Wet or Above Normal years
- 2009 NMFS Biological Opinion Reasonable and Prudent Actions

No Fall X2 Alternative Simulation

- Same as No Action with the exception of the removal of the Fall X2 requirement

Results

Summary results for combined SWP and CVP exports as well as combined storage in Shasta, Folsom, and Oroville reservoirs are presented below. Table 1 shows the combined export impacts for multiple time periods. One period is for the long term average. The long term (1922 – 2003) average impact to exports is 199 TAF per year. This means that on average, the CVP and SWP have an average export reduction of 199 TAF per year over the simulation period due to meeting Fall X2 requirements. A long-term average impact however can be a misleading oversimplification because of

the nature of California's varied yearly hydrology. California hydrology typically has dry periods followed by wet periods and vice versa. The wet periods can help the systems to recover lost reservoir storage and in a sense "reset", which can mask some shorter period impacts.

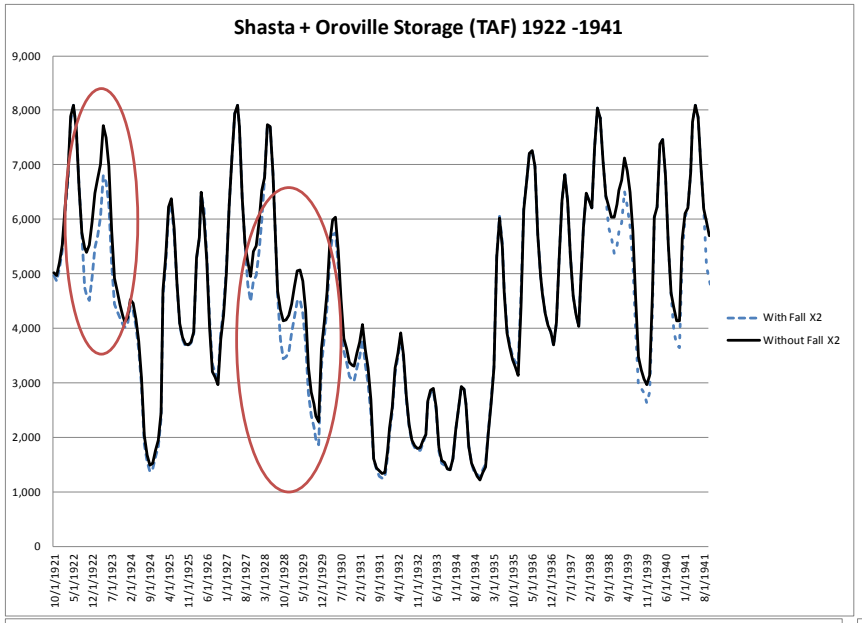
Table 1: Combined SWP and CVP Annual Export (TAF)

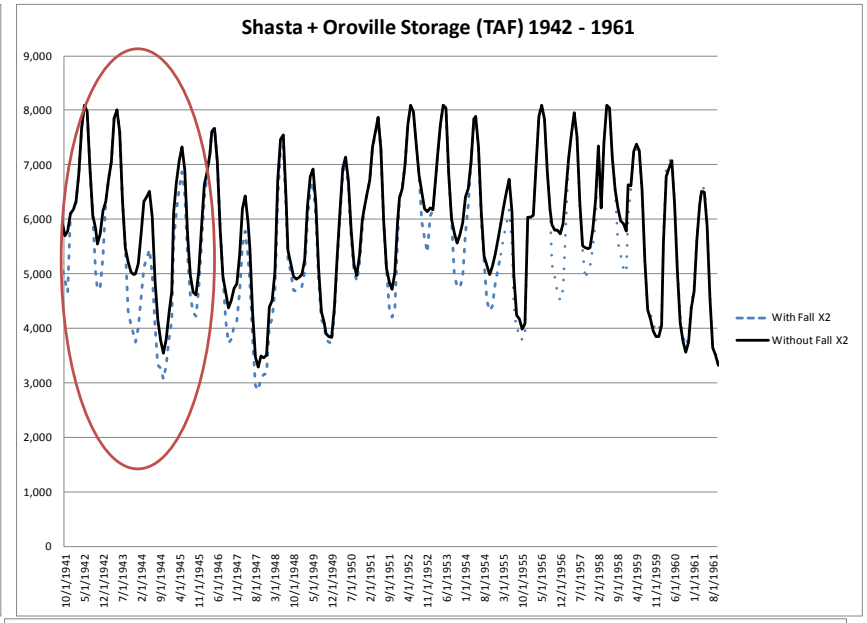
Total SWP + CVP Export	With Fall X2	Without Fall X2	Diff
1922 - 2003 Average	4728	4927	199
Average of 1 Year Following W or AN	5040	5374	335
Max Impact of Year Following (1944)	3915	4690	775
Min Impact of Year Following (2000)	4987	4997	10

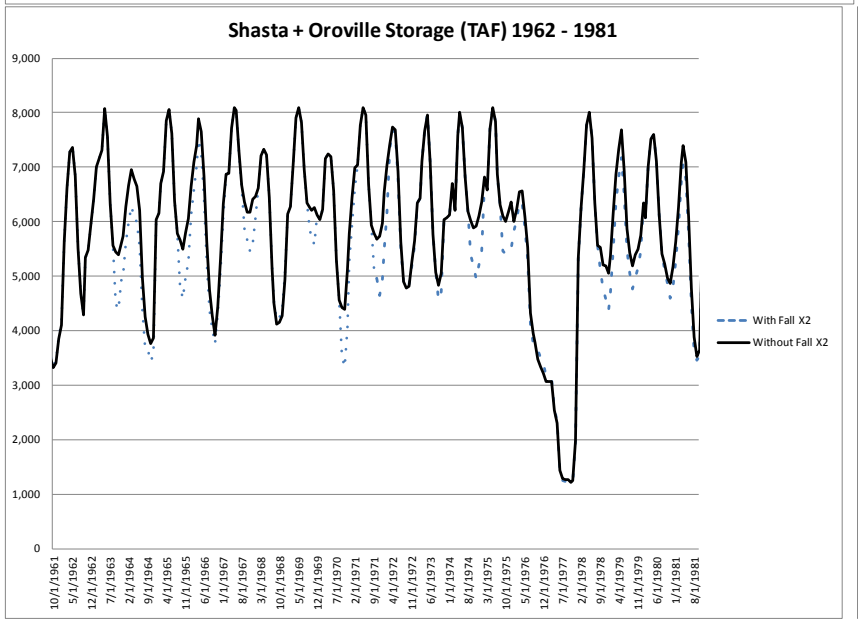
Another way to examine the impact of meeting the Fall X2 requirement is to evaluate the years immediately following a year in which Fall X2 is required. The average impact to exports for those years is 335 TAF per year. The impact for the years following the implementation of the Fall X2 requirement is obviously larger than the long-term average but may be more indicative of the magnitude of impact caused by the Fall X2 requirement. Table 1 also shows the maximum and minimum one-year impact of the Fall X2 requirement on exports for years following the action. Water Year 1944 exhibited the maximum single year export impact of 775 TAF, while Water Year 2000 showed the minimum single year export impact of 10 TAF. The maximum and minimum impacts give a range of potential impacts.

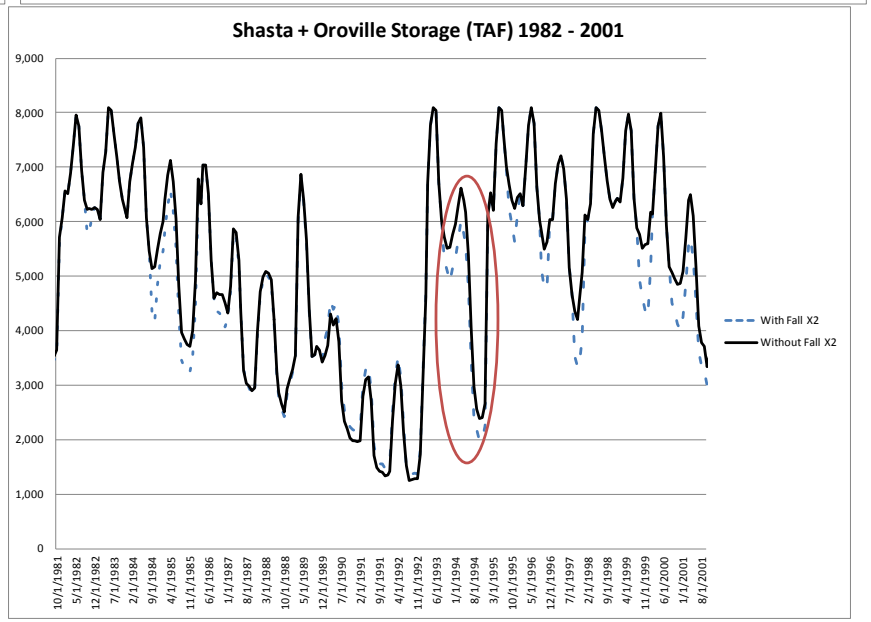
Export impacts are only one metric for evaluating system performance. Another metric is system storage. Lower storages in fall would have negative impacts on the cold water pool, as well as result in a lower carryover (storage at the end of September) for the following year to meet in-basin obligations and potential water supply impacts. For example, the impact of the Fall X2 requirement on the cold water pool at Oroville and its subsequent ability to meet various temperature requirements for the protection of listed species such as Spring-run Chinook salmon and Central Valley Steelhead could be very pronounced depending upon the following year's hydrology, i.e., if conditions are dry in the winter and spring period and storage is not recovered. As releases are made from the facilities to meet regulatory and other requirements over the course of the following year, the storage level at Oroville drops and the cold water pool is subsequently lowered. Due to the configuration of the Oroville Facilities, access to the cold water pool needed to meet temperature requirements becomes more limited as the reservoir is drawn down. Once the cold water pool goes below a certain depth, the facilities' ability to provide water at the temperatures needed to support the Feather River Hatchery and the spawning and holding habitat in the lower river below the dam becomes compromised. This in turn can lead to disease outbreaks, and in some circumstances, mortality of both eggs and fish.

Changes in exports due to increased outflow requirements are normally balanced with changes in upstream reservoir storage. The next page shows the full simulation period trace of combined Shasta and Oroville storage. Shorter periods of interest for further analysis are circled in red.

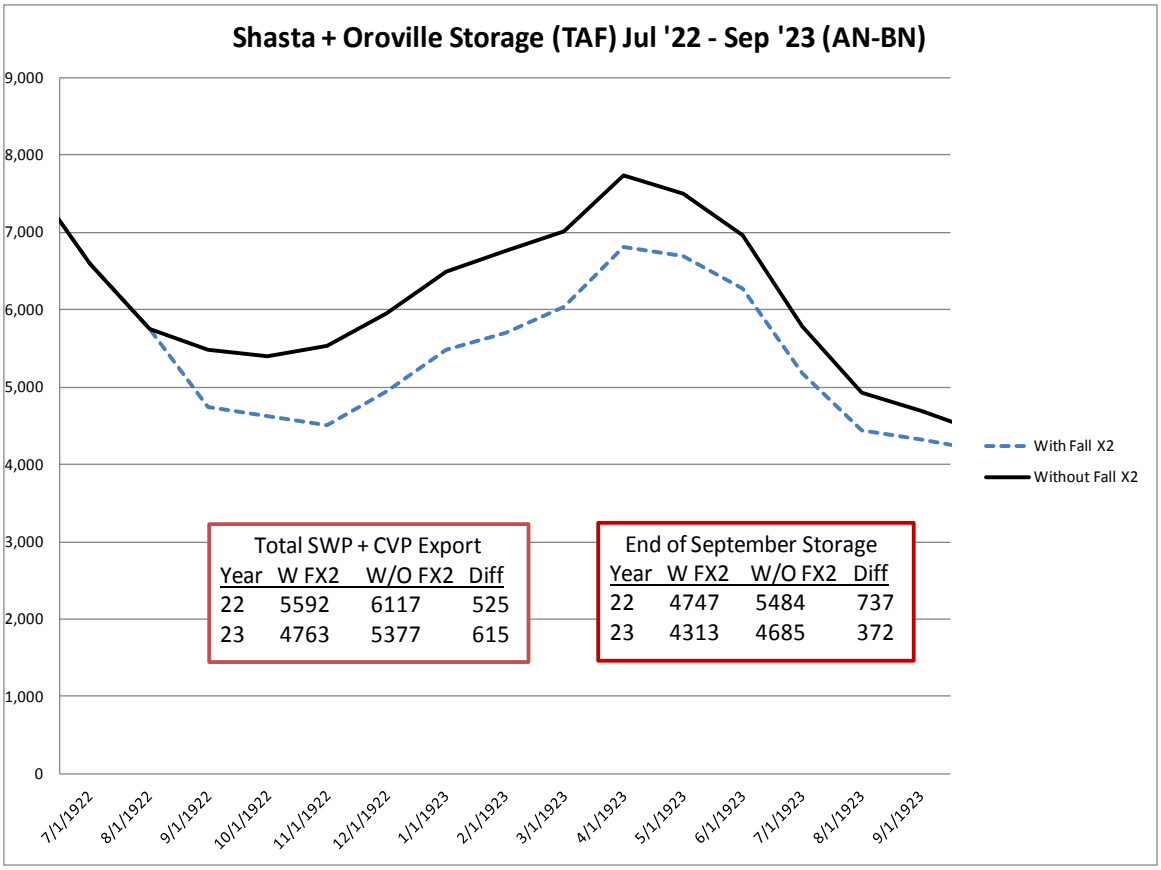

Shasta + Oroville Storage (TAF) 1922 -1941
With Fall X2
Without Fall X2


Shasta + Oroville Storage (TAF) 1942 - 1961
With Fall X2
Without Fall X2


Shasta + Oroville Storage (TAF) 1962 - 1981
With Fall X2
Without Fall X2

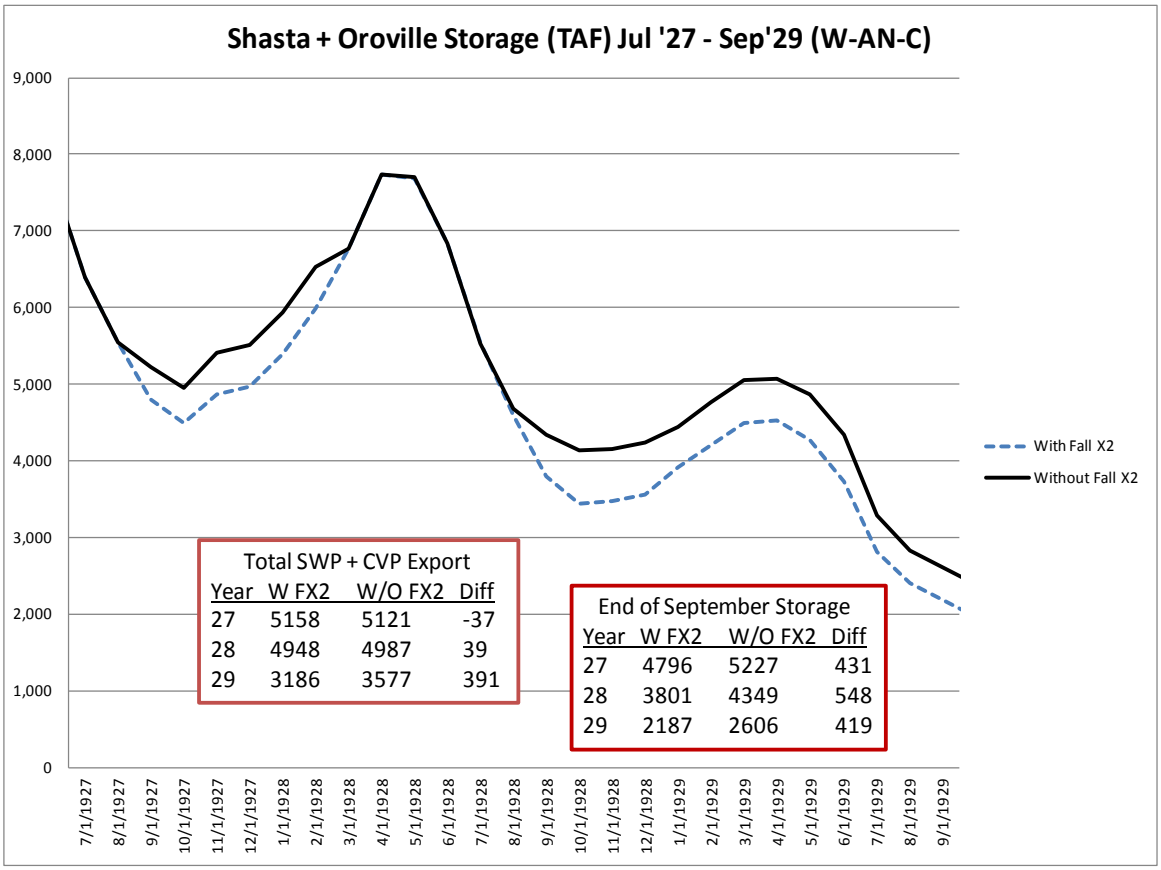

Shasta + Oroville Storage (TAF) 1982 - 2001
With Fall X2
Without Fall X2

Examining storage impacts due to Fall X2 actions over a shorter time period can give more insight into the effect of meeting the action. The first period evaluated below is July 1922 – September 1923, which is an Above Normal year followed by a Below Normal year. The two alternatives start out with similar storage.



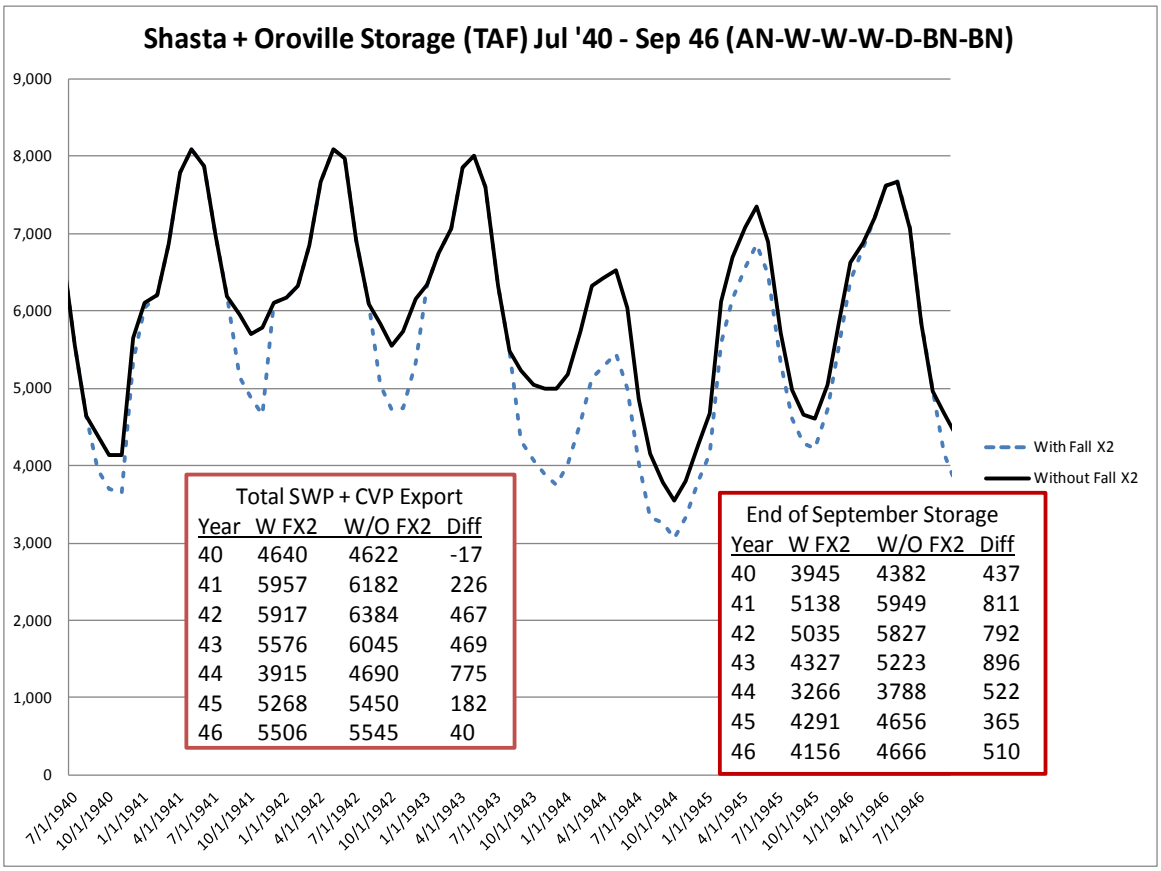
The storage then diverges beginning when the Fall X2 action is implemented in the No Action Alternative (NAA). The 1923 hydrology is dry in the winter and spring period and storage is not recovered. The decreases in combined Shasta and Oroville storage at the end of September for each year indicates the potential of an adverse impact on reservoirs' cold water pools needed to support adequate river temperatures for salmon.

The next period to be examined is July 1927 – September 1929 which is a Wet year, followed by an Above Normal year, followed by a Critical year.



In this period, the storages in each alternative again start out about the same and then diverge when the Fall X2 action is implemented in the NAA. The hydrology in Water Year 1928 is wet enough to recover the storage lost from the Fall X2 action and the storages are once again in sync between the alternatives. The storages diverge once more in the Fall of Water Year 1929 due to the implementation of the Fall X2 action and stay apart due to the Critical-year hydrology. Export impacts are minimal for 1927 and 1928 but are significant in 1929. As shown in the above chart, combined storages in Shasta and Oroville at the end of September for each of the three years are substantially lower. The reduced storages indicate the potential for significant adverse impacts on cold water pools especially for years 1928 and 1929.

The third period is July 1940 – September 1946. This is a 7 year period that starts with an Above Normal year followed by 3 Wet years, a Dry, and finally two Below Normal years.



Total SWP + CVP Export

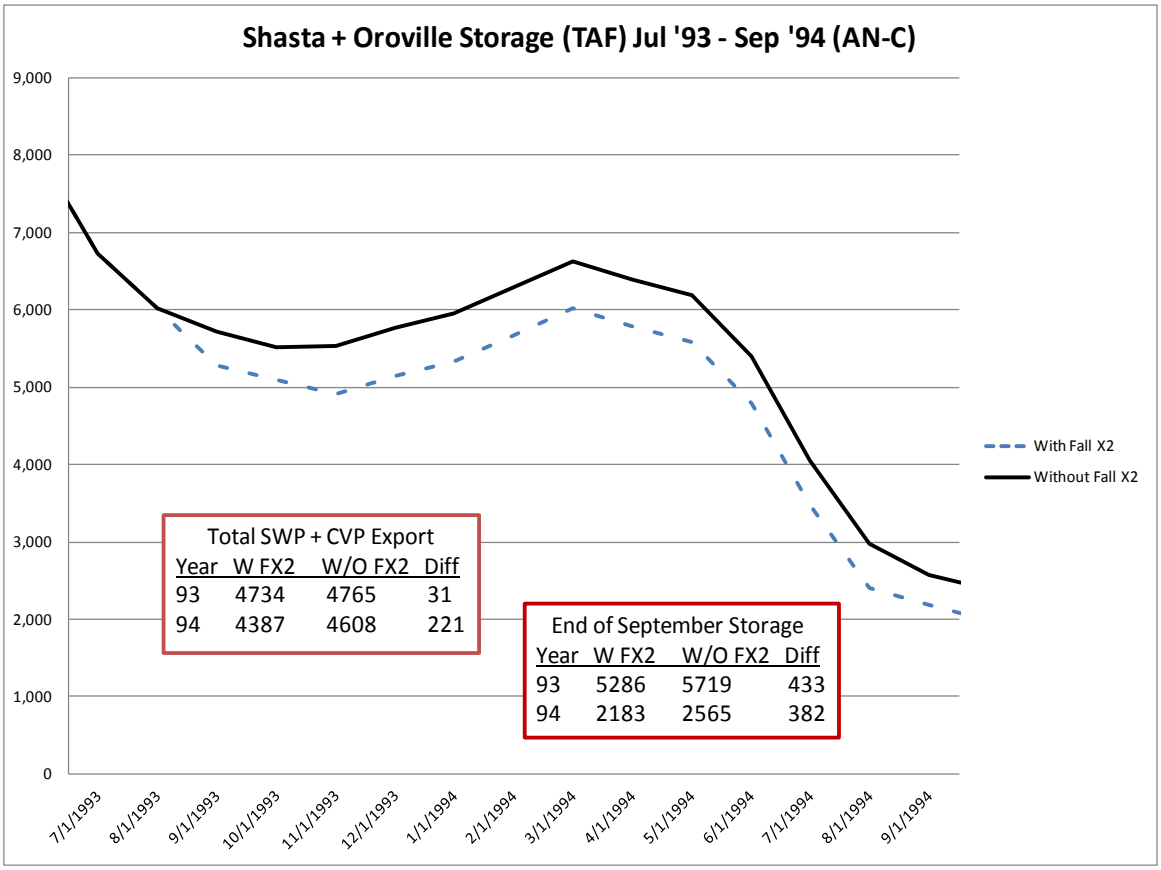
Year	W FX2	W/O FX2	Diff
40	4640	4622	-17
41	5957	6182	226
42	5917	6384	467
43	5576	6045	469
44	3915	4690	775
45	5268	5450	182
46	5506	5545	40

End of September Storage

Year	W FX2	W/O FX2	Diff
40	3945	4382	437
41	5138	5949	811
42	5035	5827	792
43	4327	5223	896
44	3266	3788	522
45	4291	4656	365
46	4156	4666	510

The four years of wetter hydrology show that the system was able to recover storage each of those years. Exports however were significantly impacted. Water Year 1944, the Dry year in the sequence, shows the largest export impact of the entire simulation. In the NAA, the storage and exports recover significantly due to the low export level of 1944 and not having Fall X2 obligations for 3 consecutive years (1944-1946). As shown, the end of September storages are significantly lower in each of the seven years. Lower fall storages in some of the years indicate potentially significant adverse impacts on the cold water pool especially year 1944.

The fourth period is from July 1993 – September 1994 and is an Above Normal year followed by a Critical year.



This sequence again starts with the storages of both alternatives nearly identical and diverging when the Fall X2 action is implemented in the NAA in the fall of 1993. The resulting storage reduction (433 TAF) is essentially carried through 1994 under the NAA. Exports also start off similar in 1993 but are reduced 221 TAF in 1994. Lower storage is especially significant for 1994. The storage projected for September 1994 in both scenarios is very low due to the dry conditions. The additional reduction of storage as shown indicates the potential for a significant impact on the cold water pool.

Conclusions

The results analysis shows that, given the operational assumptions of the CalSim-II simulations, storage is generally lower in the major CVP and SWP reservoirs when implementing the Fall X2 requirement. The storage impact can be more pronounced in periods following years when a Fall X2 requirement would be triggered under the 2008 USFWS Biological Opinion. The reduced storage condition is also accompanied by a reduction in the ability to provide water at a temperature necessary for the protection of listed species, as well as a reduction in exports.

Together, the storage impacts, temperature/species impacts and export impacts give a more complete picture of the impact of the Fall X2 action on the CVP and SWP. Monthly storage values resulting from these simulations are often used as inputs into temperature models that estimate river temperatures at certain locations in the river downstream from the reservoirs. In general, lower reservoir storage is directly correlated to warmer downstream river temperatures.

Currently, CalSim-II does not simulate water temperature directly. Temperature compliance is checked post simulation. DWR intends to incorporate temperature simulation within CalSim-II (or CalLite) using a methodology consistent with Sacramento River Water Quality Model (SRWQM). DWR hopes to have this capability ready by spring 2013.

2- CalLite Model

DWR and Reclamation have developed the CalLite model, a rapid and interactive screening model for evaluating various Central Valley water management options. The CalLite model is used as a computer aided tool for negotiations in a variety of stakeholder processes for improved understanding of the Central Valley water system operations and consensus based decision-making. CalLite maintains the same hydrologic, operational and institution integrity as represented in the full companion model, CalSim-II. CalLite simulates the most important dynamic system responses and simplifies or aggregates less important system features. Major reservoirs such as Shasta and Oroville are modeled consistent with CalSim-II, however, the accretions and depletions within Sacramento and San Joaquin Valley are aggregated and simulated on a coarser resolution. CalLite obtains the preprocessed data from the CalSim-II model as an input to the model. The simulation results obtained from a typical CalLite run are within 1% of a corresponding CalSim-II run, while the runtime is less than 10 minutes (compared to 30 minutes for a corresponding CalSim-II run) (Islam et al. 2009).

The geographical coverage of the CalLite model includes: the Upper Trinity River; the simplified Sacramento River Valley; the simplified San Joaquin River Valley; the Sacramento-San Joaquin Delta; and the Central Valley Project (CVP) and State Water Project (SWP) service areas. The model simulates in monthly time steps over a simulation period of water year 1922-2003.

CalLite allows interactive modification of a variety of water management actions including Delta regulation options, demand management, Delta channel flow, and salinity targets. Model users can choose different regulations from the graphical user interface (GUI) or can enter their own data to analyze the impact of a desired regulation. (See Figure 1)

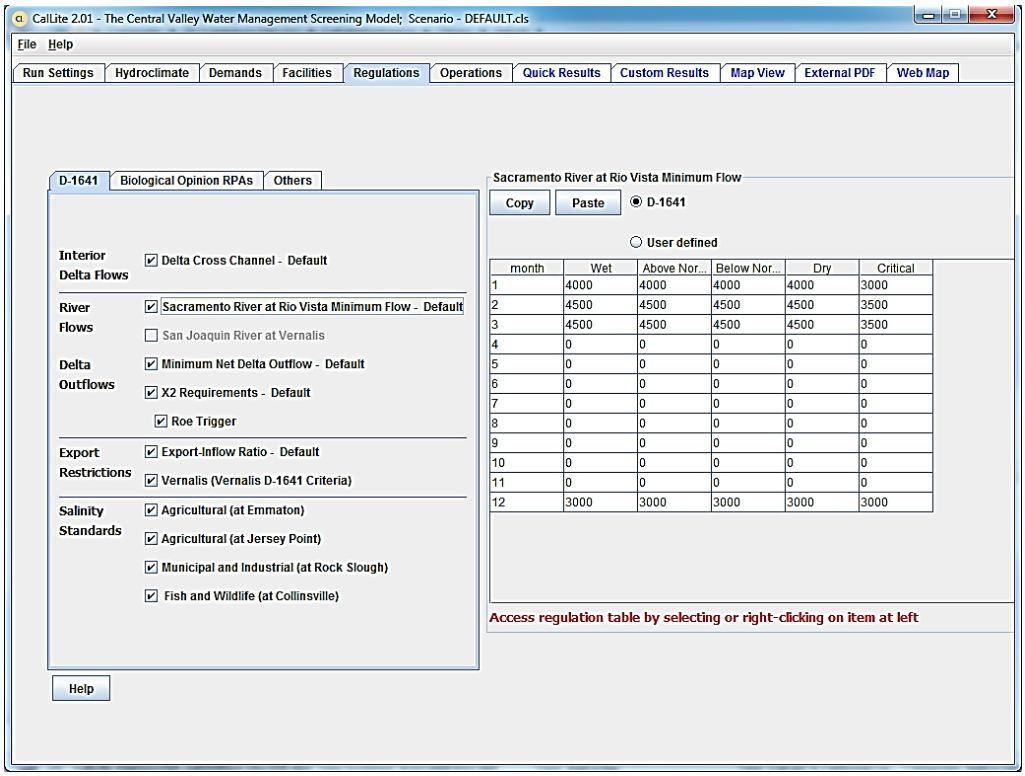


Figure 1: Delta regulation dashboard of CalLite GUI.

The GUI input dashboards permit users to specify model options such as: the simulation periods, demand levels, current and future hydrology, regulations, and operation procedures. In addition, the GUI post-processing dashboards provide quick access to key simulation results for reservoir storages, river flows, Delta inflows, salinity, and Delta outflow, and Delta exports (Figure 2). Results can be post-processed and displayed instantaneously on the GUI (Figure 3).

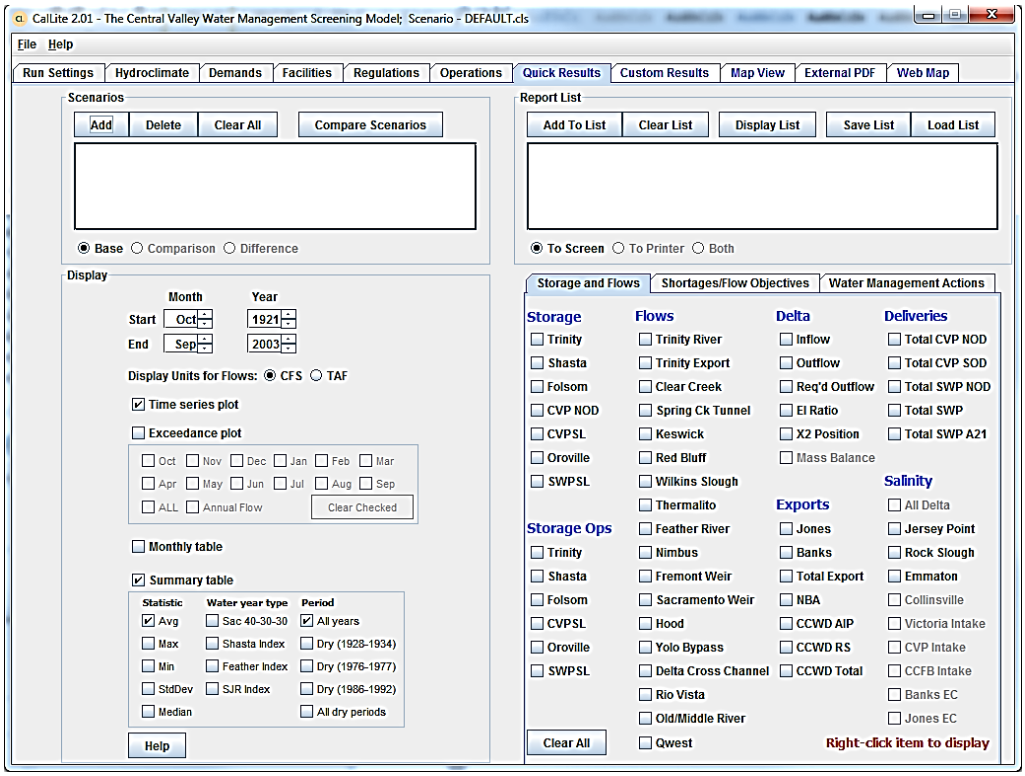


Figure 2: Results dashboard dashboard of CalLite GUI.

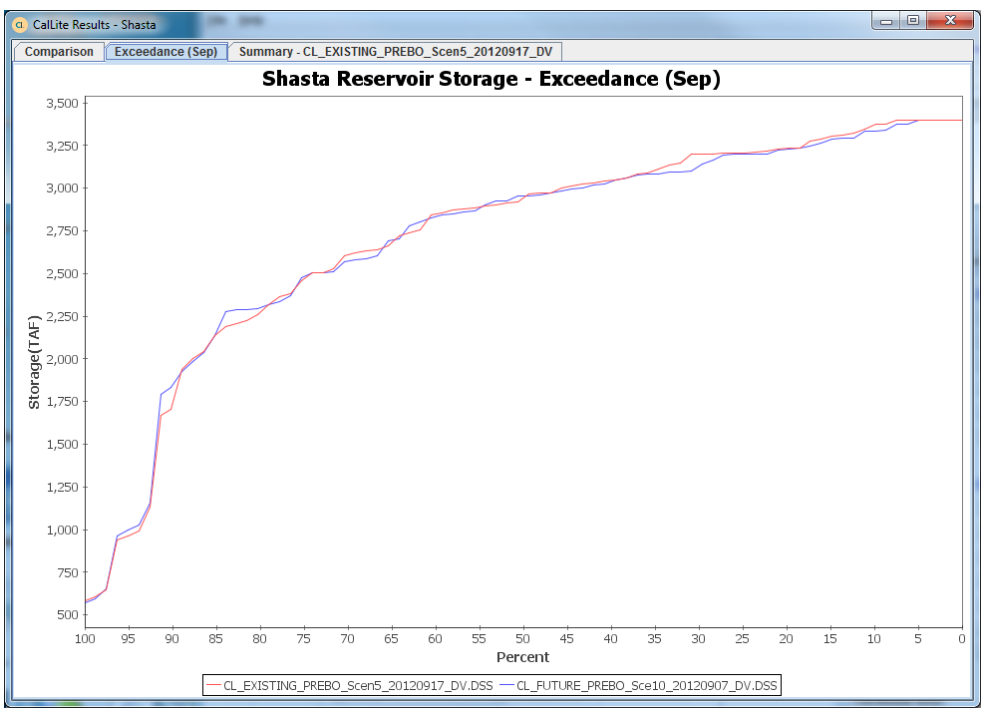


Figure 3: Example of model output from CalLite GUI result dashboard.

CalLite simulation results can be exported to other graphical and statistical software (such as Excel) for further analysis. Figure 4 demonstrates an analysis of different

regulation impacts on water deliveries for a dry period (1987-1992). The CalLite GUI has utilities to produce a report comparing two scenario results (an example is attached).

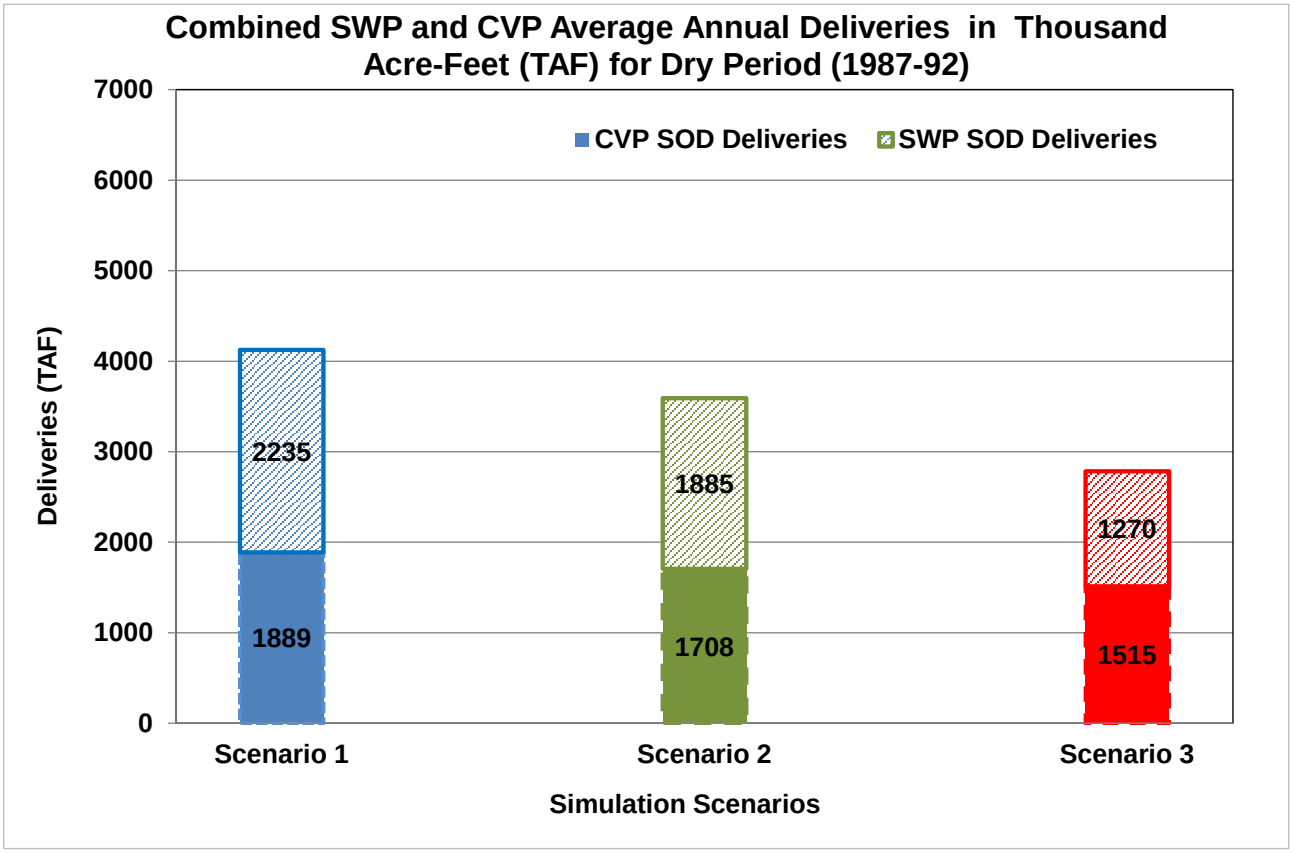


Figure 4: Example of model output from CalLite GUI postprocess in another software.

The CalLite model is best suited for screening a suite of alternatives to identify a smaller subset of promising options that should be modeled and studied more thoroughly. Examples of potential applications would be to explore and experiment with new Delta regulations, a new storage facility, or a conveyance facility. CalLite is not a replacement for existing detailed and complex models (such as CalSim-II), but rather it is informed by the data and results of existing models and allows users to explore future water management actions, improve understanding, and support more stakeholder-involved decision-making processes.

3- DSM2

The Delta Simulation Model 2 (DSM2) is a one-dimensional hydrodynamic and water quality simulation model used to simulate hydrodynamics, water quality, and particle

movement in the Sacramento-San Joaquin Delta (Delta). Although the model grid has been extended beyond the Delta for certain applications, the standard grid focuses primarily on the Delta. The DSM2 model grid is bounded by the Sacramento River at Sacramento to the North, the San Joaquin River at Vernalis to the South, Martinez to the West, and State and federal export facilities to the Southwest.

Although DSM2 can run the entire 82 years covered under CalSim–II, it is normally based on 16 years of hydrologic data (1976 through 1991). This particular hydrologic period captures about the same mix of hydrologic conditions in the 1922-2003 period. The time step for the calculations is on the order of five minutes, capturing processes influenced by tidal dynamics. Applications of DSM2 include simulating historical conditions, forecasting future conditions, and planning studies using input from CalSim-II. DSM2 represents one of the most widely used planning models for Delta tidal hydraulics and salinity transport. DSM2 has frequently been used to determine the impacts of potential changes in the Delta (salinity, flow, and water level) associated with changes in flow patterns caused by variations in conveyance, river inflows, exports, diversions, or installation of new hydraulic structures.

DSM2 was first calibrated and validated in 1997. Then in 1999-2000, in coordination with a number of other agencies, DSM2 was recalibrated through a much more comprehensive effort. The results of this effort are documented in Chapter 2, Twenty-second annual progress report (2001) of the California Department of Water Resources' San Francisco Bay-Delta Evaluation Program at:

http://modeling-prod.water.ca.gov/delta/reports/annrpt/2001/2001Ch2.pdf

and the corresponding plots can be viewed via a "clickable" map at:

http://modeling.water.ca.gov/delta/studies/validation2000/map.html

In support of the BDCP program, DSM2 underwent another recalibration effort (performed by CH2MHill staff in coordination with DWR) to update the model. The update includes the addition of the flooded Liberty Island, updated Sacramento River bathymetry in anticipation of the need to simulate the proposed diversion intakes, and an extension of the model grid along Sacramento River to the North. More information on this effort is available at:

http://baydeltaoffice.water.ca.gov/downloads/DSM2_Users_Group/BDCP/DSM2_Recalibration_102709_doc.pdf

DSM2 is appropriate for studying the existing conditions in the Delta, as well as performing simulations for the assessment of incremental environmental impacts caused by future facilities and operations. DSM2 has three separate modules: HYDRO, QUAL, and PTM.

3.1 DSM2 Hydrodynamics Model – DSM2-HYDRO (HYDRO)

HYDRO is a one-dimensional, implicit, unsteady, open channel flow model. HYDRO simulates flows, velocities, and water surface elevations and provides these values as output. The resulting HYDRO flow values are used as input for DSM2-QUAL and PTM. HYDRO uses an unconditionally stable implicit finite difference formulation. Hydro solves the equations of continuity and momentum which are discretized in both time and space. Hydro is capable of simulating hydraulic devices, including operable gates that function based on some user-defined hydrodynamic conditions.

3.2 DSM2 Water Quality Model – DSM2-QUAL (QUAL)

QUAL simulates fate and transport of both conservative and non-conservative water quality constituents, including salts, based on a flow field simulated by HYDRO. QUAL is most often used to model Electrical Conductivity (EC) (an indirect measure of salt concentration) throughout the Delta but has also been used to model the transport of non-conservative constituents.

QUAL includes the capability to simulate ten non-conservative water quality constituents including dissolved oxygen (DO), water temperature, carbonaceous biochemical oxygen demand (BOD), chlorophyll *a*, organic nitrogen, ammonia nitrogen, nitrite nitrogen, nitrate nitrogen, organic phosphorus, and dissolved phosphorus. These variables are inter-dependent and, with the exception of temperature, simulation of one requires simulation of all other variables. The rates of mass transfer from one water quality variable to another are assumed to be affected by temperature. Applications of QUAL in modeling non-conservative constituents include:

1- TMDL DO Project-- Investigation of the effectiveness of installation of low-head pumps to improve the low DO conditions in Stockton Ship Channel
2- In-Delta Storage Project-- Determine the Impacts of the releases from the In-Delta islands on the DO and temperature in the nearby areas
3- BDCP Nutrient Modeling-- This work was performed by staff from Resource Management Associates (RMA). RMA staff performed several iterations of calibration and validation for water temperature and nutrients. They also made several improvements including using multiple meteorological regions, and the addition of inflows and water quality data from most waste water treatment plants. This work also allowed an analysis of ammonia levels in the Delta, which potentially affects the primary production.
4- Turbidity Modeling: QUAL was modified using BOD function as a surrogate using a first order decay rate. However, capabilities are currently limited since sediment re-suspension is not included and settling rate is not correlated to flow velocity and suspended sediment properties. DWR in cooperation with UC Davis, has laid the foundations for the development of a sediment transport module inside

QUAL. Delta Modeling will continue the work of incorporating that functionality within DSM2.

5- The addition of mercury modeling is being investigated in response to the Regional Board's recent TMDL, however, the development of a functional mercury model may take a few years.

3.3 DSM2 Particle Transport Modeling – DSM2-PTM (PTM)

PTM simulates pseudo 3-D transport of neutrally buoyant particles based on the flow field simulated by HYDRO. PTM simulates the transport and fate of individual particles traveling throughout the Delta. PTM uses velocity, flow, and stage output from the HYDRO to monitor the location of each individual particle using assumed vertical and lateral velocity profiles and specified random movements to simulate mixing. The output of PTM is the time series of the percentage of injected particles at any user defined reach(es)/group(s) and also particle fluxes at given node(s). A graphical animation for the outputs is available. PTM has multiple applications ranging from visualization of flow patterns to simulations of discrete organisms such as fish eggs or larvae. Although, PTM has the capability to model certain particle behavior, it has only been used to a limited extent in the past.

Limitations of PTM

Like all the other models described, it is important to understand that PTM has limitations. Perhaps the most challenging application of the PTM is its use to represent migrating juvenile or adult fish. The current model has been most frequently used by simulating particles that move passively with flow. However, there is a substantial and growing body of evidence that both juveniles and adults show complex behaviors that are not adequately represented by passive particles. To try and address this issue, there has been continued development of the model to allow at least limited behaviors that might better represent target species like delta smelt, Chinook salmon, and steehead trout. The list of improvements includes:

1) Particle surfing ability: a particle can move to the upper layer or the bottom layer to make it move faster or slower depending on tides or time of day;
2) Falling velocity: vertical velocity can be added to a particle;
3) Particle mortality: the age of a particle can be tracked and mortality included through the use of some assumed decaying function.
4) Filters: preventing particles to go through a filter to simulate the effects of fish screens

The behavior features were developed based on literature and hypotheses, but these have not been validated by field observations due to the lack of Delta-wide field data. As a promising sign, Sommer et al. (2011) found that addition of particle surfing behavior (Improvement #1 above) to simulations of delta smelt upstream migration

resulted in migration rates similar to estimates based on fish trawl and salvage data. Additional field studies on fish behavior are clearly needed to refine and validate the model.

Future developments

Recent extensive field monitoring for acoustic telemetry salmon/steelhead tag studies in Georgiana Slough and the south Delta may make it possible to establish mathematical relationships that provide a better description for fish movement within the Delta waterways. These relationships can also be validated by field observations. A generalized linear model (GLM) for the route entrainment possibility has been developed by the Georgiana Slough non-physical barrier study group. The GLM relates the possibility of salmon/steelhead entering Georgiana Slough to the non-physical barrier operations, fish position at the junction, river flow conditions and timing (day or night). The application of GLM is currently limited to Georgiana Slough, and may only apply to high flow conditions since it was based on 2011 tagging data. The implementation of GLM in the PTM code has been completed. Testing and analysis are underway.

Analysis of 2012 (a drier year) acoustic telemetry tag data for Georgiana Slough and other south Delta junctions has been started and more GLMs will be produced for different river junctions and flow conditions. Once the new GLMs are developed, they will be implemented in PTM and tested within a larger geographical area and under more variable flow conditions.

In summary, while there has been substantial progress in the development of particle tracking models, there is still no widely accepted model to model fish behavior. Model refinements are needed to capture the full range of fish behaviors, and field studies are needed to provide the appropriate biological input data. This does not mean, however, that PTM models are not currently useful. For example, the models provide a helpful starting point for testing different hypotheses for potential fish behaviors, and to identify field data that are needed to accurately reflect movements. Moreover, in many circumstances (e.g. impact analyses) PTM may represent the best available tool to examine different operational scenarios. Such applications may be reasonable provided the model limitations and assumptions are clearly stated.

4- The Bay-Delta Salmon Ecosystem Simulation and Management Evaluation (SELFE) Modeling Project

The Bay-Delta SELFE project will offer users the capability to study cross-scale, multidimensional phenomena in the Bay Delta. DWR is applying SELFE, an open source, 3D computational model, to depict the major flow characteristics of the estuary with fidelity. DWR has also incorporated into SELFE many of the practical details

needed to model the Bay-Delta, such as agricultural sources and sinks, gates and seasonal gates and barriers. A full Delta calibration is planned for release in Spring 2013, and shortly after that, training is to be offered within the modeling community.

SELFE is an accurate, robust model that combines modern hydrodynamic, particle and transport algorithms with practical features for modeling the Bay-Delta. The software is open source, and has a growing user community around the world. The theoretical papers describing the algorithm can be found in Zhang and Baptista (2008), Rodrigues et al. (2009), Pinto et al. (in press), Roland et al. (2012). The model features a variety of transport, sediment and biological processes, with published shallow water applications as diverse as salt plumes and salmon larvae modeling in the Columbia River; ecological modeling in Portugal, New Zealand and Chesapeake Bay; the Prestige Oil Spill; and super-regional storm surge flooding. After a rigorous multi-year benchmark study, SELFE is one of six models certified as an inundation model by the National Tsunami Mitigation Program and the model has been used to produce tsunami inundation maps for the state of Oregon since 2008.

The model is also fast -- in 2D mode, SELFE runs extremely fast and as a parallel, 3D application the model won recognition during the IOOS/SURA project (http://testbed.sura.org/; Teng 2012) for its ability to scale well on high parallel performance computational systems. This speed allows the user to offer a medium-resolution application for the region (130,000 nodes, 35 layers, Figure 5), rather than eliminating key physics to suit computational constraints.

Applications

The core Bay-Delta application of SELFE is a 3D hydrodynamic and salinity transport model of the full Bay-Delta system. The base model is our "base case" for studies, the basis of our general ongoing calibration and validation work and is designed to model and resolve the most basic processes affecting global accuracy in the estuary. Extending from this core model are focal studies that develop particular regions or physical and ecological processes.

SESAME

SESAME is a full life cycle energy-based model of salmon migration through the upper Sacramento River, Estuary and Coastal Ocean. The project is a collaboration between DWR, NASA and NMFS. SELFE is the estuary hydrodynamic and transport component of SESAME, and the application involves hydrodynamics, biology at several trophic levels and particle tracking. In this project, focus was on transport through the Sacramento corridor, but key policy questions hinge on detrimental pathways leading to the interior Delta.

Sea Level Rise

To model the effects of sea level rise, the model domain has been extended to the ocean, including San Francisco Bay, San Pablo Bay, and the Carquinez Strait. SELFE provides features that are well suited to these types of problems. In addition to an unstructured grid that can capture undulations in the Bays and channels, the model uses a particularly accurate depiction of the bathymetry, as sea level rise fills a new part of the tidal prism. The model also resolves the vertical structure of salinity in the Carquinez Straits. Finally, the SELFE model includes atmospheric data generated from a fine grain climate re-analysis models so it is well suited to represent not only sea-level rise but also to investigate the affects of atmospheric forcing.

SELFE Modules and Capabilities

SELFE has been adapted for hydrodynamics, temperature, salt, oil spill, sediment, biology and wind-wave interaction. The complete modeling system is shown in Figure 6. The model is relatively easy for experienced modelers to set up on a new study domain, though it does require grid generation software such as SMS. The immediate project goal is to provide hydrodynamic, salinity and scalar transport support on the larger Bay-Delta domain and a thorough calibration and validation (Please see Figure 7).

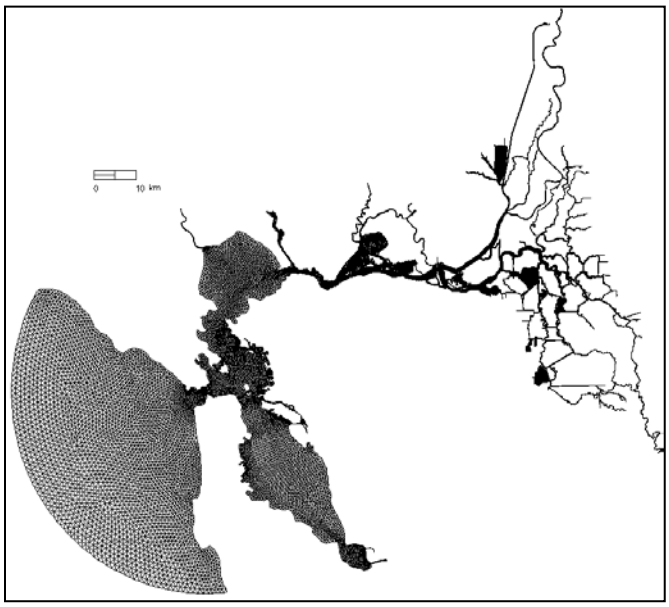


Figure 5: The Full Bay-Delta SELFE mesh.

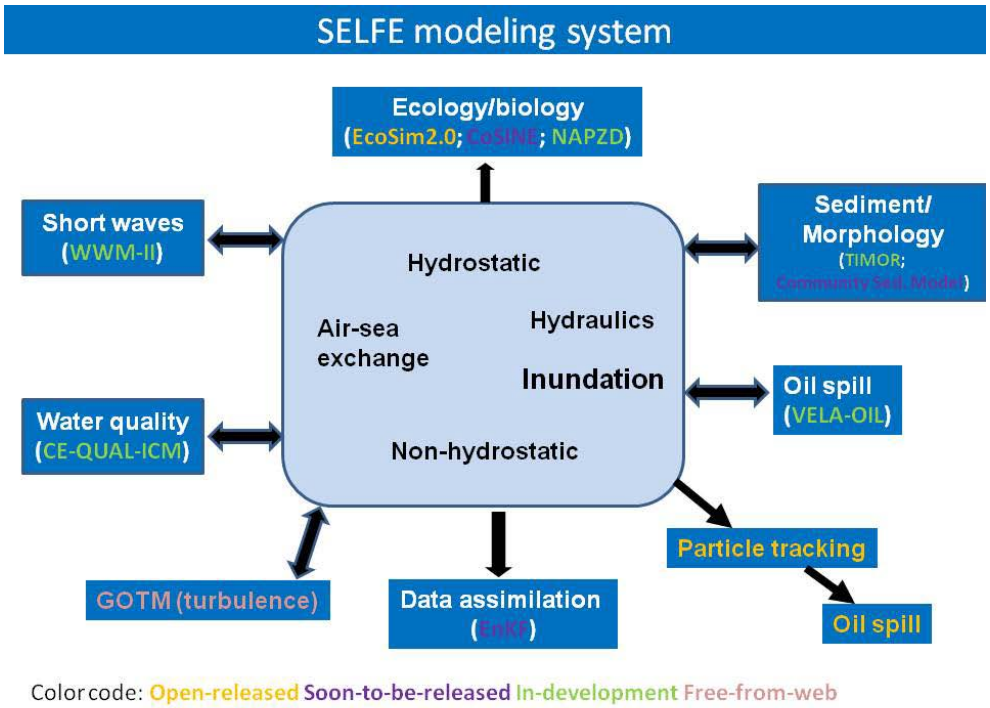


Figure 6: The SELFE modeling system.

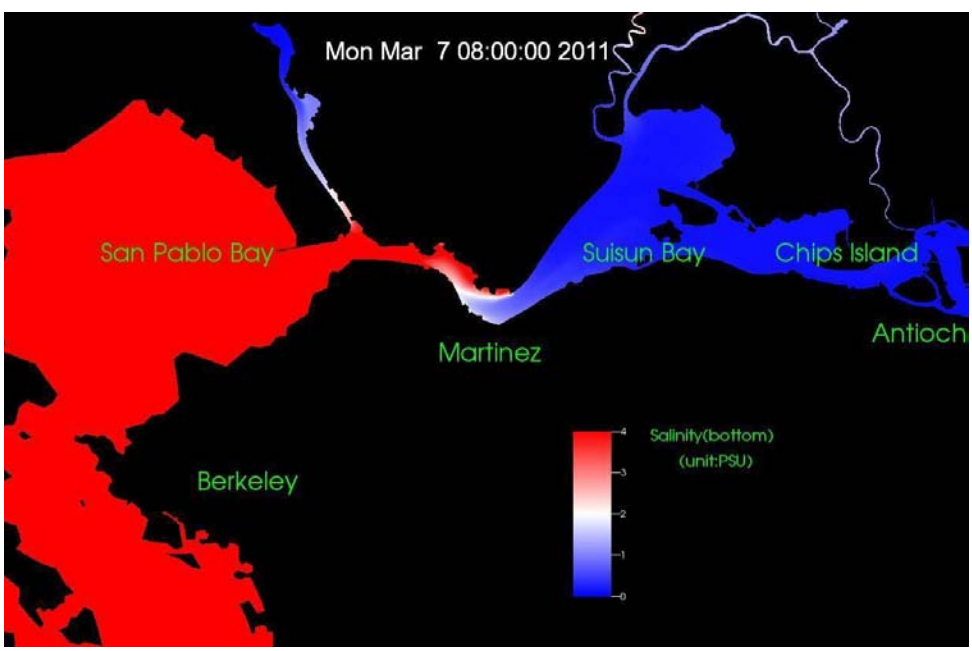


Figure 7: Still image from an animation showing the position of X2 (Shown in White)

The SELFE model application to the Bay-Delta has recently been completed within the full domain, and is already being used by DWR's NASA partners. As mentioned earlier, a full Delta calibration is to be released in Spring 2013, and shortly after that, training will be offered within the modeling community.

5- Climate Change

If the SWRCB plans to evaluate the potential future impacts of proposed changes to the water quality and flow standards of the Bay-Delta Plan, then future climate changes should be considered in the evaluation.

DWR has been and continues to be very active in developing methodologies for projecting future hydrologic conditions that take account of climate change trends. One such methodology was devised through a multi-agency effort for the BDCP to evaluate the environmental impacts and benefits of the BDCP project. This methodology is described in detail in attached draft Appendix 5A . While the process, tools, and data outlined in the attachment are illustrative of the considerations that go into a climate change analysis approach and this specific approach works well for the purposes of BDCP, it may not be appropriate for the SWRCB's purposes. For instance, the BDCP approach looks at two distinct future periods centered around 2025 and 2060. Other types of approaches provide a continuous projection of climatology and hydrology spanning from current conditions out to the future, such an approach would allow the SWRCB to look at projected impacts in any future period.

The complexity and importance of addressing climate change in the modeling work and estimations that the SWRCB may undertake while updating the Bay-Delta Plan warrant focused discussions with experts in the field to determine the appropriate level of analysis, select from existing methodologies, or develop a customized methodology. The considerations in this determination are not only technical but include issues of risk tolerance and dealing with irreducible uncertainty. As DWR mentioned in its presentation to the SWRCB at the first Bay-Delta Plan workshop, DWR has assembled a group of the leading experts in the field to discuss these topics and help us address our climate change challenges. DWR invites you to bring this matter to the DWR Climate Change Technical Advisory Group for additional focused discussions and more detailed guidance and recommendations.

6- Measured, Estimated, Natural, and Unimpaired Streamflows

Streamflow, or simply flow, is the volume of water flowing past a fixed point on a stream or on a river in a fixed unit of time. Several terminologies including measured flow, estimated flow, natural flow and unimpaired flow, have been used to describe streamflows for various purposes. Brief descriptions for each of these terminologies have been compiled to help differentiate these flows for better understanding by professionals as well as the general public.

Measured Flow vs. Estimated Flow

A widely used method of quantifying the flow of a stream is by installing streamflow gages at selected locations, presumed to be geometrically and hydraulically stable, such as at a bridge. The stage (the distance of the water surface from a specified reference datum) of the streamflow and its associated flow velocity measurement are used to compute the flow. The flow so quantified is known by various names such as measured flow, gage flow, recorded flow and observed flow.

Many times, gage flow data for a given watershed may not be available for the entire span of time period for which hydrological data is necessary for water resources planning. Some watersheds may not have measured data at all. In such situations, estimating flow is the recourse often taken. There are various methods that may be used for the flow estimations depending on the situation. For example, a statistical correlation method is most commonly used to extend shorter flow record for a watershed where a nearby watershed with longer measured flow record can be found and has similar hydrologic characteristics. Whatever the process used to estimate the flow, the flow so obtained is called estimated flow.

Natural Flow vs. Unimpaired Flow

Natural flow, which is sometimes also called full natural flow, at a certain location in a watershed is the streamflow that would have occurred naturally if the watershed hadn’t been altered by any human activities including water storage and flood control structures, water imports and exports, water diversions, channel improvements. The word natural connotes that the watershed landscape is in a pre-historical or virgin state.

Unimpaired flow is an estimate of the flow that would have occurred had water flow remained unaltered in rivers and streams instead of stored in reservoirs, imported, exported, or diverted. It is a measure of the total water supply of a watershed available for all uses after removing the impacts of upstream alterations, as they occurred historically. The word unimpaired here implies only that certain items in the measured flows have been adjusted. Unimpaired flow could be synonymous with natural flow if all of the items in the unimpaired computation matched the natural flow computation. However, in reality, this is not usually the case. It is customary to include only those items in the unimpaired flow computation for which either reliable data are readily available or reasonable estimates can be made.

In California Central Valley rim watersheds where no significant human activities may exist, the magnitudes of unimpaired flow and natural flow are assumed to be very close and their uses are interchangeable. In the valley floor area, natural flows are impossible to compute reliably due to unknown nature of impairments caused by human alterations such as channel improvements, levees, and flood bypasses.

The following two examples may further graphically demonstrate how the terminologies of measured flow, natural flow, and unimpaired flow can be used under different circumstances within the Sacramento Valley.

Streamflow below Shasta Dam: An example where Unimpaired Flow can be assumed to be Natural Flow

Shasta Lake on the Sacramento River was built in early 1940s and started regulating streamflow in November of 1942. The storage space in Shasta Lake has altered the streamflow below the Shasta dam by both storing and releasing water from the storage since then. As shown in Figure 8, the line with squares and the line with diamonds represent the measured Sacramento River flow below Shasta dam before and after the reservoir was built; the line with asterisks is the estimated unimpaired flow, obtained by removing the impact of the reservoir from the measured flow (the line with diamonds).

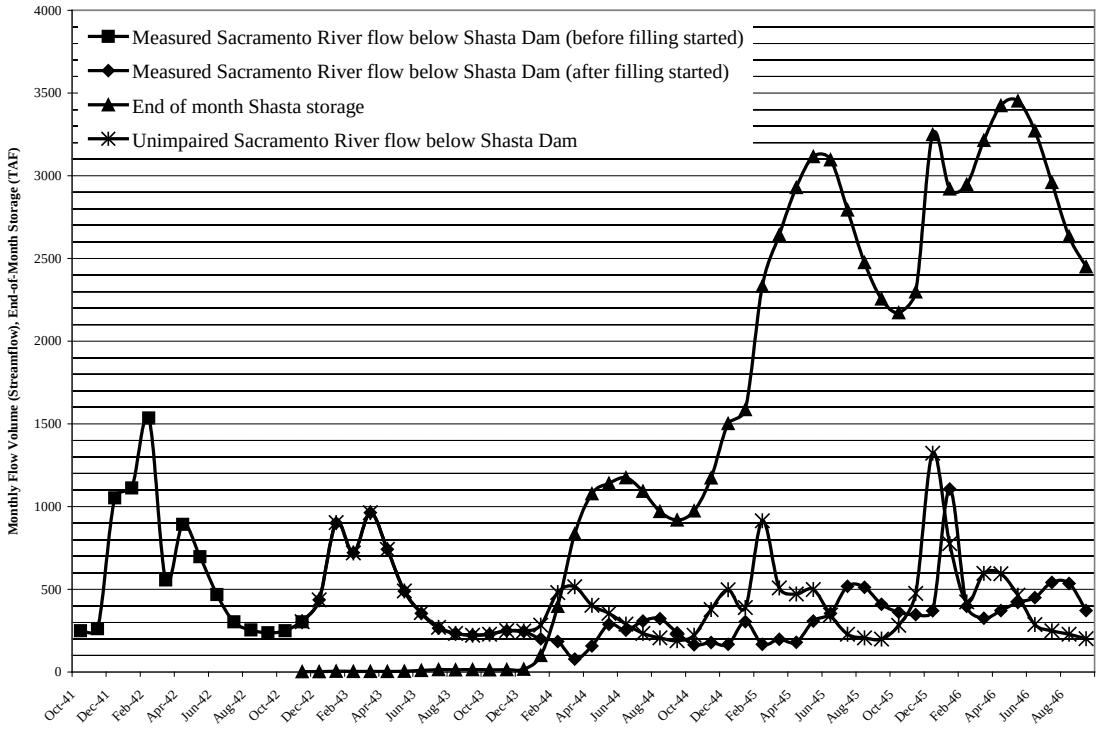


Figure 8: Measured and unimpaired flows below Shasta Dam

Since the Sacramento River watershed above Shasta Dam has generally been assumed to exist in natural state and Shasta dam is considered the only significant human alteration to the river, both terminologies of natural flow and unimpaired flow can be used to describe the measured flow before the reservoir was built (the line with squares) and the estimated unimpaired flow after the reservoir was built (the line with asterisks). The line with triangles is the end of month Shasta storage. It is the main component used in the unimpaired flow estimation. Reservoir evaporation was also used in the unimpaired flow estimation but has been omitted from the figure due to its insignificant magnitude.

Streamflow at Freeport: An example where Unimpaired Flow cannot be assumed to be Natural Flow

Figure 9 shows a comparison of the gage flow at the United States Geological Survey (USGS) gage on the Sacramento River at Freeport (the line with diamonds) with the

estimated unimpaired Sacramento River flow at the same location (the line with squares). Due to the numerous upstream human alterations of water storage and flood control structures, water imports and exports, water diversions, channel improvements and other factors, this USGS gage flow gives an impaired flow (in contrast to unimpaired flow). The unimpaired flow data used in the comparison is taken from the draft DWR report titled California Central Valley Unimpaired Flow Data, Fourth Edition, Bay-Delta Office, May 2007 and it was estimated by removing impacts of upstream water storages, diversions, imports and exports, and other adjustments that may be reasonably quantified or measured from USGS gage flow. Since the impacts of upstream channel improvements, levees, and flood bypasses impacts are difficult to remove from the gage flow, the unimpaired flow so estimated can not be called natural flow. The differences between the two lines in Figure 9 represent the impairments removed.

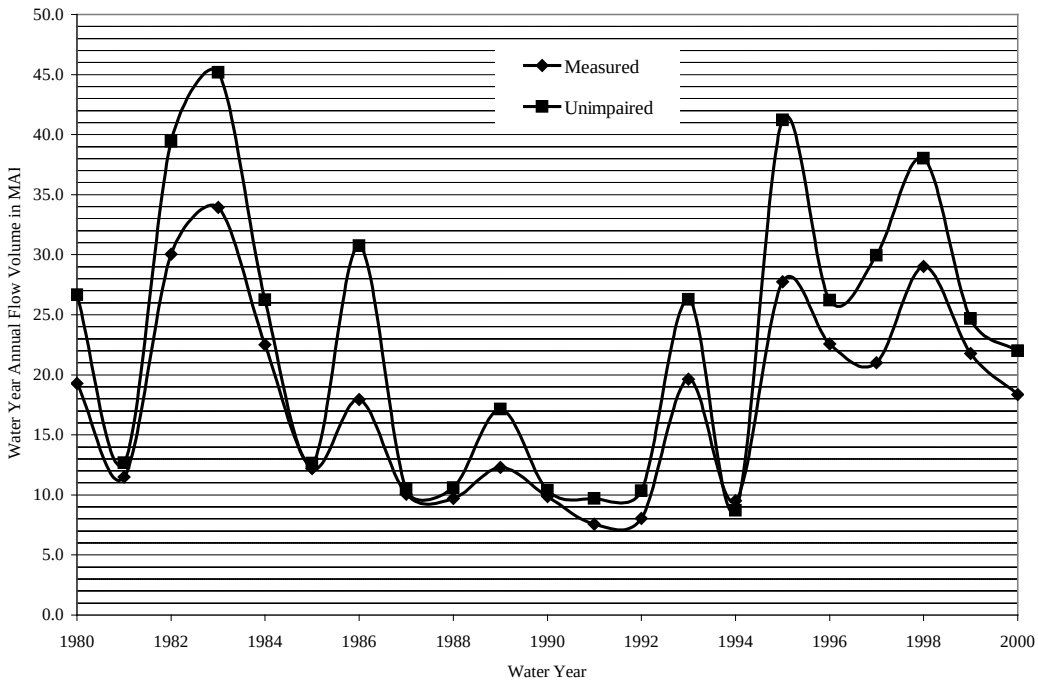


Figure 9: Sample USGS gage flow and unimpaired flow of Sacramento River at Freeport.

We would like to remind the Board that DWR gave a presentation called "Estimating California Central Valley Unimpaired Flows" on January 6, 2011 at the SWRCB workshop on " Presentation and Discussion of Draft Technical Report on the Scientific Basis for Alternative San Joaquin River Flow and Southern Delta Salinity Objectives." The purpose of the presentation was to give an overview of DWR Unimpaired Flows calculations, weaknesses, issues and pitfalls in using Unimpaired Flows for use as a basis for setting Flow objectives in the Delta.

This presentation is available at SWRCB's website at:

http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/sds_srjf/sjr/docs/dwr_uf010611.pdf

For your convenience, a copy of the presentation is attached at the end of this submittal.

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ATTACHMENTS

BDCP Appendix 5A

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BDCP EIR/EIS Modeling Technical Appendix

BDCP EIR/EIS Modeling Technical Appendix

This appendix provides information about the assumptions, modeling tools and the methods used for Bay Delta Conservation Plan Environmental Impact Report/Environmental Impact Statement (BDCP EIR/EIS) Alternatives analyses including information for Existing Conditions and No Action Alternative simulations. The Appendix also provides model results obtained from the BDCP EIR/EIS Alternatives analyses; and additional modeling information such as model limitations, limitations in climate change modeling, and extreme operating conditions.

The Appendix consists of four main sections that are briefly described below:

- Section A: Modeling Methodology
- Section B: CALSIM II and DSM2 Modeling Simulations and Assumptions
- Section C: CALSIM II and DSM2 Modeling Results
- Section D: Additional Modeling Information

Section A: Modeling Methodology

Several models are used to assess and quantify the effects of BDCP Alternatives on the long-term operations and the environment. This section provides information about the overall analytical framework explaining how the modeling information obtained from different models fit together; and descriptions of the key analytical tools that were part of the analytical framework. It also summarizes the modifications to the key analytical tools used in this process.

Section B: CALSIM II and DSM2 Modeling Simulations and Assumptions

This section describes the assumptions for the CALSIM II (Hydrology and System Operations) and DSM2 (Delta Hydrodynamics, Water Quality, and Delta Particle Tracking) model simulations of the Existing Conditions, No Action Alternative and with action Alternatives.

Section C: CALSIM II and DSM2 Modeling Results

This section provides CALSIM II and DSM2 model simulation results for alternatives evaluated for the BDCP EIR/EIS. Key parameters are selected for display; and several different formats of presentations are provided for each parameter to enable the reader to do different kinds of analyses.

Section D: Additional Modeling Information

This section is still being completed. It is planned to be included in a subsequent version of this appendix. This section will provide additional details on the analytical tools and their development and background information on modeling of climate change. In addition, it will also provide information on the model limitations, uncertainty and any sensitivity analyses performed in support of the overall analysis. Furthermore, it will include information on the appropriate use of the modeling results presented in Section C.

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Section A: Modeling Methodology

Outline

A.1. Introduction

A.2. Overview of the Modeling Approach

- A.2.1. Analytical Tools
- A.2.2. Key Components of the Analytical Framework
- A.2.3. Climate Change and Sea Level Rise

A.3. Hydrology and System Operations

- A.3.1 CALSIM II
- A.3.2. Artificial Neural Network for Flow-Salinity Relationship
- A.3.3. Application of CALSIM II to Evaluate BDCP Alternatives
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- A.4.1. SRWQM
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- A.4.3. Application of Temperature Models to Evaluate BDCP Alternatives
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- A.5.2. Delta Simulation Model (DSM2)
- A.5.3. Application of DSM2 to Evaluate BDCP Alternatives
- A.5.4. Output Parameters

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A.5.5. Modeling Limitations

A.6. Delta Particle Tracking Modeling

A.6.1. DSM2-PTM

A.6.2. DSM2-PTM Metrics

A.6.3. PTM Period Selection

A.6.4. PTM Simulations

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A.7. Climate Change Scenarios

A.7.1. Selection of BDCP Climate Scenarios

A.7.2. Downscaled Climate Projections

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A.7.4. Multi-Model Ensemble and Sub-Ensembles

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A.7.6. Sea Level Rise Scenarios

A.7.7. Changes in Tidal Amplitude

A.7.8. Analytical Process for Incorporating Climate Change

A.8. Regional Hydrologic Modeling

A.8.1. Variable Infiltration Capacity (VIC) Model

A.8.2. Application of VIC Model for BDCP Evaluations

A.8.3. Output Parameters

A.8.4. Critical Locations for Analysis

A.8.5. Modeling Limitations

A.8.6. Linkages to Other Physical Models

A.9. References

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A.1. Introduction

This section summarizes the modeling methodology used for the Bay Delta Conservation Plan Environmental Impact Report/Environmental Impact Statement (BDCP EIR/EIS) Existing Conditions, No Action Alternative and otherAlternatives. It describes the overall analytical framework and contains descriptions of the key analytical tools and approaches used in the quantitative evaluation of the Alternatives.

BDCP includes several main components that will have significant effects on SWP and CVP operations and the hydrologic response of the system. Most of the Alternatives include construction and operation of new north Delta intakes and associated conveyance, modifications to the Fremont Weir, large scale tidal marsh restoration in the Delta and changes in the operation of the existing south Delta export facilities can significantly influence the hydrologic response of the system.

For the purposes of the modeling, the Alternatives are simulated at three phases in time: Near-Term (NT), representing a point in time 5-10 years into the permit (~2015), Early Long-Term (ELT) representing a point in time 15 years into the permit (~2025), and Late Long-Term (LLT) representing the end of the 50-year permit (~2060).

In the Alternatives including the new north Delta intakes and isolated conveyance facility, the facility is assumed not to be functional until the ELT phase. All the Alternatives, except for Existing Conditions and No Action Alternative, include the tidal marsh restoration. The acreages of the tidal marsh restoration incrementally increase with each phase. NT includes 14,000 acres, ELT includes 25,000 acres and LLT includes 65,000 acres of tidal marsh restoration.

In the evaluation of the No Action Alternative and the other Alternatives at the ELT and LLT phases, sea level rise was assumed to be inherent. ELT assumes 15cm and LLT assumes 45cm sea level rise to exist. The analytical framework and the tools described in this are developed to evaluate these complex, inter-dependent, large-scale changes to the system. The full modeling assumptions for all the alternatives are provided in Section B.

For the purpose of BDCP EIR/EIS impacts evaluation, Alternatives' modeling results at LLT phase are considered.

A.2. Overview of the Modeling Approach

To support the impact analysis of the Alternatives, modeling of the physical variables (or "physical modeling") such as flows is required to evaluate changes to conditions affecting resources within the Delta as well as effects to upstream and downstream resources. A framework of integrated analyses including hydrologic, operations, hydrodynamics, water quality, and particle tracking analysis are required to provide baseline and comparative information for water supply, surface water, aquatic resources and water quality assessments. This analytical framework is also useful to assess changes in the function of the alternatives under varying assumptions of future, non-project conditions such as climate change, future demands, and changes in Delta morphology.

The Alternatives include complex changes to internal forcings such as Delta conveyance, SWP/CVP water project operations, floodplains and tidal marsh, and Delta channel structure/gates. Both these internal forcings and external forcings such as climate and sea level

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changes influence the future conditions of reservoir storage, river flow, Delta flows, exports, water quality, and tidal dynamics. Evaluation of these conditions is the primary focus of the physical modeling analyses. The interaction between many of the elements proposed under the Alternatives necessitated modifications to existing analytical tools or application of new analytical tools to account for these dynamic relationships.

Figure A-1 shows the analytical tools applied in these assessments and the relationship between these tools. Each model included in Figure A-1 provides information to the next "downstream" model in order to provide various results to support the impact analyses. Changes to the historical hydrology related to the future climate are applied in the CALSIM II model and combined with the assumed operations for each Alternative. The CALSIM II model simulates the operation of the major SWP and CVP facilities in the Central Valley and generates estimates of river flows, exports, reservoir storage, deliveries, and other parameters. The Delta boundary flows and exports from CALSIM II are then used to drive the DSM2 Delta hydrodynamic and water quality models for estimating tidally-based flows, stage, velocity, and salt transport within the estuary. Particle tracking modeling uses the velocity fields generated under the hydrodynamics to emulate movement of particles throughout the Delta system. River and temperature models for the primary river systems use the CALSIM II reservoir storage, reservoir releases, river flows, and meteorological conditions to estimate reservoir and river temperatures under each scenario. The results from this suite of physical models are used to inform the understanding of effects of each individual scenario considered in the BDCP.

A.2.1. Analytical Tools

A brief description of the hydrologic, hydrodynamic, water quality, particle transport, reservoir and river temperature modeling tools used in the analytical framework is provided below.

CALSIM II

The California Department of Water Resources (DWR)/U.S. Bureau of Reclamation (Reclamation) CALSIM II planning model was used to simulate the operation of the CVP and SWP over a range of hydrologic conditions. CALSIM II is a generalized reservoir-river basin simulation model that allows for specification and achievement of user-specified allocation targets, or goals (Draper et al. 2002). CALSIM II represents the best available planning model for the SWP and CVP system operations and has been used in previous system-wide evaluations of SWP and CVP operations (USBR, 1994, 2004, 2008).

Inputs to CALSIM II include water diversion requirements (demands), stream accretions and depletions, rim basin inflows, irrigation efficiencies, return flows, non-recoverable losses, and groundwater operations. Sacramento Valley and tributary rim basin hydrologies are developed using a process designed to adjust the historical sequence of monthly stream flows over an 82-year period (1922 to 2003) to represent a sequence of flows at a future level of development.

Adjustments to historic water supplies are determined by imposing future level land use on historical meteorological and hydrologic conditions. The resulting hydrology represents the water supply available from Central Valley streams to the CVP and SWP at a future level of development.

CALSIM II produces outputs for river flows and diversions, reservoir storage, Delta flows and exports, Delta inflow and outflow, Deliveries to project and non-project users, and controls on project operations. Reclamation's 2008 Operations Criteria and Plan (OCAP) Biological

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Assessment (BA) Appendix D provides more information about CALSIM II (USBR, 2008a).CALSIM II output provides the basis for multiple other hydrologic, hydrodynamic, and biological models and analyses. CALSIM II results are used to determine water quality, hydrodynamics, and particle tracking in the DSM2 model. The outputs feed into temperature models including the Upper Sacramento River Water Quality Model (USRWQM), the Reclamation Temperature Model, and other habitat and biological models.

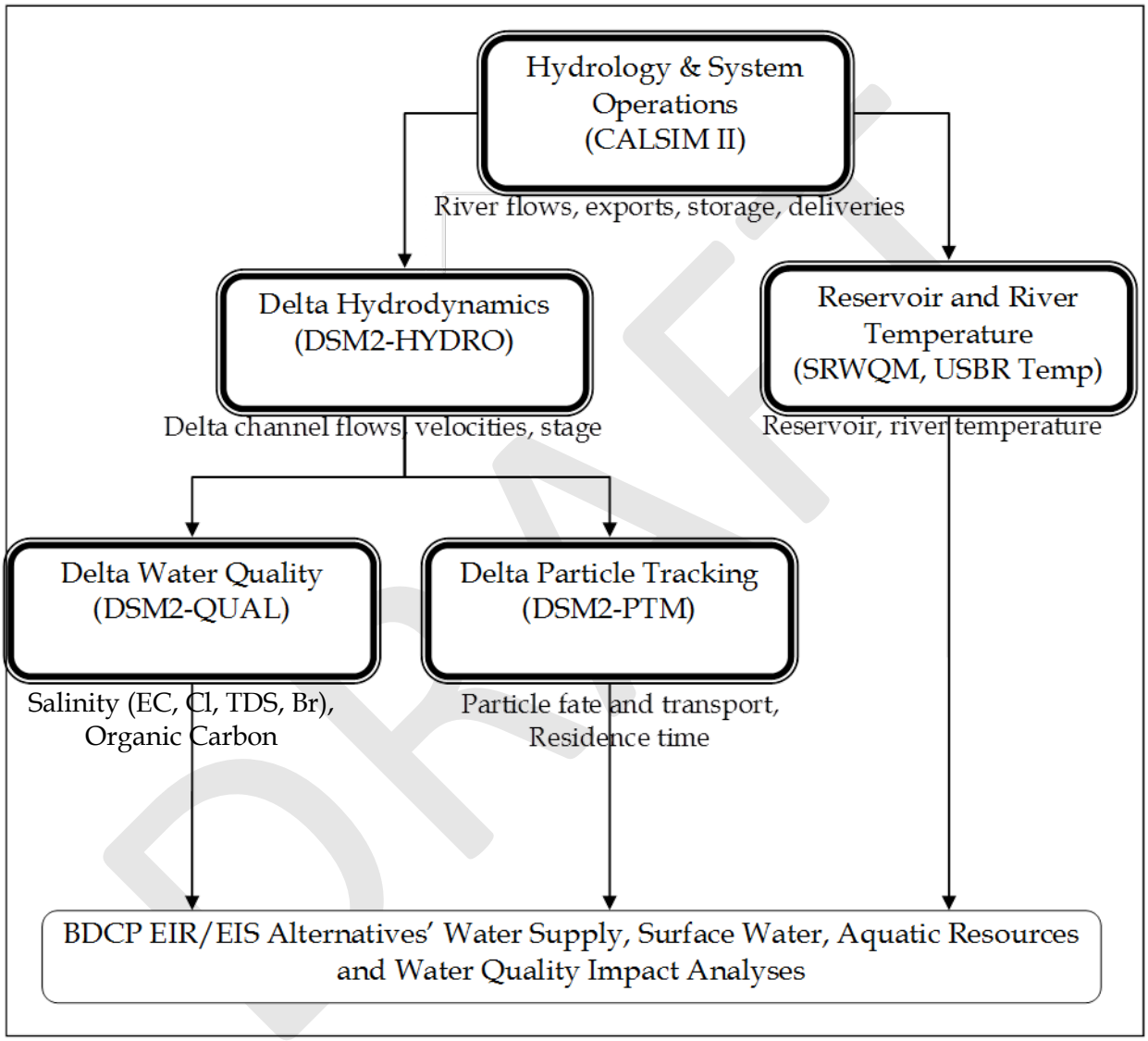

Figure A-1: Analytical Framework used to Evaluate Impacts of the Alternatives

Artificial Neural Network (ANN) for Flow-Salinity Relationships

An Artificial Neural Network (ANN) has been developed (Sandhu et al. 1999, Seneviratne and Wu, 2007) that attempts to faithfully mimic the flow-salinity relationships as modeled in DSM2, but provide a rapid transformation of this information into a form usable by the statewide CALSIM II model. The ANN is implemented in CALSIM II to constrain the operations of the upstream reservoirs and the Delta export pumps in order to satisfy particular salinity requirements. The current ANN predicts salinity at various locations in the Delta using the

following parameters as input: Sacramento River inflow, San Joaquin River inflow, Delta Cross Channel gate position, and total exports and diversions. Sacramento River inflow includes Sacramento River flow, Yolo Bypass flow, and combined flow from the Mokelumne, Cosumnes, and Calaveras rivers (East Side Streams) minus North Bay Aqueduct and Vallejo exports. Total exports and diversions include State Water Project (SWP) Banks Pumping Plant, Central Valley Project (CVP) Tracy Pumping Plant, Contra Costa Water District (CCWD) diversions including diversion to Los Vaqueros Reservoir. The ANN model approximates DSM2 model-generated salinity at the following key locations for the purpose of modeling Delta water quality standards: X2, Sacramento River at Emmaton, San Joaquin River at Jersey Point, Sacramento River at Collinsville, and Old River at Rock Slough. In addition, the ANN is capable of providing salinity estimates for Clifton Court Forebay, CCWD Alternate Intake Project (AIP) and Los Vaqueros diversion locations. A more detailed description of the ANNs and their use in the CALSIM II model is provided in Wilbur and Munévar (2001). In addition, the DWR Modeling Support Branch website (http://modeling.water.ca.gov/) provides ANN documentation.

Upper Sacramento River Water Quality Model (USRWQM)

The Upper Sacramento River Water Quality Model (USRWQM) was used to simulate the effects of operations on water temperature in the Sacramento River and Shasta and Keswick reservoirs. The USRWQM was developed using the HEC-5Q model to simulate mean daily (using 6-hour meteorology) reservoir and river temperatures at key locations on the Sacramento River. The timestep of the model is daily and provides water temperature each day for the 82 year hydrologic period used in CALSIM II. The model has been used in the previous CVP and SWP system operational performance evaluation (USBR, 2008c). Monthly flows from CALSIM II for an 82 year period (WY 1922-2003) are used as input into the USRWQM after being temporally downsized to daily average flows. Temporal downscaling is performed on the CALSIM II monthly average tributary flows to convert them to daily average flows for HEC5Q input. Monthly average flows are converted to daily tributary inflows based on 1921 through 1994 daily historical record for the following aggregated inflows:

1. Trinity River above Lewiston;

2. Sacramento River above Keswick; and

3. Incremental inflow between Keswick and Bend Bridge (Seven day trailing average for inflows below Butte City).

Each of the total monthly inflows specified by CALSIM II is scaled proportionally to one of these three historical records. Reservoir inflows were proportioned as defined above. Outflows and diversions are smoothed for a better transition at the end of the month without regard for reservoir volume constraints or downstream minimum flows. As flows are redistributed within the month, the minimum flow constraint at Keswick, Red Bluff and Knights Landing may be violated. In such cases, operation modifications are required for daily flow simulation to satisfy minimum flow requirements. A utility program is included in SRWQM to convert the monthly CALSIM II flows and releases into daily operations. More detailed description SRWQM and the temporal downscaling process is included in an RMA calibration report (RMA 2003). For more information on the USRWQM, see Appendix H of the Reclamation's 2008 OCAP BA (USBR, 2008c).

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Reclamation Temperature Model

The Reclamation Temperature Model was used to predict the effects of operations on water temperatures in the Trinity, Feather, American, and Stanislaus river basins and upstream reservoirs. The model is a reservoir and stream temperature model, which simulates monthly reservoir and stream temperatures used for evaluating the effects of CVP/SWP project operations on mean monthly water temperatures in the basin based on hydrologic and climatic input data. It has been applied to past CVP and SWP system operational performance evaluations (USBR, 2008c).

The model uses CALSIM II output to simulate mean monthly vertical temperature profiles and release temperatures for five major reservoirs (Trinity, Whiskeytown, Shasta, Oroville and Folsom), four downstream regulating reservoirs (Lewiston, Keswick, Goodwin and Natoma), and three main river systems (Sacramento, Feather and American), although the model is not be applied to the Sacramento River because the USRWQM was deemed superior as a result of its daily time step. For more information on the Reclamation Temperature Model, see Appendix H of the Reclamation's 2008 OCAP BA (USBR, 2008c).

DSM2

DSM2 is a one-dimensional hydrodynamic and water quality simulation model used to simulate hydrodynamics, water quality, and particle tracking in the Sacramento-San Joaquin Delta (DWR, 2002). DSM2 represents the best available planning model for Delta tidal hydraulic and salinity modeling. It is appropriate for describing the existing conditions in the Delta, as well as performing simulations for the assessment of incremental environmental impacts caused by future facilities and operations.

The DSM2 model has three separate components: HYDRO, QUAL, and PTM. HYDRO simulates velocities and water surface elevations and provides the flow input for QUAL and PTM. DSM2-HYDRO outputs are used to predict changes in flow rates and depths, and their effects on covered species, as a result of the BDCP and climate change.

The QUAL module simulates fate and transport of conservative and non-conservative water quality constituents, including salts, given a flow field simulated by HYDRO. Outputs are used to estimate changes in salinity, and their effects on covered species, as a result of the BDCP and climate change. Reclamation's 2008 OCAP BA Appendix F provides more information about DSM2 (USBR, 2008b).

DSM2-PTM simulates pseudo 3-D transport of neutrally buoyant particles based on the flow field simulated by HYDRO. It simulates the transport and fate of individual particles traveling throughout the Delta. The model uses velocity, flow, and stage output from the HYDRO module to monitor the location of each individual particle using assumed vertical and lateral velocity profiles and specified random movement to simulate mixing. PTM has multiple applications ranging from visualization of flow patterns to simulation of discrete organisms such as fish eggs and larvae. Additional information on DSM2 can be found on the DWR Modeling Support Branch website at http://modeling.water.ca.gov/.

A.2.2. Key Components of the Analytical Framework

Major components of the BDCP physical modeling, including Hydrology and Systems Operations Modeling, Reservoir and River Temperature Modeling, Delta Hydrodynamics and

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Water Quality Modeling and Delta Particle Transport and Fate Modeling are described in separate sections. Each section describes in detail the key tools used for modeling, data inter-dependencies and limitations. It also includes description of the process of how the tools are applied in a long-term planning analysis such as evaluating the Alternatives and describe any improvements or modifications performed for application in BDCP modeling.

Section A.3. *Hydrology and Systems Operations Modeling* describes the application of the CALSIM II model to evaluate the effects of hydrology and system operations on river flows, reservoir storage, Delta flows and exports, and water deliveries. Section A.4. *Reservoir and River Temperature Modeling* includes a description of the Sacramento River Water Quality Model for analysis of temperature in the Shasta-Whiskeytown complex and the Sacramento River. Section A.5. *Delta Hydrodynamics and Water Quality* section describes the application of the DSM2 model to implement new elements of the BDCP and resulting effects to tidal stage, velocity, flows, and salinity. Finally, Section A.6. *Delta Particle Transport and Fate Modeling* describes the methodology and application of the DSM2-PTM model for simulating particle transport in the Delta.

A.2.3. Climate Change and Sea Level Rise

The physical modeling approach applied for the BDCP integrates a suite of analytical tools in a unique manner to characterize changes to the system from "atmosphere to ocean". Figure A-2 illustrates the general flow of information for incorporating climate and sea level change in the physical modeling analyses. Climate and sea level can be considered the most upstream and most downstream boundary forcings on the system analyzed in the physical modeling for the BDCP. However, these forcings are outside of the influence of the BDCP and are considered external forcings. The effects of these forcings are incorporated into the key models used in the analytical framework.

The selection of the future climate and the sea level rise scenarios is described in Section A.7. *Climate and Sea Level Change Scenarios* section along with the process of science review, incorporation of uncertainty, and analytical methods for selecting appropriate scenarios. For all the selected future climate scenarios, regional hydrologic modeling was performed with the Variable Infiltration Capacity (VIC) hydrology model using temperature and precipitation projections of future climate. In addition to a range of hydrologic process information, the VIC model generates natural streamflows under each assumed climate condition. Section A.8. *Regional Hydrologic Modeling* describes the application of the macro-scale VIC hydrology model that translates the effects of future climate conditions on watershed processes ultimately affecting the timing and volume of runoff.

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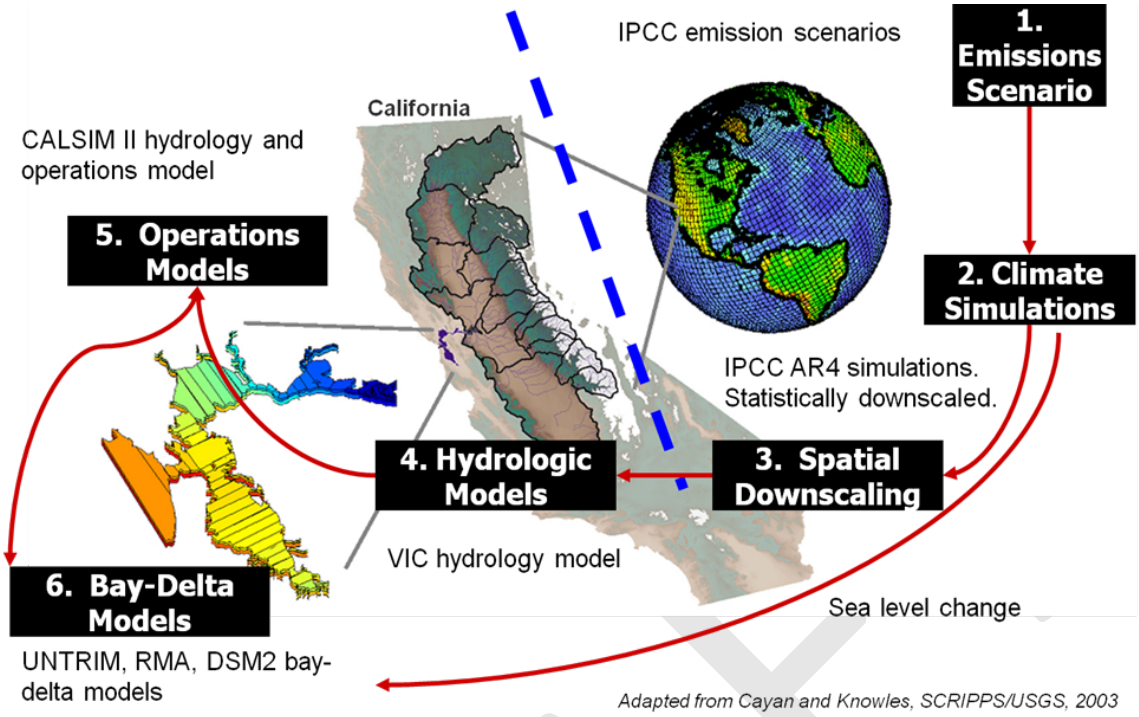

Figure A-2: Characterizing Climate Impacts from Atmosphere to Oceans

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A.3. Hydrology and System Operations

The hydrology of the Central Valley and operation of the CVP and SWP systems is a critical element toward any assessment of changed conditions in the Delta. Changes to conveyance, flow patterns, demands, regulations, and/or Delta configuration will influence the operation of the SWP and CVP reservoirs and export facilities. The operations of these facilities, in turn, influence Delta flows, water quality, river flows, and reservoir storage. The interaction between hydrology, operations, and regulations is not always intuitive and detailed analysis of this interaction often results in new understanding of system responses. Modeling tools are required to approximate these complex interactions under future conditions.

The Bay Delta Conservation Plan (BDCP) includes several main components that will have significant effects on SWP and CVP operations and the hydrologic response of the system. The proposed construction and operation of new north Delta intakes and associated conveyance, modifications to the Fremont Weir, large scale tidal marsh restoration in the Delta, and changes in the operation of the existing south Delta export facilities can significantly influence the hydrologic response of the system.

This section describes in detail the methodology used to simulate hydrology and system operations for evaluating the effects of the BDCP. It discusses the primary tool (CALSIM II) used in this process and improvements made to the model to better simulate key components of the BDCP.

A.3.1 CALSIM II

The DWR/USBR CALSIM II planning model was used to simulate the operation of the CVP and SWP over a range of hydrologic conditions. CALSIM II is a generalized reservoir-river basin simulation model that allows for specification and achievement of user-specified allocation targets, or goals (Draper et. al., 2004). The current application to the Central Valley system is called CALSIM II and represents the best available planning model for the SWP and CVP system operations. CALSIM II includes major reservoirs in the Central Valley of the California including Trinity, Lewiston, Whiskeytown, Shasta, Keswick, Folsom, Oroville, San Luis, New Melones and Millerton located along the Sacramento and San Joaquin Rivers and their tributaries. CALSIM II also includes all the major CVP and SWP facilities including Clear Creek Tunnel, Tehama Colusa Canal, Corning Canal, Jones Pumping Plant, Delta Mendota Canal, Mendota Pool, Banks Pumping Plant, California Aqueduct, South Bay Aqueduct, North Bay Aqueduct, Coastal Aqueduct and East Branch Extension. In addition, it also includes some locally managed facilities such as the Glenn Colusa Canal, Contra Costa Canal and the Los Vaqueros Reservoir. Figure A-3 shows the major reservoirs, streams and facilities included in the CALSIM II model.

The CALSIM II simulation model uses single time-step optimization techniques to route water through a network of storage nodes and flow arcs based on a series of user-specified relative priorities for water allocation and storage. Physical capacities and specific regulatory and contractual requirements are input as linear constraints to the system operation using the water resources simulation language (WRESL). The process of routing water through the channels and storing water in reservoirs is performed by a mixed integer linear programming solver. For each time step, the solver maximizes the objective function to determine a solution that delivers

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or stores water according to the specified priorities and satisfies all system constraints. The sequence of solved linear programming problems represents the simulation of the system over the period of analysis.

Figure A-3: Major Reservoirs, Streams and Facilities (both CVP and SWP) Included in the CALSIM II Model

CALSIM II includes an 82-year modified historical hydrology (water years 1922-2003) developed jointly by DWR and USBR. Water diversion requirements (demands), stream accretions and depletions, rim basin inflows, irrigation efficiencies, return flows, non-recoverable losses, and groundwater operations are components that make up the hydrology used in CALSIM II. Sacramento Valley and tributary rim basin hydrologies are developed using

a process designed to adjust the historical observed sequence of monthly stream flows to represent a sequence of flows at a future level of development. Adjustments to historic water supplies are determined by imposing future level land use on historical meteorological and hydrologic conditions. The resulting hydrology represents the water supply available from Central Valley streams to the system at a future level of development. Figure A-4 shows the valley floor depletion regions, which represent the spatial resolution at which the hydrologic analysis is performed in the model.

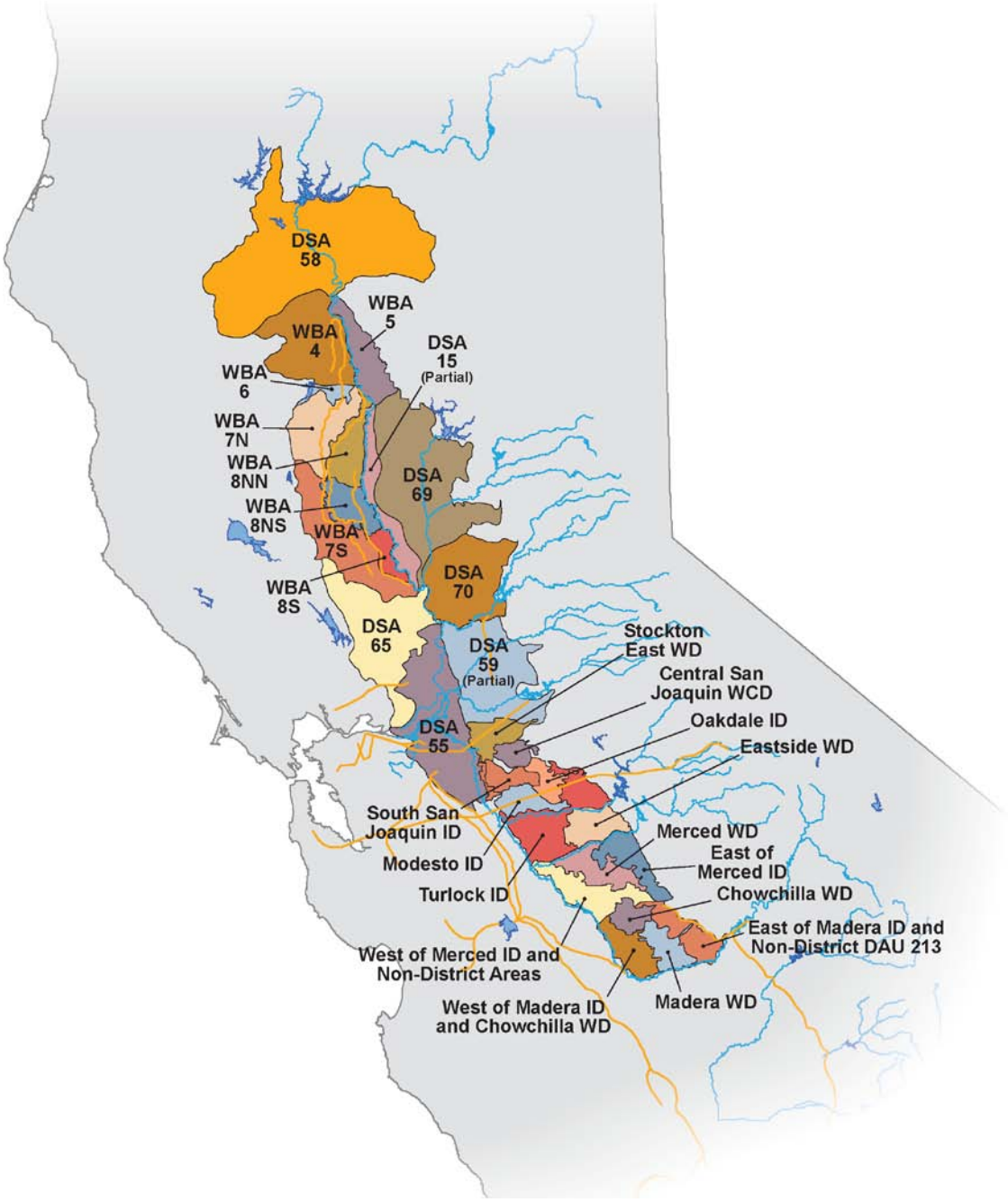

Figure A-4: CALSIM II Depletion Analysis Regions

CALSIM II uses rule-based algorithms for determining deliveries to north-of-Delta and south-of-Delta CVP and SWP contractors. This delivery logic uses runoff forecast information, which incorporates uncertainty and standardized rule curves. The rule curves relate storage levels and forecasted water supplies to project delivery capability for the upcoming year. The delivery capability is then translated into SWP and CVP contractor allocations which are satisfied through coordinated reservoir-export operations.

The CALSIM II model utilizes a monthly time-step to route flows throughout the river-reservoir system of the Central Valley. While monthly time steps are reasonable for long-term planning analyses of water operations, two major components of the BDCP conveyance and conservation strategy include operations that are sensitive to flow variability at scales less than monthly: the operation of the modified Fremont Weir and the diversion/bypass rules associated with the proposed north Delta intakes. Initial comparisons of monthly versus daily operations at these facilities indicated that weir spills were likely underestimated and diversion potential was likely overstated using a monthly time step. For these reasons, a monthly to daily flow disaggregation technique was included in the CALSIM II model for the Fremont Weir, Sacramento Weir, and north Delta intakes. The technique applies historical daily patterns, based on the hydrology of the year, to transform the monthly volumes into daily flows. The procedure is described in more detail further in this document. Reclamation's 2008 OCAP BA Appendix D provides more information about CALSIM II (USBR, 2008a).

A.3.2. Artificial Neural Network for Flow-Salinity Relationship

Determination of flow-salinity relationships in the Sacramento-San Joaquin Delta is critical to both project and ecosystem management. Operation of the SWP/CVP facilities and management of Delta flows is often dependent on Delta flow needs for salinity standards. Salinity in the Delta cannot be simulated accurately by the simple mass balance routing and coarse timestep used in CALSIM II. Likewise, the upstream reservoirs and operational constraints cannot be modeled in the DSM2 model. An Artificial Neural Network (ANN) has been developed (Sandhu et al. 1999) that attempts to mimic the flow-salinity relationships as simulated in DSM2, but provide a rapid transformation of this information into a form usable by the CALSIM II operations model. The ANN is implemented in CALSIM II to constrain the operations of the upstream reservoirs and the Delta export pumps in order to satisfy particular salinity requirements. A more detailed description of the use of ANNs in the CALSIM II model is provided in Wilbur and Munévar (2001).

The ANN developed by DWR (Sandhu et al. 1999, Seneviratne and Wu, 2007) attempts to statistically correlate the salinity results from a particular DSM2 model run to the various peripheral flows (Delta inflows, exports and diversions), gate operations and an indicator of tidal energy. The ANN is calibrated or trained on DSM2 results that may represent historical or future conditions using a full circle analysis (Seneviratne and Wu, 2007). For example, a future reconfiguration of the Delta channels to improve conveyance may significantly affect the hydrodynamics of the system. The ANN would be able to represent this new configuration by being retrained on DSM2 model results that included the new configuration.

The current ANN predicts salinity at various locations in the Delta using the following parameters as input: Northern flows, San Joaquin River inflow, Delta Cross Channel gate

position, total exports and diversions, Net Delta Consumptive Use, an indicator of the tidal energy and San Joaquin River at Vernalis salinity. Northern flows include Sacramento River flow, Yolo Bypass flow, and combined flow from the Mokelumne, Cosumnes, and Calaveras rivers (East Side Streams) minus North Bay Aqueduct and Vallejo exports. Total exports and diversions include State Water Project (SWP) Banks Pumping Plant, Central Valley Project (CVP) Jones Pumping Plant, and CCWD diversions including diversions to Los Vaqueros Reservoir. A total of 148 days of values of each of these parameters is included in the correlation, representing an estimate of the length of memory of antecedent conditions in the Delta. The ANN model approximates DSM2 model-generated salinity at the following key locations for the purpose of modeling Delta water quality standards: X2, Sacramento River at Emmaton, San Joaquin River at Jersey Point, Sacramento River at Collinsville, and Old River at Rock Slough. In addition, the ANN is capable of providing salinity estimates for Clifton Court Forebay, CCWD Alternate Intake Project (AIP) and Los Vaqueros diversion locations.

The ANN may not fully capture the dynamics of the Delta under conditions other than those for which it was trained. It is possible that the ANN will exhibit errors in flow regimes beyond those for which it was trained. Therefore, a new ANN is needed for any new Delta configuration or under sea level rise conditions which may result in changed flow – salinity relationships in the Delta.

A.3.3. Application of CALSIM II to Evaluate BDCP Alternatives

Typical long-term planning analyses of the Central Valley system and operations of the CVP and SWP have applied the CALSIM II model for analysis of system responses. CALSIM II simulates future SWP/CVP project operations based on a 82-year monthly hydrology derived from the observed 1922-2003 period. Future land use and demands are projected for the appropriate future period. The system configuration consisting of facilities, operations, and regulations are input to the model and define the limits or preferences on operation. The configuration of the Delta, while not simulated directly in CALSIM II, informs the flow-salinity relationships and several flow-related regressions for interior Delta conditions (i.e. X2 and OMR) included in the model. For each set of hydrologic, facility, operations, regulations, and Delta configuration conditions, the CALSIM II model is simulated. Some refinement of the SWP/CVP operations related to delivery allocations and San Luis target storage levels is generally necessary to have the model reflect suitable north-south reservoir balancing under future conditions. These refinements are generally made by experienced modelers in conjunction with project operators.

The CALSIM II model produces outputs of river flows, exports, water deliveries, reservoir storage, water quality, and several derived variables such as X2, Delta salinity, OMR, and QWEST. The CALSIM II model is most appropriately applied for comparing one alternative to another and drawing comparisons between the results. This is the method in which CALSIM II is applied for the BDCP. For each phase of the Alternatives a companion No Action Alternative simulation has been prepared. The No Action simulation includes the existing infrastructure, existing regulatory restrictions including the recent biological opinions, but may include future demands, climate, and sea level rise depending on the time frame. The Alternative is compared to the No Action Alternative to evaluate areas in which the project changes conditions and the seasonality and magnitude of such changes. The change in hydrologic response or system

conditions is important information that informs the effects analysis related to water-dependent resources in Sacramento-San Joaquin watersheds.

There are a number of areas in which the CALSIM II model has been improved or is applied differently for the BDCP analyses. This section briefly describes these key changes.

Changes to the CALSIM II Model Network

The main feature of the Alternatives that necessitated changes to the CALSIM II model network was the proposed diversion intakes in the north Delta along the Sacramento River. The intakes and associated conveyance allow for SWP and CVP diversions on the Sacramento River between Freeport and Courtland. Some of the Alternatives include up to 5 intakes in this reach of the river with individual diversion capacity up to 3,000 cfs. Since there are relatively small existing diversions and negligible inflows occurring in this reach of the Sacramento River, the CALSIM II aggregates all proposed diversions into a single diversion arc (Figure A-5) near Hood. This diversion arc (D400) conveys water diverted by the SWP and CVP to their respective pumping plants (either Banks PP or Jones PP) in the south Delta. Since dual conveyance – diverting from either or both north and south facilities -- is being considered, the model comingles the water at the pumping plant. Water for each project is tracked separately.

Additional changes were made to the CALSIM II network in the south Delta to allow for better estimation of the Combined Old and Middle River (OMR) flow.

The Delta island consumptive use (DICU) is applied in CALSIM II at five nodes representing regions in the north, west, central, south, and San Joaquin regions of the Delta. A review of the DICU was performed in 2009 to discern if any adjustments would be necessary to best reflect the flow available at the points of diversion. The DICU was disaggregated further, into a total of seven parts, including to split out the DICU upstream and downstream of the proposed north Delta diversion, and portion of the DICU in the south Delta to improve estimates of the OMR flow.

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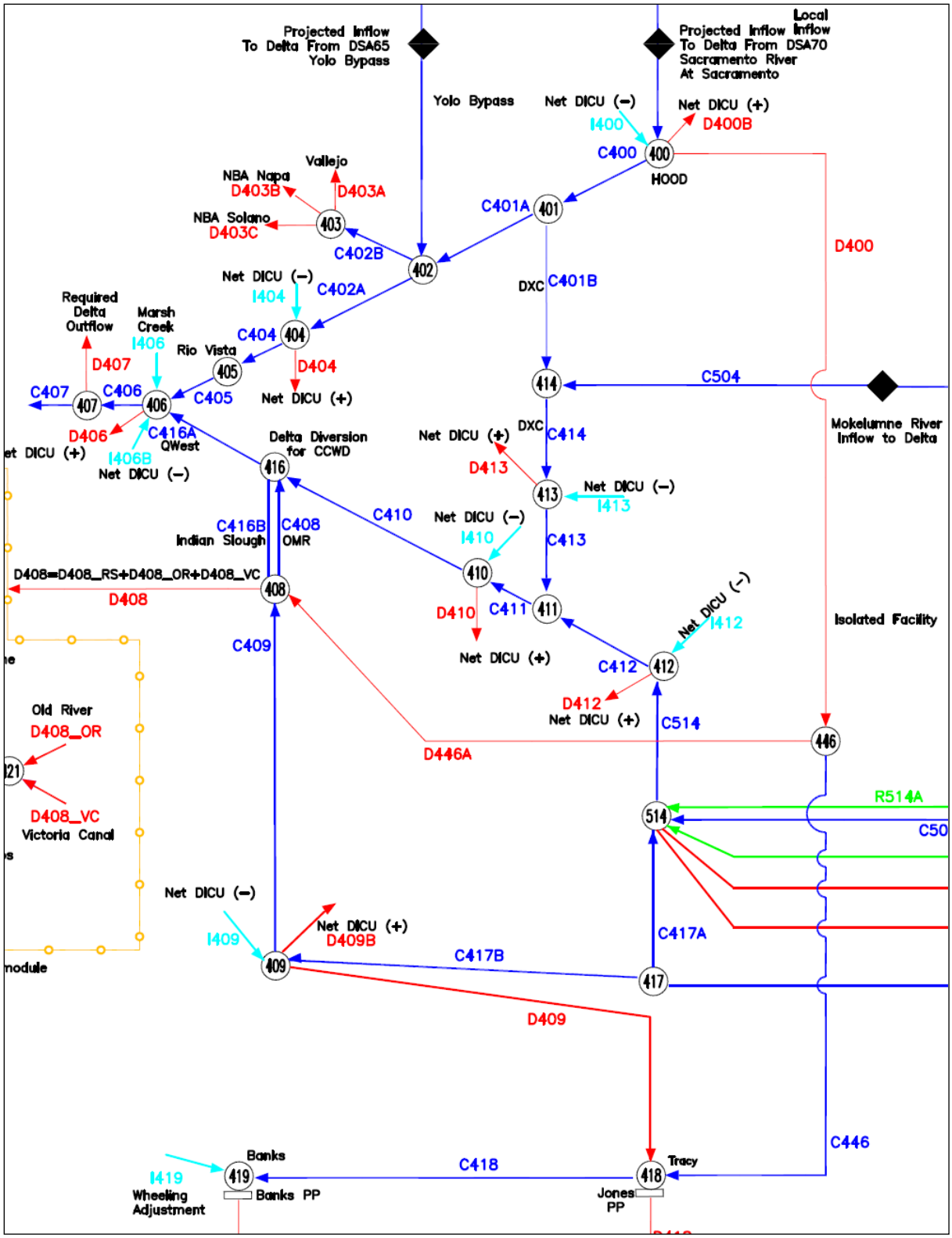

Figure A-5: Updated CALSIM II network for the inclusion of north Delta diversion (D400)

Incorporation of Sacramento River Daily Variability

As described above, the operation of the modified Fremont Weir and the diversion/bypass rules associated with the proposed north Delta intakes are sensitive to the daily variability of flows. Short duration, highly variable storms are likely to cause Fremont Weir spills. However, if flows are averaged for the month, as is done in a monthly model, it is possible to not identify any spill. Similarly, the operating criteria for the north Delta intakes include variable bypass flows and pulse protection criteria. Storms as described above may permit significant diversion but only for a short period of time. Initial comparisons of monthly versus daily operations at these facilities indicated that weir spills were likely underestimated and diversion potential was likely overstated using a monthly time step.

Figure A-6 shows a comparison of observed monthly averaged Sacramento River flow at Freeport and corresponding daily flow as an example. The figure shows that the daily flow exhibits significant variability around the monthly mean in the winter and spring period while remaining fairly constant in summer and fall months. Figure A-7 shows the daily historical patterns by water year type. It shows that daily variability is significant in the winter-spring while the summer flows are holding fairly constant in the most water year types. The winter-spring daily variability is deemed important to species of concern.

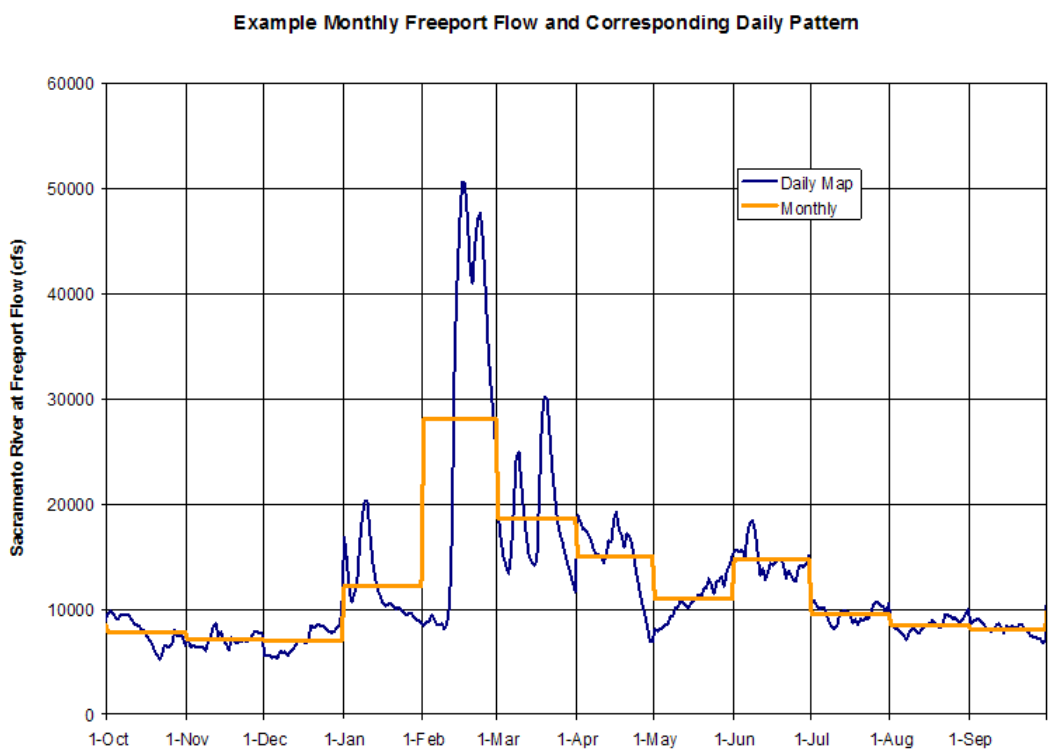

Figure A-6: Example monthly-averaged and daily-averaged flow for Sacramento River at Freeport

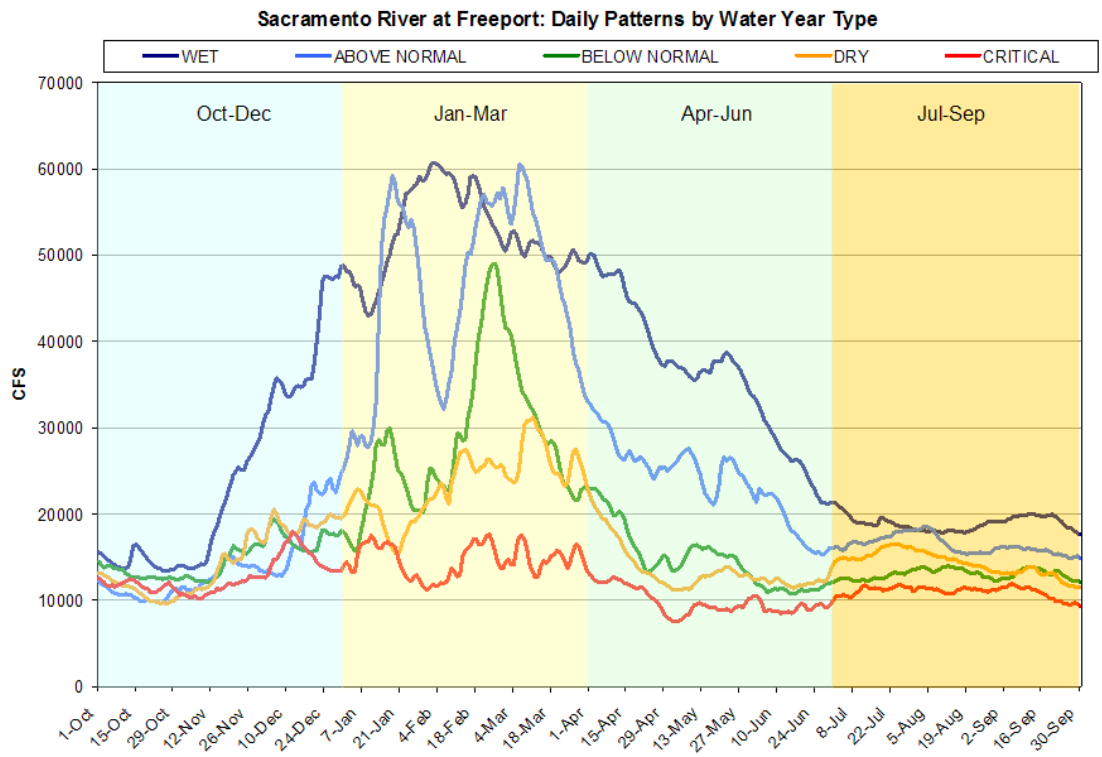

Figure A-7: Mean daily flows by Water Year Type for Sacramento River at Freeport

In an effort to better represent the sub-monthly flow variability, particularly in early winter, a monthly-to-daily flow mapping technique is applied directly in CALSIM II for the Fremont Weir, Sacramento Weir, and the north Delta intakes. The technique applies historical daily patterns, based on the hydrology of the year, to transform the monthly volumes into daily flows. Daily flow patterns are obtained from the observed DAYFLOW period of 1956-2008. In all cases, the monthly volumes are preserved between the daily and monthly flows. It is important to note that this daily mapping approach does not in any way represent the flows resulting from operational responses on a daily time step. It is simply a technique to incorporate representative daily variability into the flows resulting from CALSIM II's monthly operational decisions. It helps in refining the monthly CALSIM II operations by providing a better estimate of the Fremont and Sacramento weir spills which are sensitive to the daily flow patterns and allows in providing the upper bound of the available north Delta diversion in the Alternatives.

Observed Daily Patterns

CALSIM II hydrology is derived from historical monthly gauged flows for 1922-2003. This is the source data for monthly flow variability. DAYFLOW provides a database of daily historical Delta inflows from WY 1956 to present. This database is aligned with the current Delta infrastructure setting. Despite including the historical operational responses to various regulatory regimes existed over this period, in most winter and spring periods the reservoir operations and releases are governed by the inflows to the reservoirs.

Daily patterns from DAYFLOW used directly for mapping CALSIM II flows for water years 1956 to 2003. For water years 1922 to 1955 with missing daily flows, daily patterns are selected

from water years 1956 to 2003 based on similar total annual unimpaired Delta inflow. The daily pattern for the water year with missing daily flows is assumed to be the same as the daily pattern of the identified water year. Correlation among the various hydrologic basins is preserved by selecting same pattern year for all rivers flowing into the Delta, for a given year in the 1922-1955 period. Table A-1 lists the selected pattern years for the water years 1922 to 1955 along with the total unimpaired annual Delta inflow.

Thus, for each month in the 82-year CALSIM II simulation period, the monthly flow is mapped onto a daily pattern for computation of spills over the Fremont Weir and Sacramento Weir and for computing water available for diversions through the north Delta intakes. A preprocessed timeseries of daily volume fractions, based on Sacramento River at Freeport observed flows, is input into CALSIM II. The monthly volume as determined dynamically from CALSIM II then is multiplied by the fractions to arrive at a daily flow sequence. The calculation of daily spills and daily diversions are thus obtained. In the subsequent cycle (but still the same month), adjustments are made to the daily river flow upstream of the Sacramento Weir and the north Delta intakes to account for differences between the monthly flows assumed in the first cycle and the daily flows calculated in subsequent cycles. For example, if no spill over Fremont was simulated using a monthly flow, but when applying a daily pattern spill does occur, then the River flow at the Sacramento Weir is reduced by this amount. In this fashion, daily balance and monthly balance is preserved while adding more realism to the operation of these facilities.

TABLE A-1
Identified "Pattern" Water Year for the Water Years 1922 to 1955 with Missing Daily Historical Flows

Water Year	Total Annual Unimpaired Delta Inflow (TAF)	Selected "Pattern" Water Year	Total Annual Unimpaired Delta Inflow (TAF)
1922	32,975	1975	31,884
1923	23,799	2002	23,760
1924	8,174	1977	6,801
1925	26,893	1962	25,211
1926	18,534	1959	17,967
1927	38,636	1984	38,188
1928	26,363	1962	25,211
1929	12,899	1994	12,456
1930	20,326	1972	19,863
1931	8,734	1977	6,801
1932	24,179	2002	23,760
1933	14,126	1988	14,019
1934	12,895	1994	12,456
1935	28,486	2003	28,228
1936	30,698	2003	28,228
1937	25,448	1962	25,211
1938	56,949	1998	56,482
1939	12,743	1994	12,456
1940	37,185	1963	36,724
1941	46,746	1986	46,602
1942	42,301	1980	41,246
1943	36,870	1963	36,724
1944	17,158	1981	17,131
1945	26,757	1962	25,211
1946	28,823	2003	28,228
1947	16,206	2001	15,460
1948	23,741	1979	22,973

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TABLE A-1
Identified "Pattern" Water Year for the Water Years 1922 to 1955 with Missing Daily Historical Flows

Water Year	Total Annual Unimpaired Delta Inflow (TAF)	Selected "Pattern" Water Year	Total Annual Unimpaired Delta Inflow (TAF)
1949	19,176	1960	19,143
1950	23,272	1979	22,973
1951	39,110	1984	38,188
1952	49,270	1986	46,602
1953	30,155	2003	28,228
1954	26,563	1962	25,211
1955	17,235	1981	17,131

Fremont Weir Operations

All the Alternatives, except for Existing Conditions and No Action Alternative, include the measure for modifying the current Fremont Weir by notching it to allow for more frequent inundation in the Yolo Bypass. Details of the Fremont Weir and Yolo Bypass Hydraulics are described in Section D. The HEC-RAS modeling included in that section provides modified rating curves of the Fremont Weir for use in CALSIM II. CALSIM II simply includes two sets of rating curves, one with the "notch" and one without the notch. Input tables allow specification of when the notch is assumed to be operated. The amount of spill over the Fremont Weir or the notch is computed using the daily patterned Sacramento River flow at Verona and the rating curves included in the model.

North Delta Diversion Operations

Several of the Alternatives include new intakes (1 to 5 intakes depending on the Alternative) on Sacramento River upstream of Sutter Slough, in the north Delta. Each intake is proposed to have 3,000 cfs maximum pumping capacity. It is also proposed that the intakes will be screened using positive barrier fish screens to eliminate entrainment at the pumps. Water diverted at the five intakes is conveyed to a new forebay in the south Delta via a new isolated conveyance facility capable of conveying up to a maximum flow of 15,000 cfs (the conveyance capacity depends on the Alternative). Detailed assumptions for each Alternative are provided in Section B.

The BDCP proposes bypass (in-river) rules, which govern the amount of water required to remain in the river before any diversion can occur. Bypass rules are designed with the intent to avoid increased upstream tidal transport from downstream channels, to maintain flow supporting the migration of the salmonid and transport of pelagic species to regions of suitable habitat, to preserve shape of the natural hydrograph which may act as cue to important biological functions, to lower potential for increased tidal reversals that may occur because of the reduced net flow in the river and to provide flows to minimize predation effects downstream. The bypass rules include three important components:

- An initial pulse protection during the Nov – Jan period,
- A post-pulse operations that permit a percentage of river flow above a certain threshold to be diverted (and transitioning from Level I to Level II to Level III), and
- Consideration of a constant low level pumping of up to 300 cfs at each intake depending on the flow in the Sacramento River during the Dec – Jun period.

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The bypass rules are simulated in CALSIM II using daily mapped Sacramento River flows as described above to determine the maximum potential diversion that can occur in the north Delta for each day. The simulation identifies which of the three criteria is governing, based on antecedent daily flows and season. An example of the north Delta flows and diversion is illustrated in Figure A-8. As can be seen in this figure, bypass rules begin at Level I in October until the Sacramento River pulse flow develops. During the pulse flow, the constant low level pumping (Level 0) is permitted, but is limited to a certain percentage of river flow. After longer periods of high bypass flows, the bypass flow requirements moves to Level II and eventually Level III which permit greater potential diversion. CALSIM II uses the monthly average of this daily potential diversion as one of the constraints in determining the final monthly north Delta diversion.

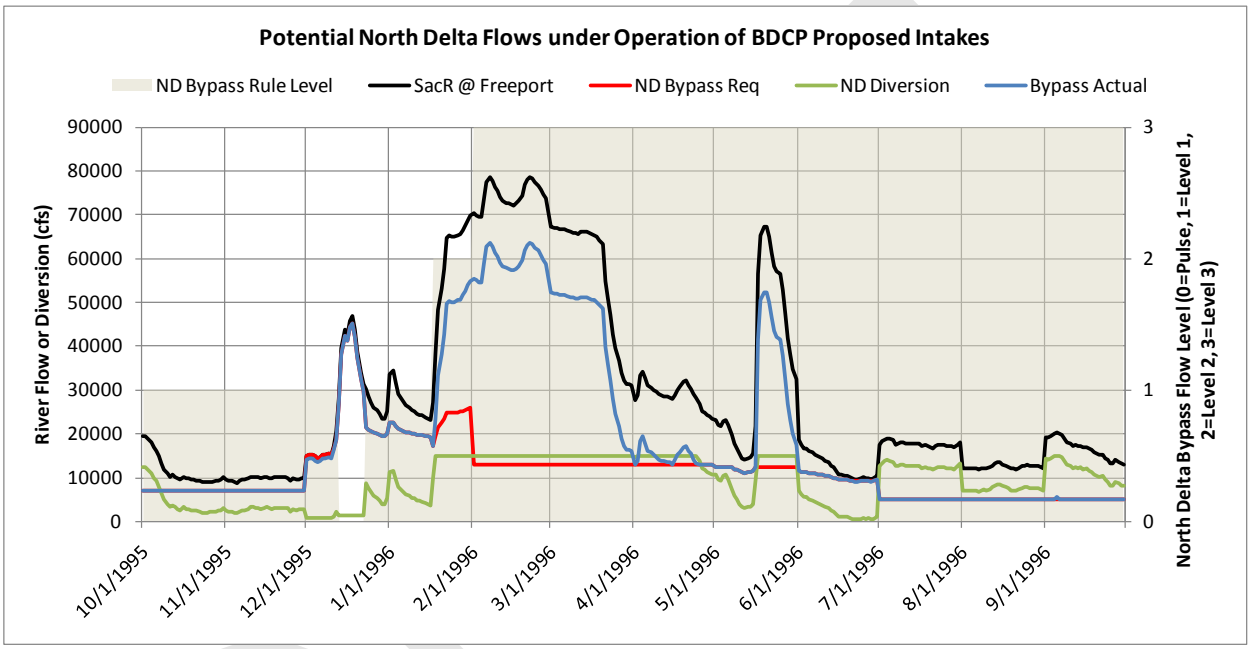

Figure A-8: Example year daily patterns and operation of the north Delta intakes. Note: the grey shading indicates the active bypass rule (0=pulse/low level pumping, 1=level I, 2=level II, and 3=level III).

ANN Retraining

ANNs are used for flow-salinity relationships in CALSIM II. They are trained on DSM2 outputs and therefore, emulate DSM2 results. ANN requires retraining whenever the flow – salinity relationship in the Delta changes. As mentioned earlier, BDCP analysis assumes different tidal marsh restoration acreages at NT, ELT and LLT phases and 15cm and 45cm sea level rise at ELT and LLT, respectively. Each combination of restoration and sea level condition results in a different flow – salinity relationship in the Delta and therefore require a new ANN. New ANNs have been developed by DWR for each new proposed combination of tidal marsh and sea level. ANN retraining process is described in Section A.5.3.

Incorporation of Climate Change

Climate and sea level change are incorporated into the CALSIM II model in two ways. As described in Section A.8., changes in runoff and streamflow are simulated through VIC modeling under representative climate scenarios. These simulated changes in runoff are applied to the CALSIM II inflows as a fractional change from the observed inflow patterns (simulated future runoff divided by historical runoff). These fraction changes are first applied for every month of the 82-year period consistent with the VIC simulated patterns. A second order correction is then applied to ensure that the annual shifts in runoff at each location are consistent with that generated from the VIC modeling. A spreadsheet tool has been prepared to process this information and generate adjusted inflow time series records for CALSIM II. Once the changes in flows have been resolved, water year types and other hydrologic indices that govern water operations or compliance are adjusted to be consistent with the new hydrologic regime.

Sea level rise and restored tidal marsh effects on the flow-salinity response is incorporated in the new ANNs. CALSIM II model simulations require the modeler to select which hydrology should be paired with which sea level/tidal marsh ANN.

The following input parameters are adjusted in CALSIM II to incorporate the effects of climate change:

- Inflow time series records for all major and minor streams in the Central Valley
- Sacramento and San Joaquin Valley water year types
- Runoff forecasts used reservoir operations and allocation decisions
- Delta water temperature as used in triggering biological opinion smelt criteria
- Modified ANNs to reflect the flow-salinity response under sea level change scenarios

The CALSIM II simulations do not consider future climate change adaptation which may manage the SWP and CVP system in a different manner than today to reduce climate impacts. For example, future changes in reservoir flood control reservation to better accommodate a seasonally changing hydrograph may be considered under future programs, but are not considered under the BDCP. Thus, the CALSIM II BDCP results represent the risks to operations, water users, and the environment in the absence of dynamic adaptation for climate change.

A.3.4. Output Parameters

The Hydrology and System Operations models produce the following key parameters on a monthly time-step:

- River flows and diversions
- Reservoir storage
- Delta flows and exports
- Delta inflow and outflow

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- Deliveries to project and non-project users
- Controls on project operations

Some operations have been informed by the daily variability included in the CALSIM II model for the BDCP, and where appropriate, these results are presented. However, it should be noted that CALSIM II remains a monthly model. The daily variability in the CALSIM II model to better represent certain operational aspects, but the monthly results are utilized for water balance.

A.3.5. Linkages to Other Physical Models

The Hydrology and System Operations models generally require input assumptions relating to hydrology, demands, regulations, and flow-salinity responses. DWR and USBR have prepared hydrologic inputs and demand assumptions for various levels of development (future land use and development assumptions) based on historical hydroclimatic conditions. Regulations and associated operations are translated into operational requirements. The flow-salinity ANN, representing appropriate Delta configuration, is embedded into the system operations model. The river flows and Delta exports from the CALSIM II model are used as input to the Delta Hydrodynamics and Water Quality models and reservoir storage and releases are used as input to the River and Reservoir Temperature models.

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A.4. Reservoir and River Temperature

The CVP and SWP are required to operate the reservoirs and releases such that specific temperature compliance objectives are met downstream in the rivers, to protect habitat for the anadramous fish. Models are necessary to study the impacts of operational changes on the river and reservoir temperatures. Several models are available to study the impacts to the water temperatures on various river systems in the Central Valley. These models in general are capable of simulating mean monthly and mean daily downstream temperatures for long-term operational scenarios taking into consideration the selective withdrawal capabilities at the reservoirs. 2008 OCAP BA Technical Appendix H (USBR, 2008c) provides a good summary of the temperature modeling tools used in this section.

This section briefly describes the tools used to model the reservoir and river temperatures as part of the BDCP physical modeling.

A.4.1. SRWQM

Sacramento River Water Quality Model (SRWQM) was developed by Reclamation to simulate temperature in the upstream CVP reservoirs and the upper Sacramento River. It was developed using integrated HEC-5 and HEC-5Q models. The HEC-5 component of SRWQM simulates daily flow operations in the upper Sacramento River. The HEC-5Q component of SRWQM simulates mean daily reservoir and river temperatures at Shasta, Trinity, Lewiston, Whiskeytown, Keswick and Black Butte Reservoirs and the Trinity River, Clear Creek, the upper Sacramento River from Shasta to Knights Landing, and Stony Creek based on the flow and meteorological parameters on a 6-hour time step. Figure A-9 shows the model schematic for HEC-5 component of the SRWQM. HEC-5Q is a cross-section based model and has a higher spatial resolution in comparison to the HEC-5 component of SRWQM. The HEC-5Q was customized to simulate the operations of the temperature control device at Shasta Dam.

SRWQM was successfully calibrated based on the observed temperatures in the reservoirs and the upper Sacramento River. More detailed description SRWQM and the calibration performance is included in the calibration report (RMA, 2003).

A.4.2. Reclamation Temperature Model

Reclamation Temperature Model includes reservoir and stream temperature models, which simulate monthly reservoir and stream temperatures used for evaluating the effects of CVP/SWP project operations on mean monthly water temperatures in the basin. The model simulates temperatures in seven major reservoirs (Trinity, Whiskeytown, Shasta, Oroville, Folsom, New Melones and Tulloch), four downstream regulating reservoirs (Lewiston, Keswick, Goodwin and Natoma), and five main river systems (Trinity, Sacramento, Feather, American and Stanislaus). The river component of the Reclamation Temperature model calculates temperature changes in the regulating reservoirs, below the main reservoirs. With regulating reservoir release temperature as the initial river temperature, the river model computes temperatures at several locations along the rivers. The calculation points for river temperatures generally coincide with tributary inflow locations. The model is one-dimensional in the longitudinal direction and assumes fully mixed river cross sections. The effect of tributary inflow on river temperature is computed by mass balance calculation. The river temperature

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calculations are based on regulating reservoir release temperatures, river flows, and climatic data.

A.4.3. Application of Temperature Models to Evaluate BDCP Alternatives

The temperature modeling for planning analysis is driven by the long term operations modeled using CALSIM II. The objective is to find temperature variability in the reservoirs and streams, given CVP/SWP operations, and compare between existing and assumed future scenarios. This section briefly describes the general temperature modeling approach used in a planning analysis and any changes to the approach as part of the BDCP.

SRWQM

SRWQM is designed for long-term planning simulation of temperature at key locations on the Sacramento River at a mean daily time step that captures diurnal fluctuations and is sensitive to fishery management objectives. The geographical scope of the model ranges from Shasta Dam and Trinity Dam to Knights Landing. Monthly flows, simulated by the CALSIM II model for an 82 year period (WY 1922-2003), are used as input to the SRWQM. Temporal downscaling is performed on the CALSIM II monthly average tributary flows to convert them to daily average flows for SRWQM input. Monthly average flows are converted to daily tributary inflows based on 1921 through 1994 daily historical record for the following aggregated inflows:

- Trinity River above Lewiston.
- Sacramento River above Keswick.
- Incremental inflow between Keswick and Bend Bridge (Seven day trailing average for inflows below Butte City).

Each of the total monthly inflows specified by CALSIM II is scaled proportional to one of these three historical records. Outflows and diversions are smoothed for a better transition at the end of the month without regard for reservoir volume constraints or downstream minimum flows. As flows are redistributed within the month, the minimum flow constraint at Keswick, Red Bluff and Knights Landing may be violated. In such cases, operation modifications are required for daily flow simulation to satisfy minimum flow requirements. A utility program is included in SRWQM to convert the monthly CALSIM II flows and releases into daily operations. More detailed description of SRWQM and the temporal downscaling process is included in calibration report (RMA, 2003). The boundary conditions required for simulating SRWQM planning run are listed in Table A-2.

Reclamation Temperature Models

The Reclamation temperature model suite is a monthly time-step model. It was applied to estimate temperatures in the Trinity, Feather, American, and Stanislaus River systems. Monthly flows, simulated by the CALSIM II model for an 82 year period (WY 1922-2003), are used as input to the model. Because of the CALSIM II model's complex structure, where applicable, flow arcs were combined at the appropriate temperature nodes to insure compatibility with the temperature model (see Table A-3). Monthly mean historical air temperatures for the 82-year period and other long-term average climatic data for Trinity, Shasta, Whiskeytown, Redding,

Red Bluff, Colusa, Marysville, Folsom, Sacramento, New Melones, and Stockton were obtained from National Weather Service records and used to represent climatic conditions for the four river systems.

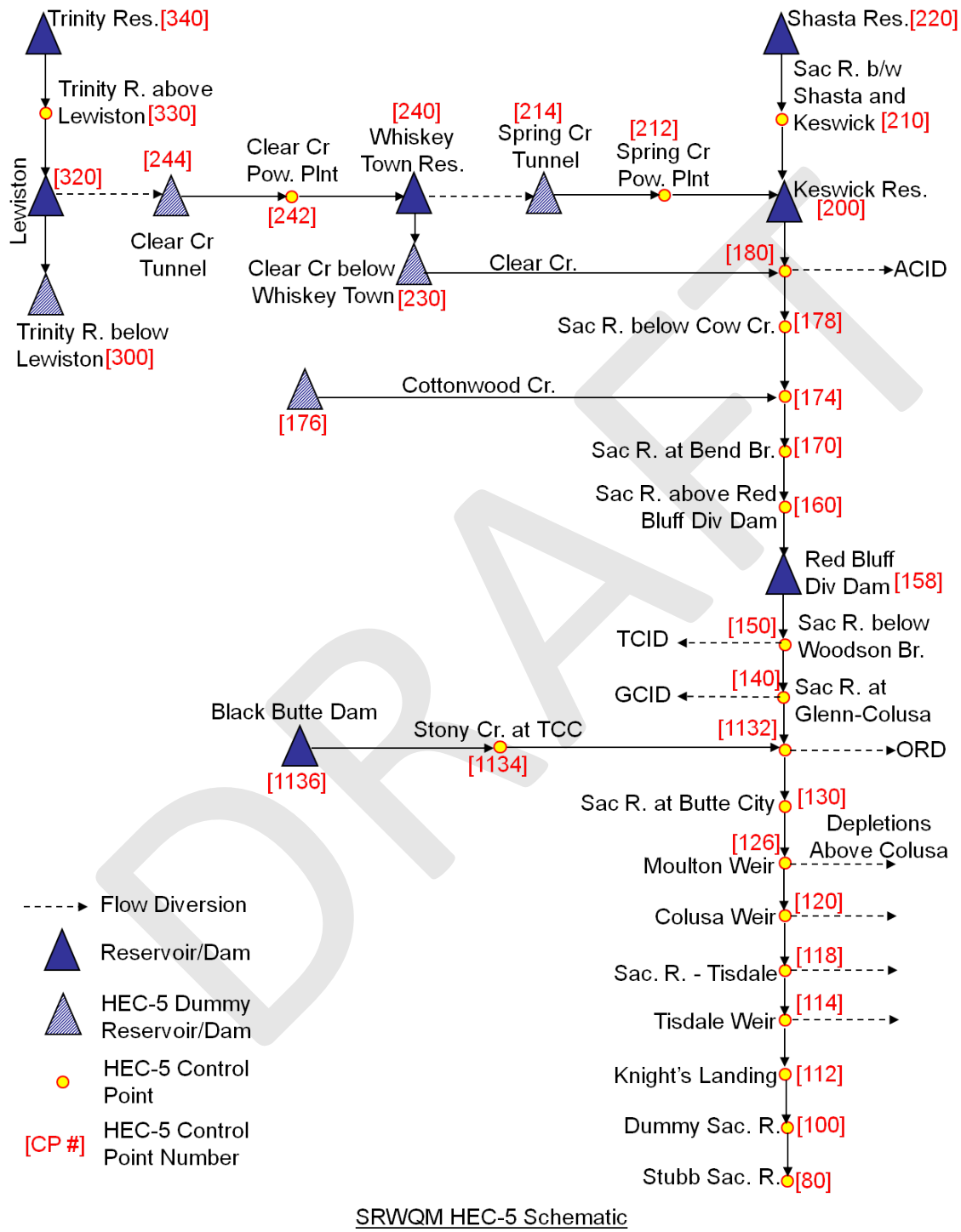

Figure A-9: SRWQM HEC-5 Model Schematic

A.4.4. Incorporating Climate Change Inputs

When simulating alternatives with climate change, some of the inputs to the temperature models are required to be modified. This section states the assumptions and approaches used for modifying meteorological and inflow temperatures in the temperature models.

SRWQM

SRWQM requires meteorological inputs specified in the form of equilibrium temperatures, exchange rates, shortwave radiation and wind speed. The exchange rates and equilibrium temperatures are computed from hourly observed data at Gerber gauging station. Considering the uncertainties associated with climate change impacts, it was assumed that the equilibrium temperature inputs derived from observed data would be modified by the change in daily average air temperature in the climate change scenarios.

The inflow temperatures in SRWQM are specified as seasonal curve fit values with diurnal variations superimposed as a function of heat exchange parameters. The seasonal temperature values are derived based on the observed flows and temperatures for each inflow. SRWQM superimposes diurnal variations on the seasonal values specified using the heat exchange parameter inputs. The diurnal variations are superimposed by adjusting the equilibrium temperature to reflect the inflow location environment and scaling it based on the heat exchange rate scaling factor and the weighting factor for emphasis on the seasonal values specified (RMA, 1998). In this fashion, any changes in the equilibrium temperature are translated to the inflow temperatures in the SRWQM. Therefore, for the climate change scenarios, the equilibrium temperatures were adjusted for the projected change in temperature, and these influence the inflow temperature, but independent inflow temperature inputs were not changed.

Reclamation Temperature Models

The Reclamation temperature models require mean monthly meteorological inputs of air and equilibrium temperature, and heat exchange rates. The heat exchange rates and equilibrium temperatures are computed from the mean monthly air temperature data and long-term estimates of solar radiation, relative humidity, wind speed, cloud cover, solar reflectivity and river shading. Considering the uncertainties associated with climate change impacts, it was assumed that the equilibrium temperature and heat exchange rate inputs would be modified by the change in mean monthly air temperature in the climate change scenarios.

Reservoir inflow temperatures were derived from the available record of observed data and averaged by month. The mean monthly inflow temperatures are then repeated for each study year. The inflow temperatures were further modified based on the computed change in mean annual air temperature, by climate-change scenario.

A.4.5. Output Parameters

SRWQM results in daily averaged temperature results. The Reclamation Temperature Models provide monthly averaged results. In general, the following outputs are generated from the temperature models:

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- Reservoir temperature thermocline used to compute cold water pool volume in the reservoirs
- River temperature at locations along the streams

TABLE A-2
Inputs Required for SRWQM Planning Analysis

Input Type	Location	Description of the Input
Initial Storage	Trinity Lake	End-of-day storage to initialize reservoir storage condition at the start of the SRWQM run
	Whiskeytown Lake	
	Shasta Lake	
	Black Butte Reservoir	
Reservoir Inflows	Trinity Lake	Daily net inflow to reservoirs computed based on the reservoir inflow and the evaporation
	Lewiston Reservoir	
	Whiskeytown Lake	
	Shasta Lake	
	Black Butte Reservoir	
Tributary Inflows	Cottonwood Creek	Local unregulated tributary inflows
	Thomes Creek	
	Colusa Drain	
Distributed flows	Bend Bridge	Net inflows, accretions and depletions along the Sacramento River distributed along the River
	Lower River	
Outflow	Trinity Lake	Daily reservoir release specification
	Whiskeytown Lake	
	Shasta Lake	
	Black Butte Reservoir	
Diversions	Clear Creek Tunnel from Lewiston Reservoir	Inter-basin transfer reservoir releases
	Spring Creek Tunnel from Whiskeytown Lake	
	Anderson Cottonwood Irrigation District Canal	Lumped diversions along various reach of the River specified at point locations
	Tehama Colusa Canal	

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TABLE A-2
Inputs Required for SRWQM Planning Analysis

Input Type	Location	Description of the Input
	Glenn Colusa Canal	
	Miscellaneous Diversions above Ord	
	West Banks Diversions	
	Diversions near Colusa Weir	
	Lower River Diversions	
Meteorological Inputs including Equilibrium Temperature, Exchange Rate, Shortwave Radiation and Wind Speed	Entire Spatial Domain	Meteorological inputs on 6-hour time step derived primarily from Gerber gauging station. Calibration report provides more details (RMA, 2003). This dataset remains unchanged as long as the climate conditions are the same across the alternatives.
Inflow Temperatures	Reservoir and tributary inflows included in the model	Seasonal temperatures based on historical flows and temperatures. These inputs remain unchanged for all alternatives
Target Temperatures	Shasta Lake Tail Water	Seasonal temperature targets specified based on the end-of-May Shasta storage conditions

TABLE A-3
Reclamation Temperature Model Nodes

River or Creek System	Location
Trinity River	Lewiston Dam
	Douglas City
	North Fork
Feather River	Oroville Dam
	Fish Barrier Dam
	Upstream of Thermalito Afterbay
	Thermalito Afterbay Release
	Downstream of Thermalito Afterbay
	Gridley
	Honcut Creek
	Yuba River

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TABLE A-3
Reclamation Temperature Model Nodes

River or Creek System	Location
	Bear River
	Nicolaus
	Nelson Slough
	Confluence
American River	Folsom Dam
	Nimbus Dam
	Sunrise Bridge
	Cordova Park
	Arden Rapids
	Watt Avenue Bridge
	American River Filtration Plant
	H Street
	16th Street
	Confluence
Stanislaus River	New Melones Dam
	Tulloch Dam
	Goodwin Dam
	Knights Ferry
	Orange Blossom
	Oakdale
	Riverbank
	McHenry Bridge
	Ripon
	Confluence

A.4.6. Use of Model Results

Since the temperature models are driven by the operations simulated in CALSIM II on a monthly time step, typically the temperature results are presented on a monthly time step from both SRWQM and the Reclamation Temperature Models. Monthly flows and temperatures are unlikely to address the daily variability in the river temperatures, but reflect changes in the mean. The daily variability, around a changed mean, could be added to the monthly temperature results by scaling the historical daily temperature patterns to reflect the monthly means. However, this approach of incorporating daily variability does not account for the uncertainty associated with the daily flow conditions which are not included in the boundary

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flows used by the temperature models. Thus, while the models generate daily results they need to be interpreted with the understanding that the monthly changes are the most appropriate use of the modeling results.

A.4.7. Modeling Limitations

The Reclamation temperature models operate on a monthly time-step. Mean monthly flows and temperatures do not define daily variations that could occur in the rivers due to dynamic flow and climatic conditions. It is important to note that even though SRWQM runs on a daily time step, it adheres to the CALSIM II in terms of the reservoir releases and other operations. Neither SRWQM nor the Reclamation temperature models alter operations to meet a temperature requirement downstream in the River. There is no feedback to CALSIM II to alter the operations, either. Using the daily results from SRWQM to check the compliance includes some uncertainty. Both SRWQM and the Reclamation temperature models perform selective temperature withdrawal based on the tail water temperature target and this may or may not meet the temperature requirement downstream in the River.

A.4.8. Linkages to Other Physical Models

The Reservoir and River Temperature models require inputs for representative meteorological conditions, reservoir storage, reservoir release rates, tributary flows, and channel morphology. The output from the Reservoir and River Temperature models are sometimes used to evaluate performance of satisfying temperature requirements and refine the simulated project operation in CALSIM II. The temperature outputs are commonly used in the biological assessments of salmonid mortality.

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A.5. Delta Hydrodynamics and Water Quality

Hydrodynamics and water quality modeling is essential to understand the impact of proposed modifications to the morphology of the Delta and the operations of the CVP and SWP. Changes to the configuration of the Delta, restoration of tidal marsh, and project operations will influence the hydrodynamics and water quality conditions in the Delta. The analysis and understanding of the hydrodynamics and water quality changes as a result of these complex changes are critical in understanding the impacts to habitat, species and water users that depend on the Delta.

Large scale tidal marsh restoration and a north Delta diversion are two main components of the BDCP that can significantly alter the hydrodynamics in the Delta, along with the external forcing, sea level rise.

This document describes in detail the methodology used for simulating Delta hydrodynamics and water quality for evaluating the alternatives. It discusses the primary tool (DSM2) used in this process and any improvements to it briefly. Any additional detail is included in Section D and appropriate references are provided in here. The portions of the modeling that were performed by elsewhere are only described briefly in this document with appropriate references included.

A.5.1. Overview of Hydrodynamics and Water Quality Modeling Approach

Some of the Alternatives assume changes to the existing Delta morphology through the restoration of large acreages of tidal marshes in the Delta. Also, changes in sea level are assumed in the analysis of the future scenarios. These changes result in modified hydrodynamics and salinity transport in the Sacramento – San Joaquin Delta.

There are several tools available to simulate hydrodynamics and water quality in the Delta. Some tools simulate detailed processes, however are computationally intensive and have long runtimes. Other tools approximate certain processes and have short runtimes, while only compromising slightly on the accuracy of the results. For a planning analysis it is ideal to understand the resulting changes over several years such that it covers a range of hydrologic conditions. So, a tool which can simulate the changed hydrodynamics and water quality in the Delta accurately and that has short runtimes is desired. Delta Simulation Model (DSM2), a one-dimensional hydrodynamics and water quality model serves this purpose.

DSM2 has a limited ability to simulate two-dimensional features such as tidal marshes and three-dimensional processes such as gravitational circulation which is known to increase with sea level rise in the estuaries. Therefore, it is imperative that DSM2 be recalibrated or corroborated based on a dataset that accurately represents the conditions in the Delta under restoration and sea level rise. Since the proposed conditions are hypothetical, the best available approach to estimate the Delta hydrodynamics would be to simulate higher dimensional models which can resolve the two- and three-dimensional processes well. These models would generate the data sets needed to corroborate or recalibrate DSM2 under the proposed conditions so that it can simulate the hydrodynamics and salinity transport with reasonable accuracy.

Figure A-10 shows a schematic of how the hydrodynamics and water quality modeling is formulated for BDCP. UnTRIM Bay-Delta Model (MacWilliams et al., 2009), a three-dimensional hydrodynamics and water quality model was used to simulate the sea level rise

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effects on hydrodynamics and salinity transport under the historical operations in the Delta. RMA Bay-Delta Model (RMA, 2005), a two-dimensional hydrodynamics and water quality model was used to simulate tidal marsh restoration effects with and without sea level rise on hydrodynamics and salinity transport under the historic operations. The results from the UnTRIM model were used to corroborate RMA and DSM2 models so that they simulate the effect of sea level rise accurately. The results from the RMA model were used to corroborate DSM2 so that it can simulate the effect of tidal marsh restoration with and without sea level rise accurately.

The corroborated DSM2 was used to simulate hydrodynamics and water quality in the Delta by integrating the tidal marsh restoration and sea level rise effects over a 16-year period (WY 1976 – 1991), using the hydrological inputs and exports determined by CALSIM II under the projected operations. It was also used to retrain ANNs that can emulate modified flow-salinity relationship.

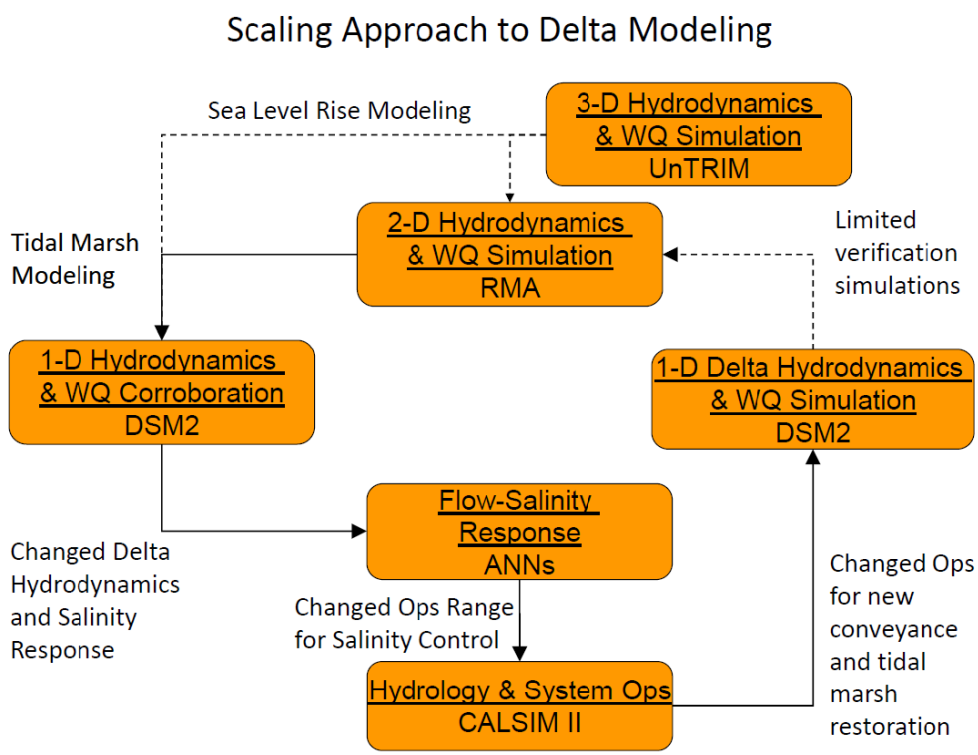

Figure A-10: Hydrodynamics and Water Quality Modeling Approach used in the BDCP

A.5.2. Delta Simulation Model (DSM2)

DSM2 is a one-dimensional hydrodynamics, water quality and particle tracking simulation model used to simulate hydrodynamics, water quality, and particle tracking in the Sacramento-San Joaquin Delta (Anderson and Mierzwa, 2002). DSM2 represents the best available planning model for Delta tidal hydraulics and salinity modeling. It is appropriate for describing the existing conditions in the Delta, as well as performing simulations for the assessment of incremental environmental impacts caused by future facilities and operations. The DSM2 model has three separate components: HYDRO, QUAL, and PTM. HYDRO simulates one-dimensional hydrodynamics including flows, velocities, depth, and water surface elevations. HYDRO

provides the flow input for QUAL and PTM. QUAL simulates one-dimensional fate and transport of conservative and non-conservative water quality constituents given a flow field simulated by HYDRO. PTM simulates pseudo 3-D transport of neutrally buoyant particles based on the flow field simulated by HYDRO.

DSM2 v8.0.4 was used in modeling of the BDCP Existing Conditions, No Action Alternative and the other Alternatives. The v8 of the DSM2 includes several enhancements compared to the v6 such as improved data management, increased speed and robustness, ability to simulate gates with multiple structures and the ability to specify Operating Rules in the HYDRO module. The Operating Rules form a powerful tool which triggers changes in gate operations or source/sink flow boundaries while model is running, based on the current value of a state variable (flow, stage or velocity), pre-specified timeseries or the simulation timestep.

DSM2 hydrodynamics and salinity (EC) were initially calibrated in 1997(DWR, 1997). In 2000, a group of agencies, water users, and stakeholders recalibrated and validated DSM2 in an open process resulting in a model that could replicate the observed data more closely than the 1997 version (DSM2PWT, 2001). In 2009, CH2M HILL performed a calibration and validation of DSM2 by including the flooded Liberty Island in the DSM2 grid, which allowed for an improved simulation of tidal hydraulics and EC transport in DSM2 (CH2M HILL, 2009). The model used for evaluating the BDCP scenarios was based on this latest calibration.

Simulation of Dissolved Organic Carbon (DOC) transport in DSM2 was successfully validated in 2001 by DWR (Pandey, 2001). The temperature and Dissolved Oxygen calibration was initially performed in 2003 by DWR (Rajbhandari, 2003). Recent effort by RMA in 2009 allowed for improved calibration of temperature, DO and the nutrients transport in DSM2.

DSM2-HYDRO

The HYDRO module is a one-dimensional, implicit, unsteady, open channel flow model that DWR developed from FOURPT, a four-point finite difference model originally developed by the USGS in Reston, Virginia. DWR adapted the model to the Delta by revising the input-output system, including open water elements, and incorporating water project facilities, such as gates, barriers, and the Clifton Court Forebay. HYDRO simulates water surface elevations, velocities and flows in the Delta channels (Nader-Tehrani, 1998). HYDRO provides the flow input necessary for QUAL and PTM modules.

The HYDRO module solves the continuity and momentum equations fully implicitly. These partial differential equations are solved using a finite difference scheme requiring four points of computation. The equations are integrated in time and space, which leads to a solution of stage and flow at the computational points. HYDRO enforces an “equal stage” boundary condition for all the channels connected to a junction. The model can handle both irregular cross-sections derived from the bathymetric surveys and trapezoidal cross-sections. Even though, the model formulation includes a baroclinic term, the density is held constant, generally, in the HYDRO simulations.

HYDRO allows the simulation of hydraulic gates in the channels. A gate may have a number of associated hydraulic structures such as radial gates, flash boards, boat ramps etc., each of which may be operated independently to control flow. Gates can be placed either at the upstream or downstream end of a channel. Once the location of a gate is defined, the boundary condition for

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the gated channel is modified from "equal stage" to "known flow," with the calculated flow. The gates can be opened or closed in one or both directions by specifying a coefficient of zero or one.

Reservoirs are used to represent open bodies of water that store flow. Reservoirs are treated as vertical walled tanks in DSM2, with a known surface area and bottom elevation and are considered instantly well-mixed. The flow interaction between the open water area and one or more of the connecting channels is determined using the general orifice formula. The flow in and out of the reservoir is controlled using the flow coefficient in the orifice equation, which can be different in each direction. DSM2 does not allow the cross-sectional area of the inlet to vary with the water level.

DSM2v8 includes a new feature called "operating rules" using which the gate operations or the flow boundaries can be modified dynamically when the model is running based on the current value of a state variable (flow, stage or velocity). The change can also be triggered based on a timeseries that's not currently simulated in the model (e.g. daily averaged EC) or based on the current timestep of the simulation (e.g. a change can occur at the end of the day or end of the season). The operating rules include many functions which allow derivation of the quantities to be used as trigger, from the model data or outside timeseries data. Operating rules allow a change or an action to occur when the trigger value changes from false to true.

DSM2-QUAL

The QUAL module is a one-dimensional water quality transport model that DWR adapted from the Branched Lagrangian Transport Model originally developed by the USGS in Reston, Virginia. DWR added many enhancements to the QUAL module, such as open water areas and gates. A Lagrangian feature in the formulation eliminates the numerical dispersion that is inherently in other segmented formulations, although the tidal dispersion coefficients must still be specified. QUAL simulates fate and transport of conservative and non-conservative water quality constituents given a flow field simulated by HYDRO. It can calculate mass transport processes for conservative and non-conservative constituents including salts, water temperature, nutrients, dissolved oxygen, and trihalomethane formation potential.

The main processes contributing to the fate and transport of the constituents include flow dependent advection and tidal dispersion in the longitudinal direction. Mass balance equations are solved for all quality constituents in each parcel of water using the tidal flows and volumes calculated by the HYDRO module. Additional information and the equations used are specified in the 19th annual progress report by DWR (Rajbhandari, 1998).

The QUAL module is also used to simulate source water finger printing which allows determining the relative contributions of water sources to the volume at any specified location. It is also used to simulate constituent finger printing which determines the relative contributions of conservative constituent sources to the concentration at any specified location. For fingerprinting studies, six main sources are typically tracked: Sacramento River, San Joaquin River, Martinez, eastside streams (Mokelumne, Cosumnes and Calaveras combined), agricultural drains (all combined), and Yolo Bypass. For source water fingerprinting a tracer with constant concentration is assumed for each source tracked, while keeping the concentrations at other inflows as zero. For constituent (e.g., EC) fingerprinting analysis, the

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concentrations of the desired constituent is specified at each tracked source, while keeping the concentrations at other inflows as zero (Anderson, 2003).

DSM2 Input Requirements

DSM2 requires input assumptions relating to physical description of the system (e.g. Delta channel, marsh, and island configuration), description of flow control structures such as gates, initial estimates for stage, flow and EC throughout the Delta, and time-varying input for all boundary river flows and exports, tidal boundary conditions, gate operations, and constituent concentrations at each inflow. Figure A-11 illustrates the hydrodynamic and water quality boundary conditions required in DSM2. For long-term planning simulations, output from the CALSIM II model generally provides the necessary input for the river flows and exports.

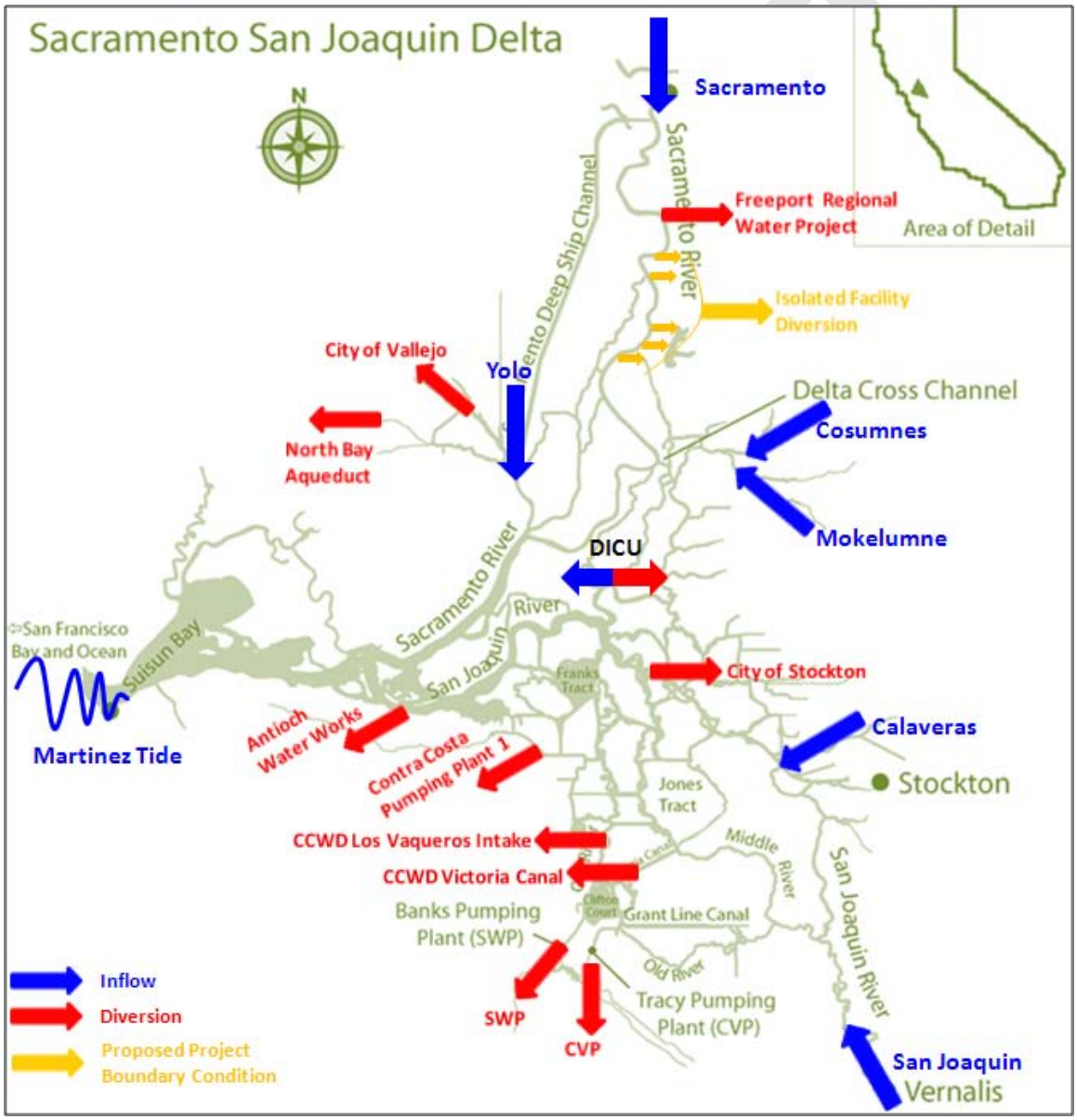

Figure A-11: Hydrodynamic and Water Quality Boundary Conditions in DSM2

For long-term planning simulations, output from the CALSIM II model generally provides the necessary input for the river flows and exports. Assumptions relating to Delta configuration and gate operations are directly input into the hydrodynamic models. Adjusted astronomical tide (Ateljevich, 2001a) normalized for sea level rise (Ateljevich and Yu, 2007) is forced at Martinez boundary. Constituent concentrations are specified at the inflow boundaries, which are either estimated from historical information or CALSIM II results. EC boundary condition at Vernalis location is derived from the CALSIM II results. Martinez EC boundary condition is derived based on the simulated net Delta outflow from CALSIM II and using a modified G-model (Atljevich, 2001b).

The major hydrodynamic boundary conditions are listed in Table A-4 and the locations at which constituent concentrations are specified for the water quality model are listed in Table A-5.

TABLE A-4
DSM2 HYDRO Boundary Conditions

Boundary Condition	Location/Control Structure	Typical Temporal Resolution
Tide	Martinez	15min
Delta Inflows	Sacramento River at Freeport	1day
	San Joaquin River at Vernalis	1day
	Eastside Streams (Mokelumne and Cosumnes Rivers)	1day
	Calaveras River	1day
	Yolo Bypass	1day
Delta Exports/Diversions	Banks Pumping Plant (SWP)	1day
	Jones Pumping Plant (CVP)	1day
	Contra Costa Water District Diversions at Rock Slough, Old River at Highway 4 and Victoria Canal	1day
	North Bay Aqueduct	1day
	City of Vallejo	1day
	Antioch Water Works	1day
	Freeport Regional Water Project	1day
	City of Stockton	1day
	Isolated Facility Diversion	1day
Delta Island Consumptive Use	Diversion	1mon
	Seepage	1mon

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TABLE A-4
DSM2 HYDRO Boundary Conditions

Boundary Condition	Location/Control Structure	Typical Temporal Resolution
	Drainage	1mon
Gate Operations	Delta Cross Channel	Irregular Timeseries
	South Delta Temporary Barriers	dynamically operated on 15min
	Montezuma Salinity Control Gate	dynamically operated on 15min

TABLE A-5
DSM2 QUAL Boundary Conditions Typically used in a Salinity Simulation

Boundary Condition	Location/Control Structure	Typical Temporal Resolution
Ocean Salinity	Martinez	15min
Delta Inflows	Sacramento River at Freeport	Constant
	San Joaquin River at Vernalis	1mon
	Eastside Streams (Mokelumne and Cosumnes Rivers)	Constant
	Calaveras River	Constant
	Yolo Bypass	Constant
Delta Island Consumptive Use	Drainage	1mon (repeated each year)

Notes: For other water quality constituents, concentrations are required at the same locations

A.5.3. Application of DSM2 to Evaluate BDCP Alternatives

Several long-term planning analyses used DSM2 to evaluate Delta hydrodynamics and water quality, in the past. In those studies, DSM2 was run for a 16-year period from WY1976 to WY1991, on a 15-min timestep. Typically the inputs needed for DSM2 – inflows, exports, and Delta Cross Channel (DCC) gate operations were provided by the 82-year CALSIM II simulations. The tidal boundary condition at Martinez was provided by an adjusted astronomical tide (Ateljevich and Yu, 2007). Monthly Delta channel depletions (i.e., diversions, seepage and drainage) were estimated using DWR's Delta Island Consumptive Use (DICU) model (Mahadevan, 1995).

CALSIM II provides monthly inflows and exports in the Delta. Traditionally, the Sacramento and San Joaquin River inflows are disaggregated to a daily time step for use in DSM2 either by

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applying rational histosplines, or by assuming that the monthly average flow as constant over the whole month. The splines allow a smooth transition between the months. The smoothing reduces sharp transitions at the start of the month, but still results in constant flows for most of the month. Other inflows, exports and diversions were assumed to be constant over the month.

Delta Cross Channel gate operation input in DSM2 is based on CALSIM II output. For each month, DSM2 assumes the DCC gates are open for the "number of the days open" simulated in CALSIM II, from the start of the month.

The operation of the south Delta Temporary Barriers, if included in the model is determined dynamically in using the operating rules feature in DSM2. These operations generally depend on the season, San Joaquin River flow at Vernalis and tidal condition in the south Delta. Similarly, the Montezuma Slough Salinity Control Gate operations are determined using an operating rule that sets the operations based on the season, Martinez salinity and tidal condition in the Montezuma Slough.

For salinity, EC at Martinez is estimated using the G-model on a 15-min timestep, based on the Delta outflow simulated in CALSIM II and the pure astronomical tide at Martinez (Ateljevich, 2001a). The monthly averaged EC for the San Joaquin River at Vernalis estimated in CALSIM II for the 82-year period is used in DSM2. For other river flows, which have low salinity, constant values are assumed. Monthly average values of the EC associated with Delta agricultural drainage and return flows was estimated for three regions in the Delta based on observed data identifying the seasonal trend. These values are repeated for each year of the simulation.

For BDCP, several enhancements were incorporated in the planning analysis approach traditionally used for DSM2. Some of the changes were to address the assumptions for BDCP while the others are improvements which make the DSM2 planning simulations more realistic.

The changes that are based on the BDCP assumptions include modifications to DSM2 to capture the effect of sea level rise, tidal marsh restoration with and without sea level rise, and north Delta diversion intakes. The DSM2 models incorporating above changes were used in developing new ANNs for CALSIM II.

The other enhancement is with regard to the flow boundary conditions used in DSM2. As described above, traditional approach does not represent the variability that would exist in the Delta inflows within a month. Since CALSIM II, from which the boundary flows are derived is a monthly time step model, a new approach was developed to incorporate daily variability in the DSM2 boundary flows using the monthly results from CALSIM II.

The following sections describe in detail various enhancements and changes made to the DSM2 hydrodynamics, salinity and nutrient modeling methods as part of the BDCP analyses.

Changes to the DSM2 Grid

DSM2 model grid from the 2009 recalibration (CH2M HILL, 2009) was further modified in the north Delta to locate the DSM2 nodes at the proposed north Delta diversion intake locations as agreed on January 29th BDCP Steering Committee meeting. Two new nodes and two new channels are added to the grid and several existing nodes were relocated and channel lengths were modified in the reach upstream of Delta Cross Channel. Figure A-12 shows the grid used

in the baseline models for BDCP. The DSM2 grid includes several other changes related to the north Delta diversion intakes and the tidal marsh restoration.

Incorporation of Daily Hydrologic Inputs to DSM2

DSM2 is simulated on a 15-minute time step to address the changing tidal dynamics of the Delta system. However, the boundary flows are typically provided from monthly CALSIM II results. In all previous planning-level evaluations, the DSM2 boundary flow inputs were applied on a daily time step but used constant flows equivalent to the monthly average CALSIM II flows except at month transitions.

As shown in Figures A-6 and A-7, Sacramento River flow at Freeport exhibits significant daily variability around the monthly mean in the winter and spring period in the most water year types. The winter-spring daily variability is deemed important to species of concern. In an effort to better represent the sub-monthly flow variability, particularly in early winter, a monthly-to-daily flow mapping technique is applied to the boundary flow inputs to DSM2. The daily mapping approach used in CALSIM II and DSM2 are consistent. The incorporation of daily mapping in CALSIM II is described in the Section A.3.3. A detailed description of the implementation of the daily variability in DSM2 boundary conditions is provided in Section D.

It is important to note that this daily mapping approach does not in any way represent the flows that would result from any operational responses on a daily time step. It is simply a technique to incorporate representative daily variability into the flows resulting from CALSIM II's monthly operational decisions.

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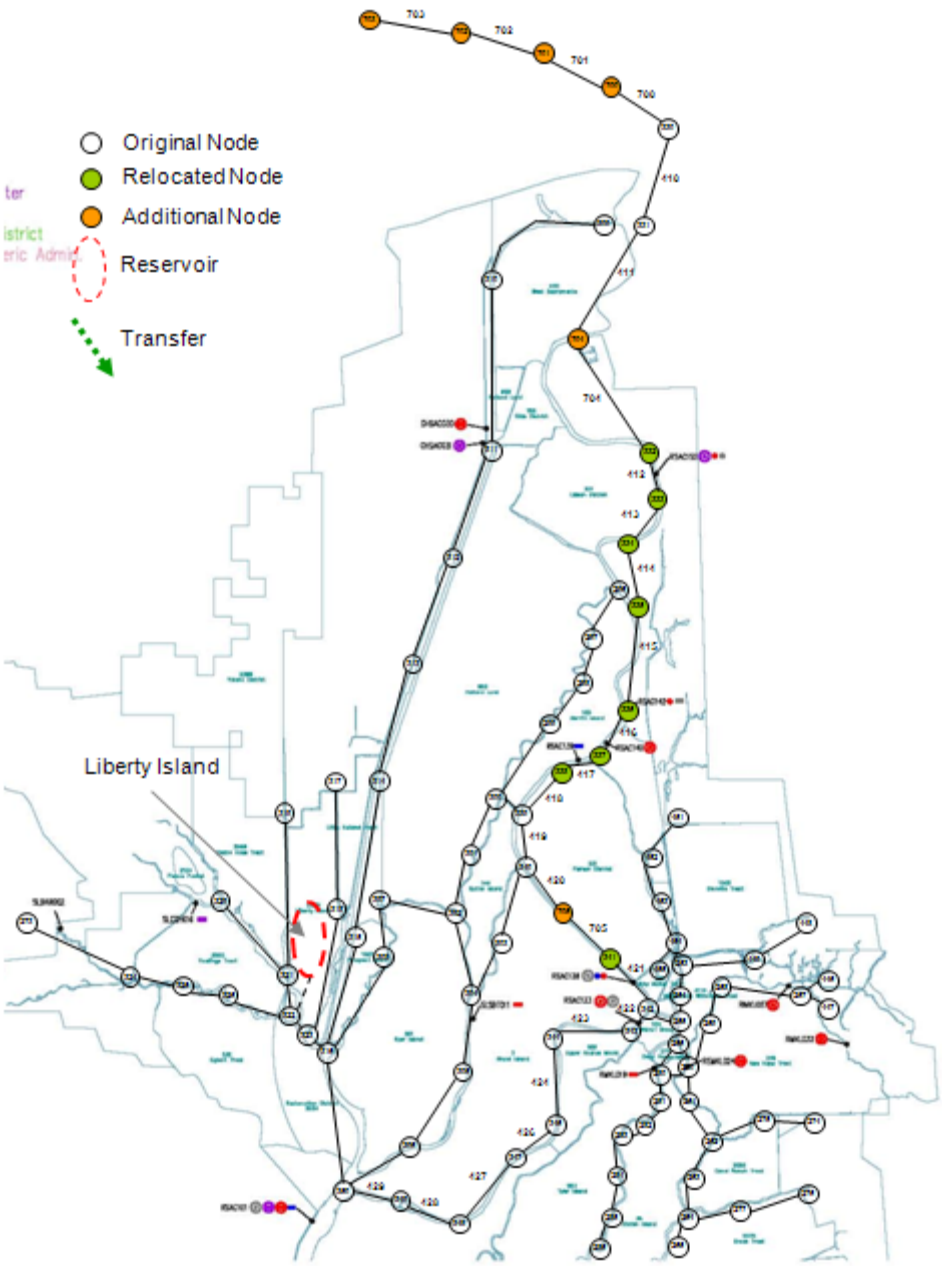

Figure A-12: North Delta DSM2 grid used in the BDCP Modeling

Incorporation of Tidal Marsh Restoration and Sea Level Rise Effects in DSM2 Planning Simulations

Using the corroboration described above described, seven (7) separate DSM2 grid configurations and model setups were prepared for use in the planning simulations for the Alternatives. Each configuration corresponds to one combination of sea level rise and restoration scenario.

Using the results from the RMA current conditions and tidal marsh models, three sets of regression relationships were developed to estimate the stage and EC at Martinez location for the 14,000ac (NT), 25,000ac (ELT) and 65,000ac (LLT) restoration scenarios based on the baseline stage and EC at Martinez. Similarly, using the results from the UnTRIM models, two sets of correlations were developed to compute the resulting stage and EC at Martinez location for the 15cm (ELT) and 45cm (LLT) sea level rise scenarios.

Based on the RMA integrated tidal marsh and sea level rise scenarios, two sets of correlations were developed for estimating Martinez stage and EC resulting for the 25,000ac restoration under 15cm sea level rise (ELT) and for the 65,000ac restoration under 45cm sea level rise (LLT) scenarios.

Table A-6 shows the Martinez stage and EC correlations for these seven (7) scenarios described above. It also shows the lag in minutes between the baseline stage or EC and the resulting stage or EC under the scenario with sea level rise and/or restoration. The regressed baseline stage or EC timeseries needs to be shifted by the lag time noted in the Table A-6.

Accurate effects of the tidal marsh restoration and sea level rise are incorporated in DSM2 simulations for the Alternatives in two ways. First, by incorporating consistent grid configuration and model setup identified in corroboration process into the DSM2 model for the selected Alternative, based on the tidal marsh restoration acreage and sea level rise assumptions selected for the Alternative. Second, by modifying the downstream stage and EC boundary conditions at Martinez in the DSM2 model inputs using the regression relationships identified in the corroboration process for the selected restoration and sea level rise assumptions.

As noted earlier, adjusted astronomical tide at Martinez is used as the downstream stage boundary in the DSM2 planning simulation representing current Delta configuration without any sea level rise or tidal marsh restoration. This stage timeseries is modified using one of the stage correlation equations identified in Table A-6 for use in a planning simulation with either restoration or sea level rise or both.

The EC boundary condition in a DSM2 planning simulation is estimated using the G-model based on the monthly net Delta outflow simulated in CALSIM II and the pure astronomical tide (Ateljevich, 2001b). Even though the rim flows and exports are patterned on a daily step in DSM2, the operational decisions are still on a monthly timestep. This means that the net Delta outflow may or may not meets the standards on a daily timestep. Therefore, to estimate the EC boundary condition at Martinez, monthly net Delta outflow simulated in CALSIM II is used. For a planning simulation with either restoration or sea level rise or both, EC timeseries from the G-model is regressed using one of the EC correlations listed in Table A-6 to account for the anticipated changes at Martinez.

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TABLE A-6
Correlations to Transform Baseline Martinez Stage and EC for use in DSM2 BDCP Planning Runs with Tidal Marsh Restoration, Sea Level Rise or both Restoration and Sea Level Rise

Scenario	Martinez Stage (ft NGVD 29)		Martinez EC (µS/cm)	
	Correlation	Lag (min)	Correlation	Lag (min)
NT (14,000ac)	Y = 0.966 * X + 0.04	-3	Y = 1.001 * X + 191.5	8
ELT (25,000ac)	Y = 0.964 * X + 0.04	-4	Y = 0.999 * X + 114.7	10
LLT (65,000ac)	Y = 0.943 * X + 0.06	-3	Y = 0.996 * X + 68.2	13
15cm SLR	Y = 1.0033*X + .47	-1	Y = 0.9954* X + 556.3	0
45cm SLR	Y = 1.0113*X + 1.4	-2	Y = 0.98* X + 1778.9	-2
ELT (25,000ac &15cm SLR)	Y = 0.968 * X + 0.5	-5	Y = 0.999 * X + 357.78	9
LLT (65,000ac & 45cm SLR)	Y = 0.958 * X + 1.49	-9	Y = 1.002 * X + 1046.3	11

Notes: X = Baseline Martinez stage or EC and Y = Scenario Martinez stage or EC

ANN Retraining

ANNs are used for flow-salinity relationships in CALSIM II. They are trained on DSM2 outputs and therefore, emulate DSM2 results. ANN requires retraining whenever the flow – salinity relationship in the Delta changes. BDCP analysis assumes different restoration acreages at NT, ELT and LLT phases. In addition it includes 15cm and 45cm sea level rise at ELT and LLT, respectively. Each combination of restoration and sea level condition results in a different flow – salinity relationship in the Delta and therefore require a new ANN. Table A-7 lists the ANNs developed and used as part of the BDCP analysis.

DWR Bay-Delta Modeling staff has retrained the ANNs for each scenario. ANN retraining process involved following steps:

- Corroboration of the DSM2 model for each scenario as described above
- Range of example long-term CALSIM II scenarios to provide range of boundary conditions for DSM2 models
- Using the grid configuration and the correlations from the corroboration process several 16-year planning runs are simulated based on the boundary conditions from the identified CALSIM II scenarios to create a training dataset for each new ANN
- ANNs are trained using the Delta flows and DCC operations from CALSIM II, EC results from DSM2and the Martinez tide
- The training dataset is divided into two parts. One is used for training the ANN and the other to validate
- Once the ANN is ready a full circle analysis is performed to assess the performance of the ANN

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Detailed description of the ANN training procedure and the full circle analysis is provided in DWR's 2007 annual report (Seneviratne and Wu, 2007).

TABLE A-7
List of ANNs Developed and Used in the BDCP Modeling

ANN	Description	Reference DSM2 Model
BST_noSLR_111709	Represents current Delta configuration with no sea level rise	2009 DSM2 Recalibration
BDCP_ROA0ac_SLR15cm_16Mar2010	Represents current Delta configuration with 15cm sea level rise	DSM2 model corroborated with UnTRIM results for 15cm sea level rise case
BDCP_ROA0ac_SLR45cm_18Mar2010	Represents current Delta configuration with 45cm sea level rise	DSM2 model corroborated with UnTRIM results for 45cm sea level rise case
BDCP_ROA14Kac_SLR0cm_22Dec2009	Represents 14000ac tidal marsh restoration assumed, with no sea level rise	DSM2 model corroborated with RMA results for 14,000ac restoration proposed for NT phase
BDCP_ROA25Kac_SLR0cm_29Dec2009	Represents 25000ac tidal marsh restoration assumed, with no sea level rise	DSM2 model corroborated with RMA results for 25,000ac restoration proposed for ELT phase
BDCP_ROA65Kac_SLR0cm_30Mar2010	Represents 65000ac tidal marsh restoration assumed, with no sea level rise	DSM2 model corroborated with RMA results for 65,000ac restoration proposed for LLT phase
BDCP_ROA25Kac_SLR15cm_14Apr2010	Represents 25000ac tidal marsh restoration assumed, with 15cm sea level rise	DSM2 model corroborated with RMA results for 25,000ac restoration proposed for ELT phase under 15cm sea level rise
BDCP_ROA65Kac_SLR45cm_30Mar2010	Represents 65000ac tidal marsh restoration assumed, with 45cm sea level rise	DSM2 model corroborated with RMA results for 65,000ac restoration proposed for LLT phase under 45cm sea level rise

North Delta Diversion Operations

As described in Section A.3.3, several Alternatives include new intakes on Sacramento River upstream of Sutter Slough, in the north Delta. The diversions at the intakes are governed by the bypass rules. The bypass rules are simulated in CALSIM II using daily mapped Sacramento River flow, which provides the maximum potential diversion that can occur in the north Delta for each day. CALSIM II uses the monthly average of this daily potential diversion as one of the constraints in determining the final monthly north Delta diversion. For use in DSM2, the monthly diversion output for the north Delta intakes is mapped onto the daily pattern of the potential diversion estimated in CALSIM II.

In DSM2 diversion at each intake is determined on a 15 min timestep, subject to sweeping velocity criteria so that the fish migrating past the fish screens do not impinge on them. For BDCP, Delta Smelt criterion of 0.4fps, required by DFG (DFG, 2009) is used in determining whether or not water can be diverted at an intake. The intake operations are also subjected to ramping rates that are required to shut off or start the pumps. The current design allows

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ramping up or down the pumps between 0 and 3,000cfs in less than an hour. These criteria cannot be simulated in CALSIM II. They are dynamically simulated using the operating rules feature in DSM2.

The north Delta diversion operating rule in the DSM2 allows diverting up to the amount specified by CALSIM II each day while subjecting each intake to the sweeping velocity and the ramping criteria. The intakes are operated as long as the daily diversion volume specified by CALSIM II is not met. Once the specified volume is diverted for the day, the pumps are shut off until next day.

The volume corresponding to first 100cfs per intake (for five intakes 500 cfs) of the daily north Delta diversion specified by CALSIM II is diverted equally at all the intakes included for the Alternative. The remaining volume for the day will be diverted such that operation of the upstream intakes is prioritized over the downstream intakes. Intake diversions are ramped over an hour to allow smooth transitions when they are turned on and off.

In the current modeling of the Alternatives, the diversion flow at an intake for each time step is estimated assuming that the remaining diversion volume in a day would have to be diverted in one time step at the upstream-most intake first and immediate downstream one next and so on until the daily specified total is diverted. However, the estimated amount of diversion at each intake is only diverted when the velocity measured just downstream of the DSM2 diversion node is greater than or equal to 0.4fps. If in any time step this criteria is violated then the diversion occurs in a future time step when the velocity is above 0.4fps or may occur at a different intake. The sweeping velocity criterion is measured at 1000ft downstream from the diversion node in DSM2 to minimize potential instabilities in the model. Even though DSM2 produces a cross-sectional averaged velocity, it is not corrected for the velocity profile across the cross-section as the actual screen location is still uncertain.

New channels, transfers and a reservoir are added to the DSM2 grid to simulate up to five (5) north Delta diversion intakes as shown in the Figure A-13. Five channels, 601 – 605, divert water off the Sacramento River and transfer to channel 607 and 608, from where the total diverted water is transferred to a new reservoir (IF_FOREBAY). Figure A-14 shows an example timeseries of sweeping velocities and the diversions at each intake. The plot shows how the intakes are ramped up and down when the velocity falls below 0.4 ft/s.

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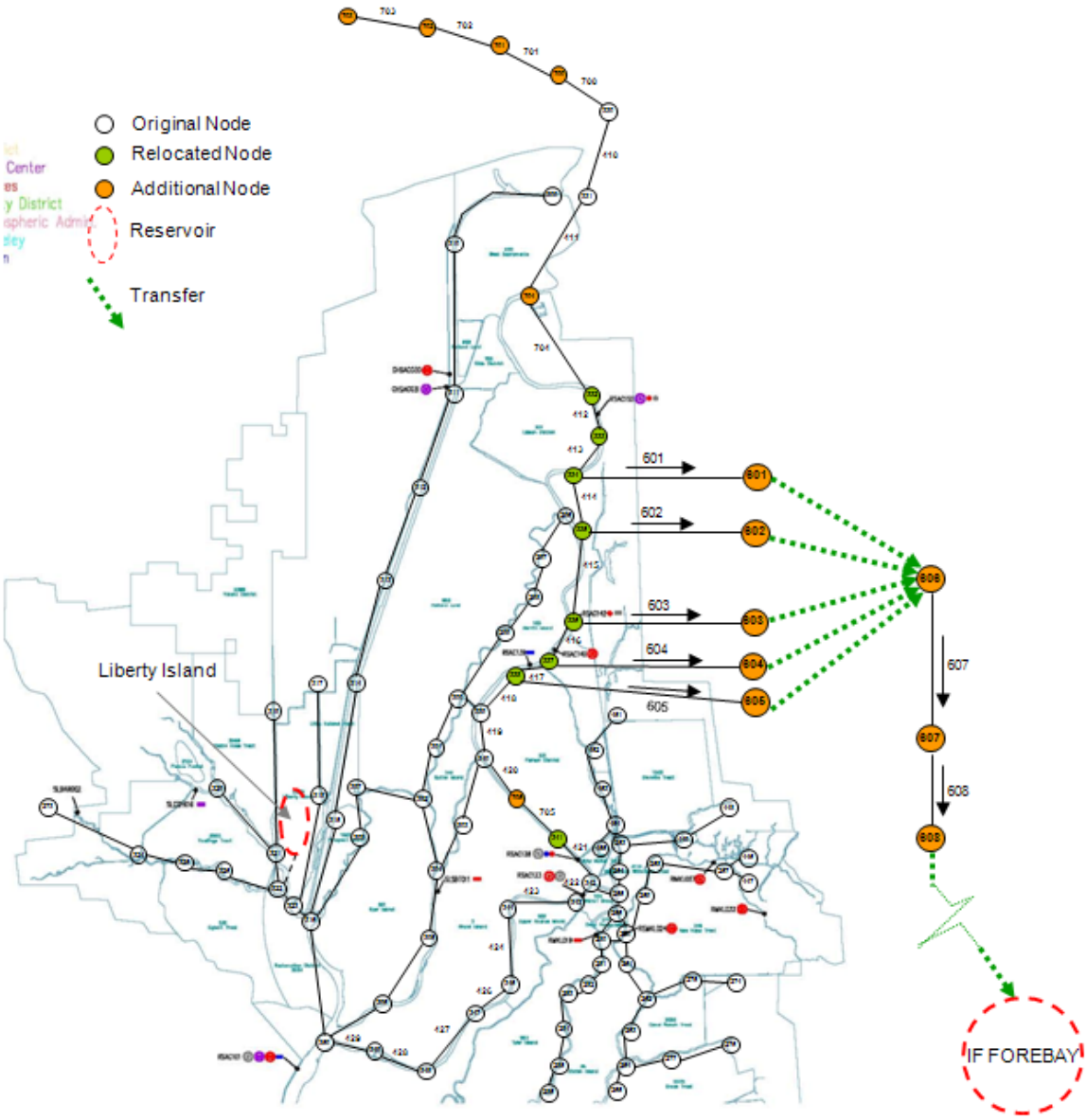

Figure A-13: North Delta DSM2 Grid Modifications for Simulating North Delta Diversions

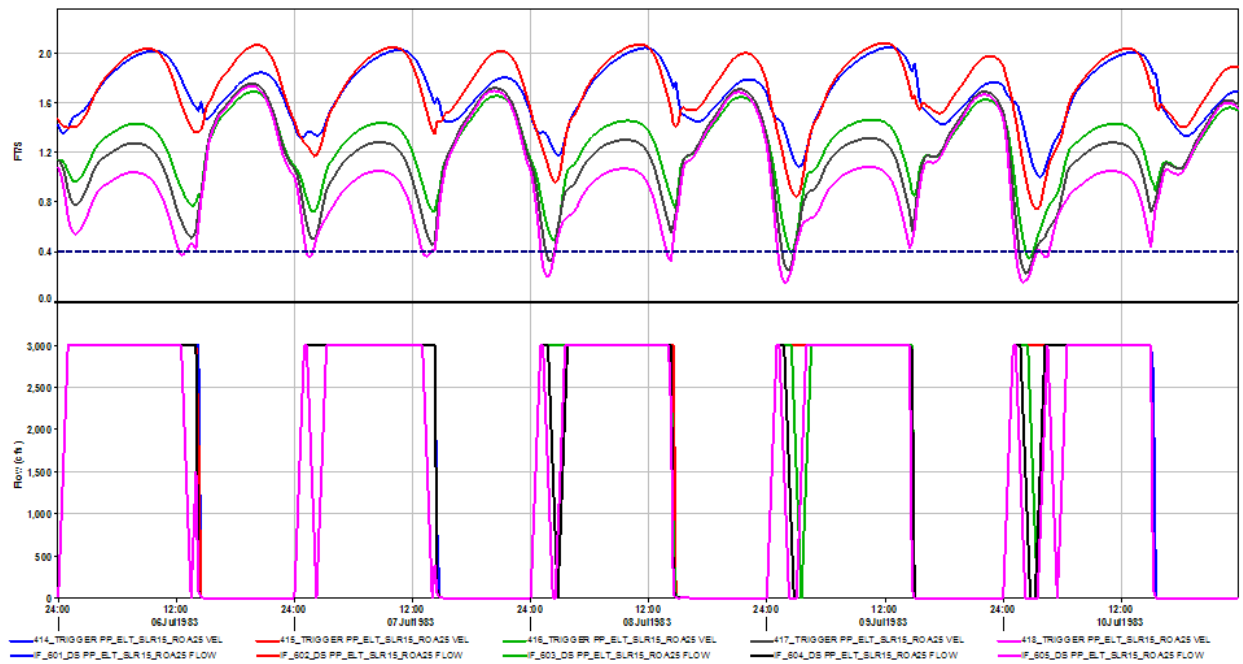

Figure A-14: An Example of Sweeping Velocity and the Diversion at the Five Intakes Simulated in DSM2

A.5.4. Output Parameters

DSM2 HYDRO provides the following outputs on a 15-minute time step:

- Tidal flow
- Tidal stage
- Tidal velocity

Following variables can be derived from the above outputs:

- Net flows
- Mean sea level, mean higher high water, mean lower low water and tidal range
- Water depth
- Tidal reversals
- Flow splits, etc.

DSM2 QUAL provides the following outputs on a 15-minute time step:

- Salinity (EC)
- DOC
- Source water and constituent fingerprinting

Following variables can be derived from the above QUAL outputs:

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- Bromide, chloride, and total dissolved solids
- Selenium and mercury

In a planning analysis, the flow boundary conditions that drive DSM2 are obtained from the monthly CALSIM II model. The agricultural diversions, return flows and corresponding salinities used in DSM2 are on a monthly time step. The implementation of Delta Cross Channel gate operations in DSM2 assumes that the gates are open from the beginning of a month, irrespective of the water quality needs in the south Delta.

The input assumptions stated above should be considered when DSM2 EC results are used to evaluate performance of a baseline or an alternative against the standards. Even though CALSIM II releases sufficient flow to meet the standards on a monthly average basis, the resulting EC from DSM2 may be over the standard for part of a month and under the standard for part of the month, depending on the spring/neap tide and other factors (e.g. simplification of operations). It is recommended that the results are presented on a monthly basis. Frequency of compliance with a criterion should be computed based on monthly average results. Averaging on a sub-monthly (14-day or more) scale may be appropriate as long as the limitations with respect to the compliance of the baseline model are described in detail and the alternative results are presented as an incremental change from the baseline model. A detailed discussion is required in this case.

In general, it is appropriate to present DSM2 QUAL results including EC, DOC, volumetric fingerprinting and constituent fingerprinting on a monthly time step. When comparing results from two scenarios, computing differences based on these mean monthly statistics would be appropriate.

A.5.5. Modeling Limitations

DSM2 is a 1D model with inherent limitations in simulating hydrodynamic and transport processes in a complex estuarine environment such as the Sacramento – San Joaquin Delta. DSM2 assumes that velocity in a channel can be adequately represented by a single average velocity over the channel cross-section, meaning that variations both across the width of the channel and through the water column are negligible. DSM2 does not have the ability to model short-circuiting of flow through a reach, where a majority of the flow in a cross-section is confined to a small portion of the cross-section. DSM2 does not conserve momentum at the channel junctions and does not model the secondary currents in a channel. DSM2 also does not explicitly account for dispersion due to flow accelerating through channel bends. It cannot model the vertical salinity stratification in the channels.

It has inherent limitations in simulating the hydrodynamics related to the open water areas. Since a reservoir surface area is constant in DSM2, it impacts the stage in the reservoir and thereby impacting the flow exchange with the adjoining channel. Due to the inability to change the cross-sectional area of the reservoir inlets with changing water surface elevation, the final entrance and exit coefficients were fine tuned to match a median flow range. This causes errors in the flow exchange at breaches during the extreme spring and neap tides. Using an arbitrary bottom elevation value for the reservoirs representing the proposed marsh areas to get around the wetting-drying limitation of DSM2 may increase the dilution of salinity in the reservoirs. Accurate representation of RMA's tidal marsh areas, bottom elevations, location of breaches,

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breach widths, cross-sections, and boundary conditions in DSM2 is critical to the agreement of corroboration results.

For open water bodies DSM2 assumes uniform and instantaneous mixing over entire open water area. Thus it does not account for the any salinity gradients that may exist within the open water bodies. Significant uncertainty exists in flow and EC input data related to in-Delta agriculture, which leads to uncertainty in the simulated EC values. Caution needs to be exercised when using EC outputs on a sub-monthly scale. Water quality results inside the water bodies representing the tidal marsh areas were not validated specifically and because of the bottom elevation assumptions, preferably do not use it for analysis.

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A.6. Delta Particle Tracking Modeling

Particle tracking models (PTM) are excellent tools to visualize and summarize the impacts of modified hydrodynamics in the Delta. These tools can simulate the movement of passive particles or particles with behavior representing either larval or adult fish through the Delta. The PTM tools can provide important information relating hydrodynamic results to the analysis needs of biologists that are essential in assessing the impacts to the habitat in the Delta.

A.6.1. DSM2-PTM

DSM2-PTM simulates pseudo 3-D transport of neutrally buoyant particles based on the flow field simulated by HYDRO. The PTM module simulates the transport and fate of individual particles traveling throughout the Delta. The model uses geometry files, velocity, flow, and stage output from the HYDRO module to monitor the location of each individual particle using assumed vertical and lateral velocity profiles and specified random movement to simulate mixing. The location of a particle in a channel is determined as the distance from the downstream end of the channel segment (x), the distance from the centerline of the channel (y), and the distance above the channel bottom (z).PTM has multiple applications ranging from visualization of flow patterns to simulation of discrete organisms such as fish eggs and larvae.

The longitudinal distance traveled by a particle is determined from a combination of the lateral and vertical velocity profiles in each channel. The transverse velocity profile simulates the effects of channel shear that occurs along the sides of a channel. The result is varying velocities across the width of the channel. The average cross-sectional velocity is multiplied by a factor based on the particle's transverse location in the channel. The model uses a fourth order polynomial to represent the velocity profile. The vertical velocity profile shows that particles located near the bottom of the channel move more slowly than particles located near the surface. The model uses the Von Karman logarithmic profile to create the velocity profile. Particles also move because of random mixing. The mixing rates (i.e., distances) are a function of the water depth and the velocity in the channel. High velocities and deeper water result in greater mixing.

At a junction the path of a particle is determined randomly based on the proportion of flow. The proportion of flow determines the probability of movement into each reach. A random number based on this determined probability then determines where the particle will go. A particle that moves into an open water area, such as a reservoir, no longer retains its position information. A DSM2 open water area is considered a fully mixed reactor. The path out of the open water area is a decision based on the volume in the open water area, the time step, and the flow out of the area. At the beginning of a time step the volume of the open water area the volume of water leaving at each opening of the open water area is determined. From that the probability of the particle leaving the open water area is calculated. Particles entering exports or agricultural diversions are considered "lost" from the system. Their final destination is recorded. Once particles pass the Martinez boundary, they have no opportunity to return to the Delta. (Smith, 1998, Wilbur, 2001, Miller, 2002)

A.6.2. DSM2-PTM Metrics

The particle transport and fate metrics resulting from DSM2 PTM are outlined below.

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1. Fate Mapping – an indicator of entrainment. It is the percent of particles that go past various exit points in the system at the end of a given number of days after insertion.
2. Delta-wide Residence Time – an indicator of transport of larval fish and plankton. It is the time taken for 75% of the particles inserted to leave the system via all the exit points.

A.6.3. PTM Period Selection

PTM simulation periods for the residence time and fate computations were selected based on the simulated Delta inflows and the exports from the No Action Alternative CALSIM II results. A two-pronged approach was used to identify the particle insertion periods such that the selected periods cover the entire range of hydrology and also represent full range of export operations that occurred in the 82-year simulation period. Representative periods with various combinations of total inflow and exports were identified over the whole range of simulated values.

Briefly, the process included sorting all the months in the 82-year period into 25 hydrology bins based on the percent ranks of monthly Sacramento and San Joaquin inflows as shown in Figure A-15. The 984 months were then sorted based on the monthly total Delta inflow and the monthly exports as shown in Figure A-16. Several months falling on the 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 EI ratio isopleths were manually identified such that they cover all the hydrology bins. Figures A-17 and A-18 show the selected periods plotted on the hydrology binning plot and the EI ratio plot, respectively. Both the plots show that the selected periods cover the full range of hydrology and export operations. Figure A-19 shows number of selected periods in each month. The selected periods were reviewed to ensure representation of all the seasons. The selection was biased to include more periods in the Dec – Jun period. The variability captured in the selected periods, in terms of the hydrology and the operations, is mostly sustained for both the early long-term and late long-term conditions.

A.6.4. PTM Simulations

PTM simulations are performed to derive the metrics described above. PTM model can track flux at twenty locations in one simulation. The particles are inserted at the 39 locations shown in Figure A-20. These locations are listed in Table A-8. The locations were identified based on the 20mm Delta Smelt Survey Stations. They also include special interest stations such as Mokelumne River and Cache Complex.

A total of 39 PTM simulations are performed in a batch mode for each insertion period. For each insertion period, 4000 particles are inserted at the identified locations over a 24.75-hour period, starting on the 1st of the selected month. The fate of the inserted particles is tracked continuously over a 120-day simulation period. The particle flux is tracked at the key exit locations – exports, Delta agricultural intakes, past Chipps Island, to Suisun Marsh and past Martinez and at several internal tracking locations as shown in Figure A-20. Generally, the fate of particles at the end of 30 days, 60 days, 90 days and 120 days after insertion is computed for the fate mapping analysis. For the Delta-wide residence time analysis, the number of days taken for 25%, 50%, 75% of the total inserted particles to be removed via all the exit points in the Delta are computed.

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Table A-8: List of Particle Insertion Locations for Residence Time and Fate Computations

Location	DSM2 Node
San Joaquin River at Vernalis	1
San Joaquin River at Mossdale	7
San Joaquin River D/S of Rough and Ready Island	21
San Joaquin River at Buckley Cove	25
San Joaquin River near Medford Island	34
San Joaquin River at Potato Slough	39
San Joaquin River at Twitchell Island	41
Old River near Victoria Canal	75
Old River at Railroad Cut	86
Old River near Quimby Island	99
Middle River at Victoria Canal	113
Middle River u/s of Mildred Island	145
Grant Line Canal	174
Frank's Tract East	232
Threemile Slough	240
Little Potato Slough	249
Mokelumne River d/s of Cosumnes confluence	258
South Fork Mokelumne	261
Mokelumne River d/s of Georgiana confluence	272
North Fork Mokelumne	281
Georgiana Slough	291
Miner Slough	307
Sacramento Deep Water Ship Channel	314
Cache Slough at Shag Slough	321
Cache Slough at Liberty Island	323
Lindsey slough at Barker Slough	324
Sacramento River at Sacramento	330
Sacramento River at Sutter Slough	339
Sacramento River at Ryde	344
Sacramento River near Cache Slough confluence	350
Sacramento River at Rio Vista	351
Sacramento River d/s of Decker Island	353
Sacramento River at Sherman Lake	354
Sacramento River at Port Chicago	359
Montezuma Slough at Head	418
Montezuma Slough at Suisun Slough	428
San Joaquin River d/s of Dutch Slough	461
Sacramento River at Pittsburg	465
San Joaquin River near Jersey Point	469

A.6.5. Output Parameters

The particle tracking models can be used to assist in understanding passive fate and transport, or through consideration of behavior or residence time. In, general the following outputs are generated:

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- Fate of particles and cut lines or regions
- Time of travel breakthrough curves
- Residence time

Spatial plots of fate and residence time can be prepared as shown in the Figure A-21 and A-22. Scatter plots of entrainment with a hydrologic variable as shown in Figure A-23 can be helpful in assessing the correlation between hydraulics and entrainment, as well as the spatial extent over which such correlations hold.

A.6.6. Limitations

PTM results are most often used to understand the potential movement of eggs and larval fish with flow changes. Similarly, the PTM is also used to study the changes in the residence time (residence time being a surrogate of the water quality conditions in the Delta) in the Delta associated with flow changes. However, the PTM only approximates movement of neutrally-buoyant particles based on the hydraulics of flow. They do not include elements of fish behavior such as active swimming or tidal surfing which may be important for certain species and life stages. The version of the PTM model used in this analysis does not have a capability to simulate fish behavior. The PTM model requires input of channel velocity fields from HYDRO model, which leads to the translation of the limitations inherent to HDYRO to the PTM model. The partitioning of the particles at a junction is simplistic and is based on the flow split into different branches at a junction. Information related to higher order hydraulics such as acceleration around the bend and secondary are not simulated in the PTM, despite its use of an approximate 3D velocity field. Use of the PTM results to analyze certain species and life stages with significant active behavior responses should be used with caution. The PTM model used for this analysis is incapable of simulating fish screens and blocking the particles from entering small sump pumps in the Delta channels. While some uncertainty exists in the PTM results, the model is a reasonable tool to compare the movement and fate of particles across various scenarios, if results are interpreted within the context of these limitations.

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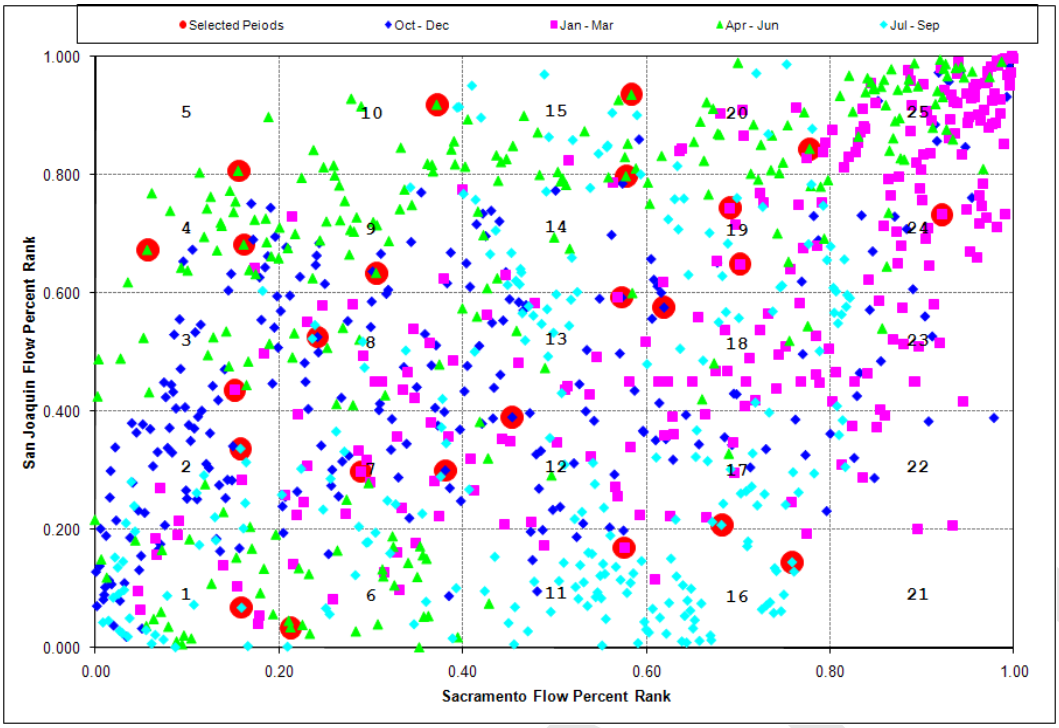

Figure A-15: Sorting of the 984 months (82-years) into 25 hydrology bins based on the percent rank of Sacramento River inflow and San Joaquin River inflow

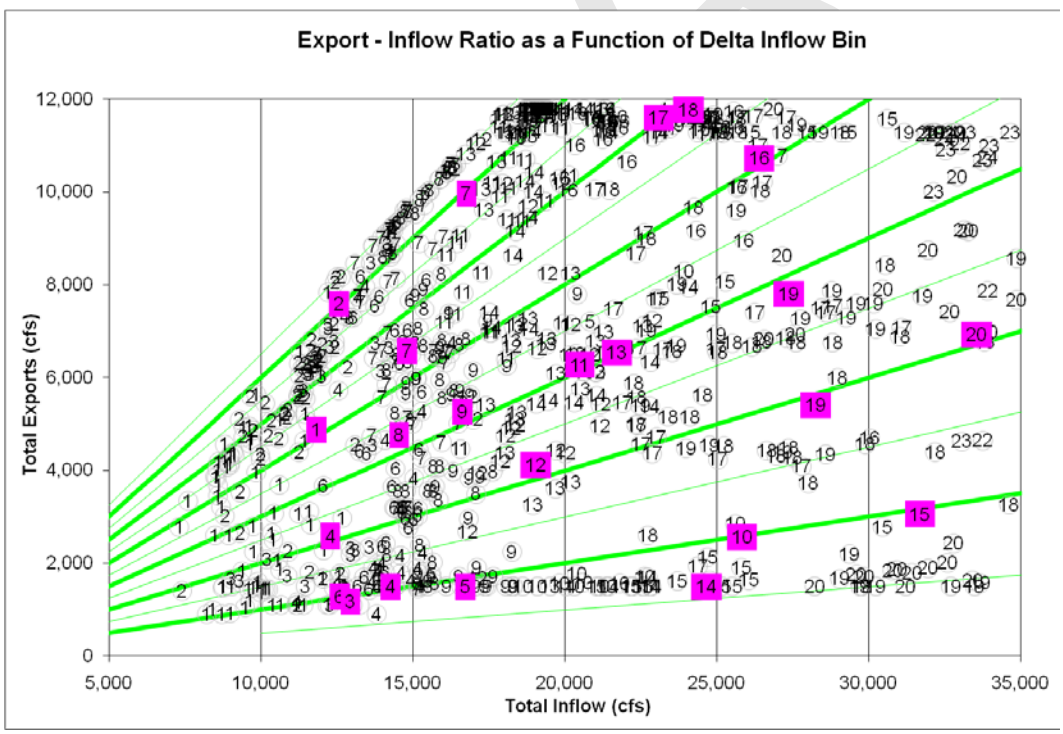

Figure A-16: Identification of months falling on the 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 EI ratio isopleths while covering the full range of hydrology bins (Numeric labels indicate hydrology bin)

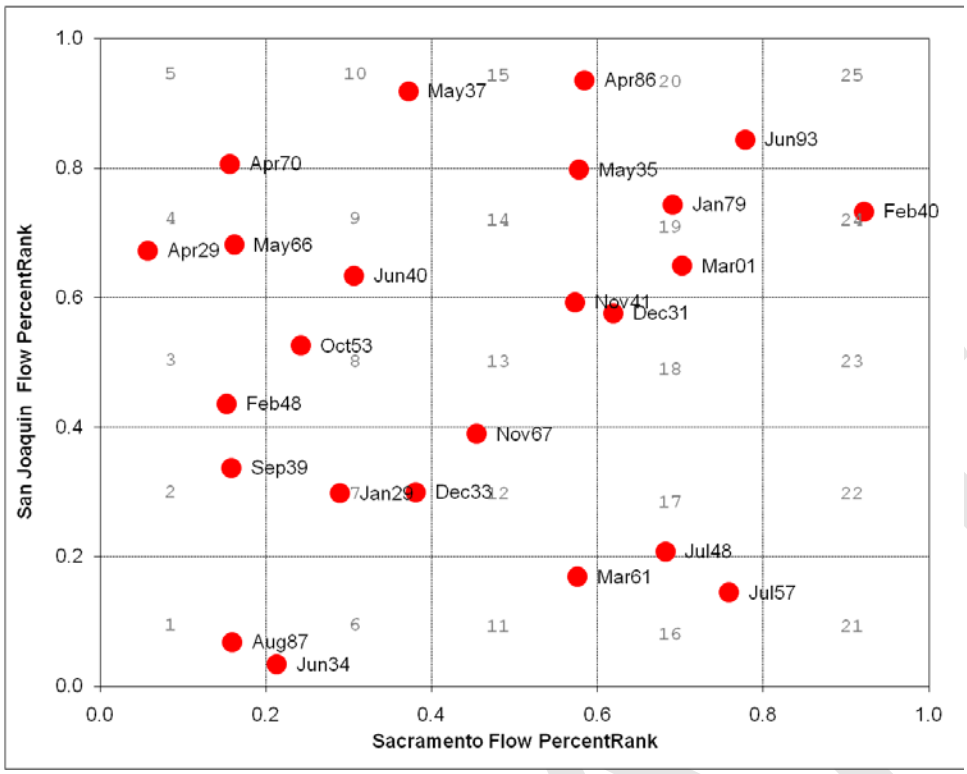

Figure A-17: Selected PTM insertion periods plotted on the Sacramento River and San Joaquin River inflow hydrology bins with month and year identified for each insertion period

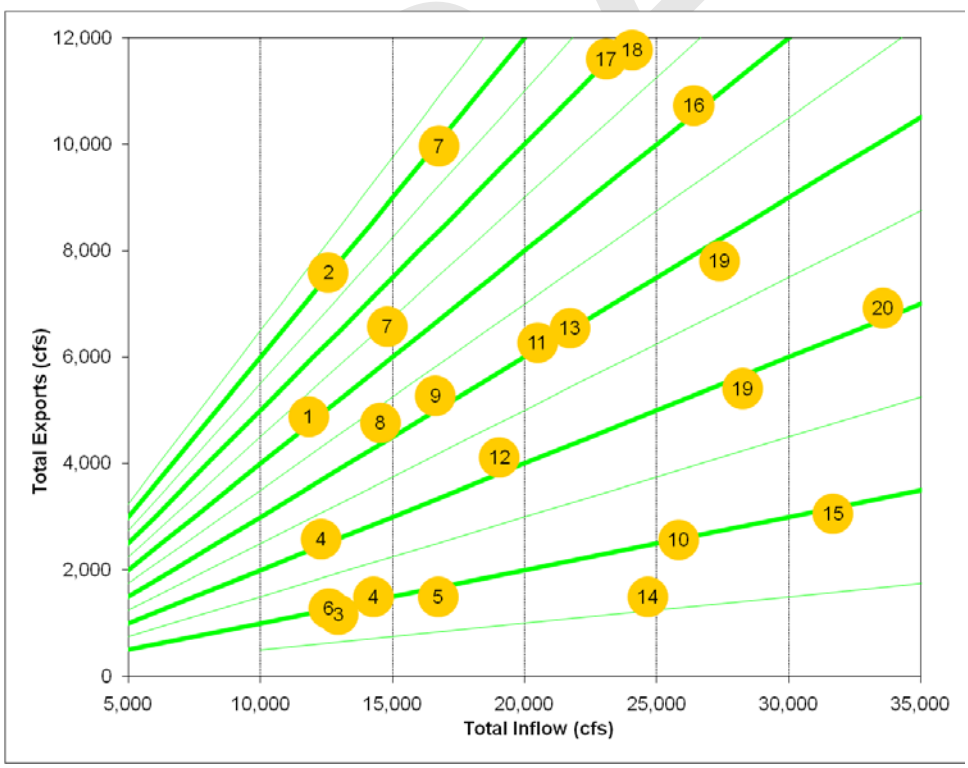

Figure A-18: Selected PTM insertion periods plotted on the EI ratio plot with the hydrology bin for each period identified

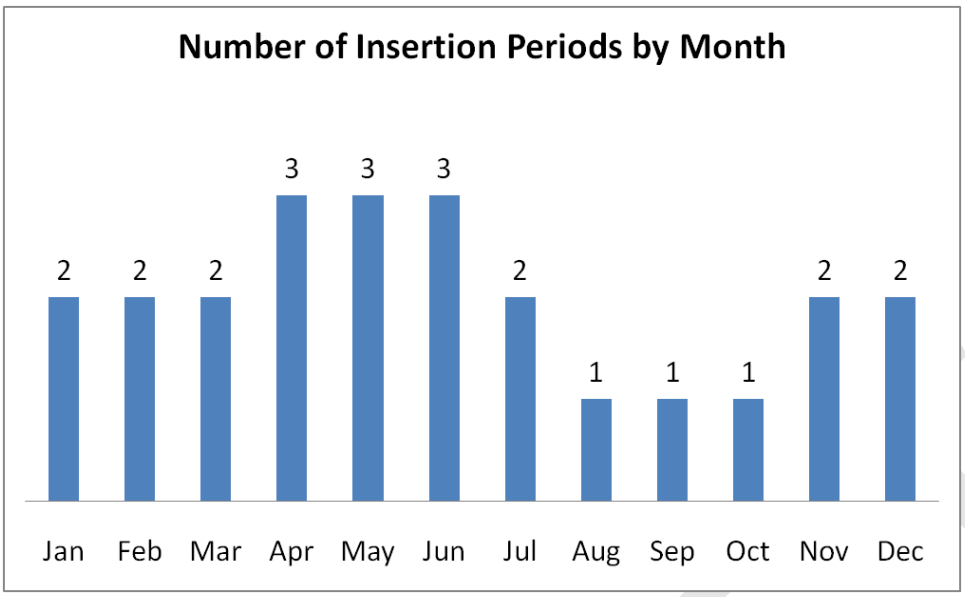

Figure A-19: Number of selected PTM insertion periods in each Month

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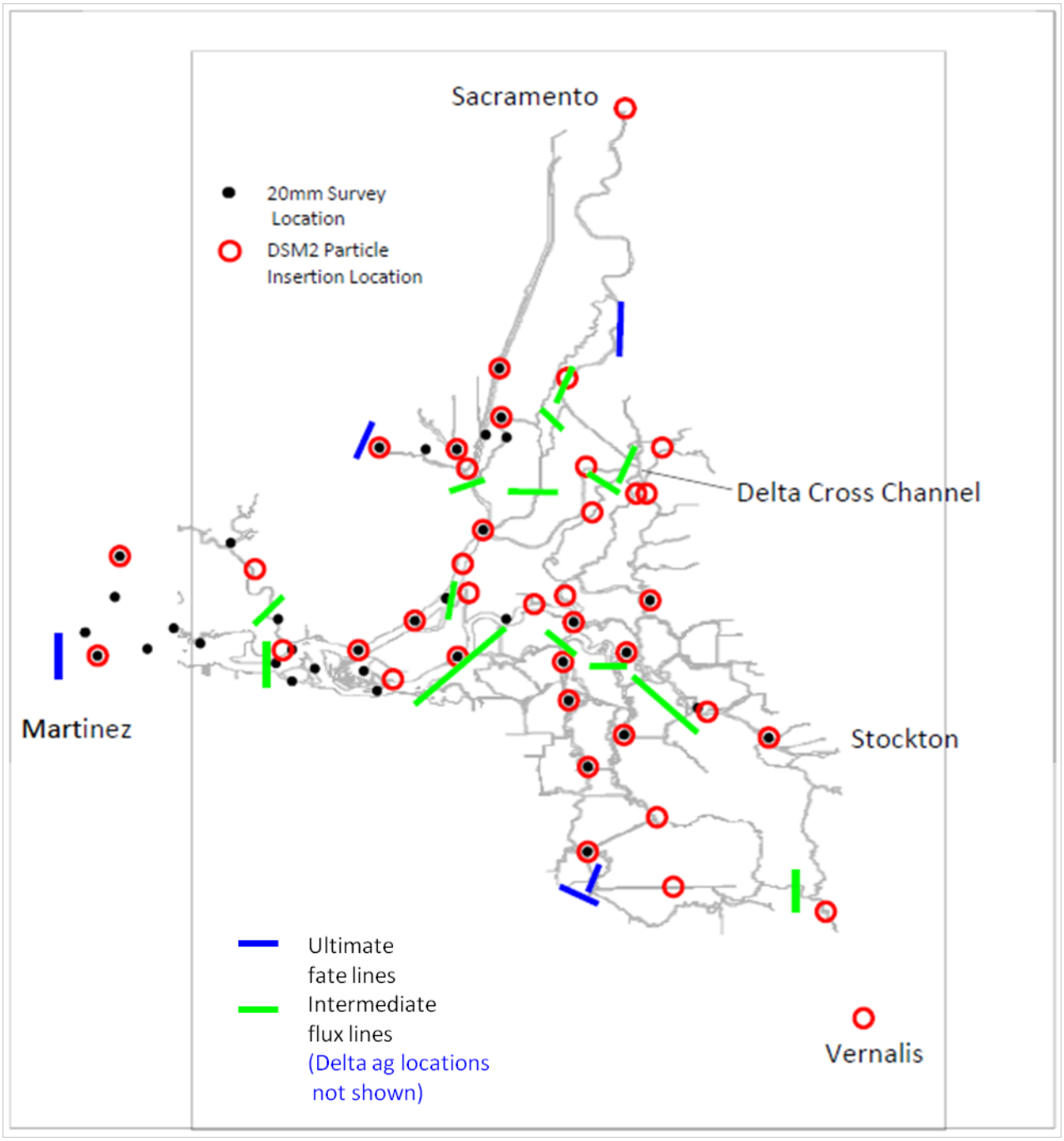

Figure A-20: Particle insertion and tracking locations for residence time and fate computations

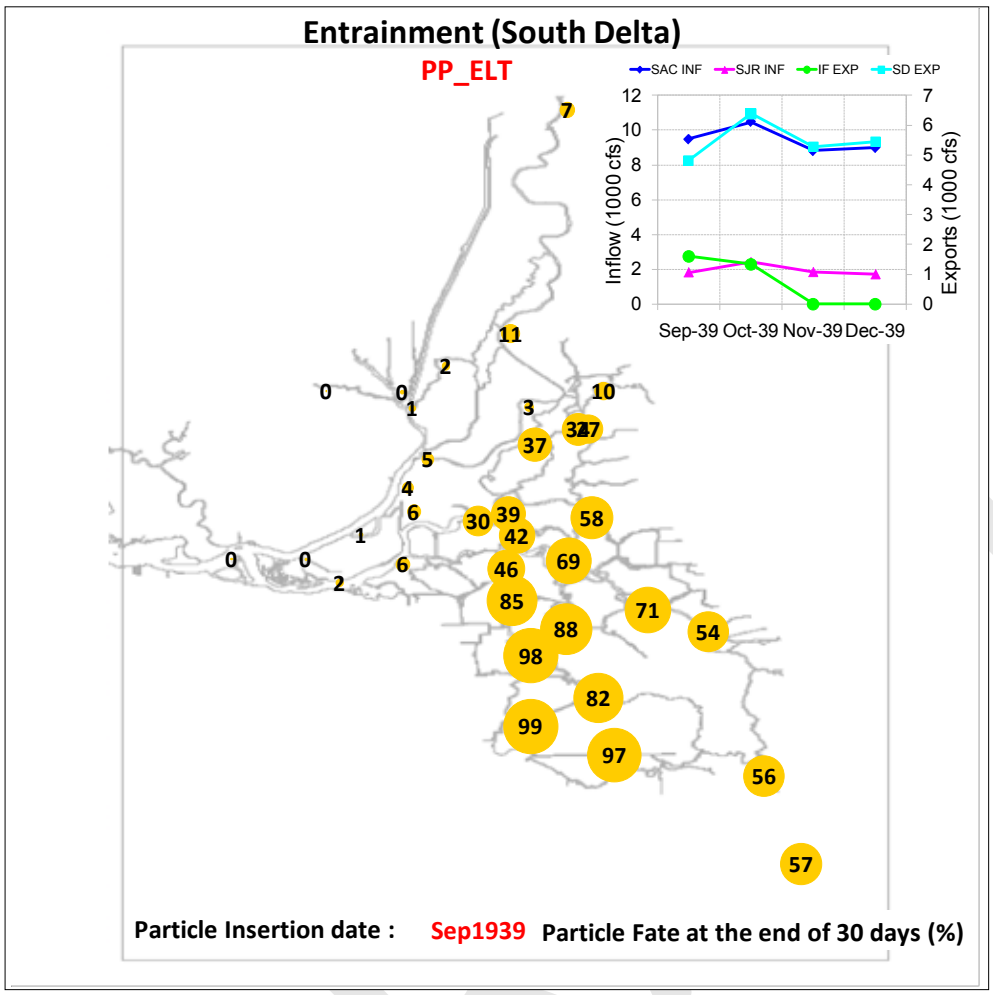

Figure A-21: An example spatial plot showing the percent entrainment for particles released at various locations in the Delta at the end of 30 days after insertion

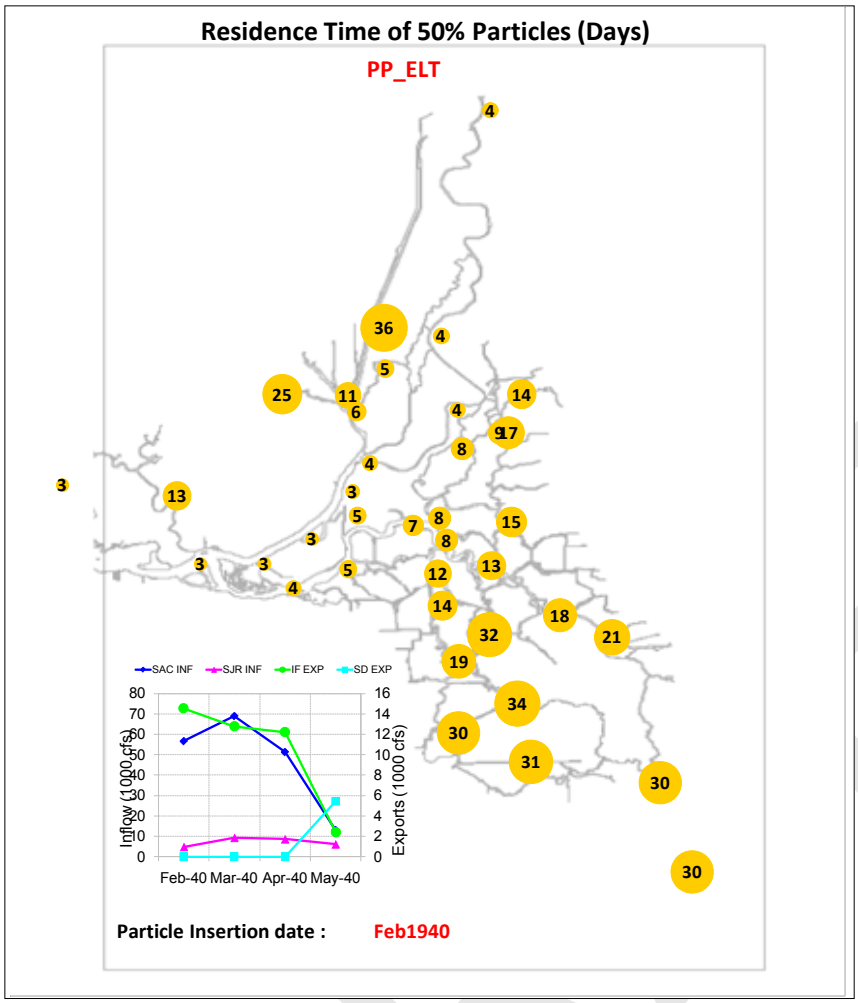

Figure A-22: An example spatial plot showing the residence time for 50 percent particles to exit the Delta

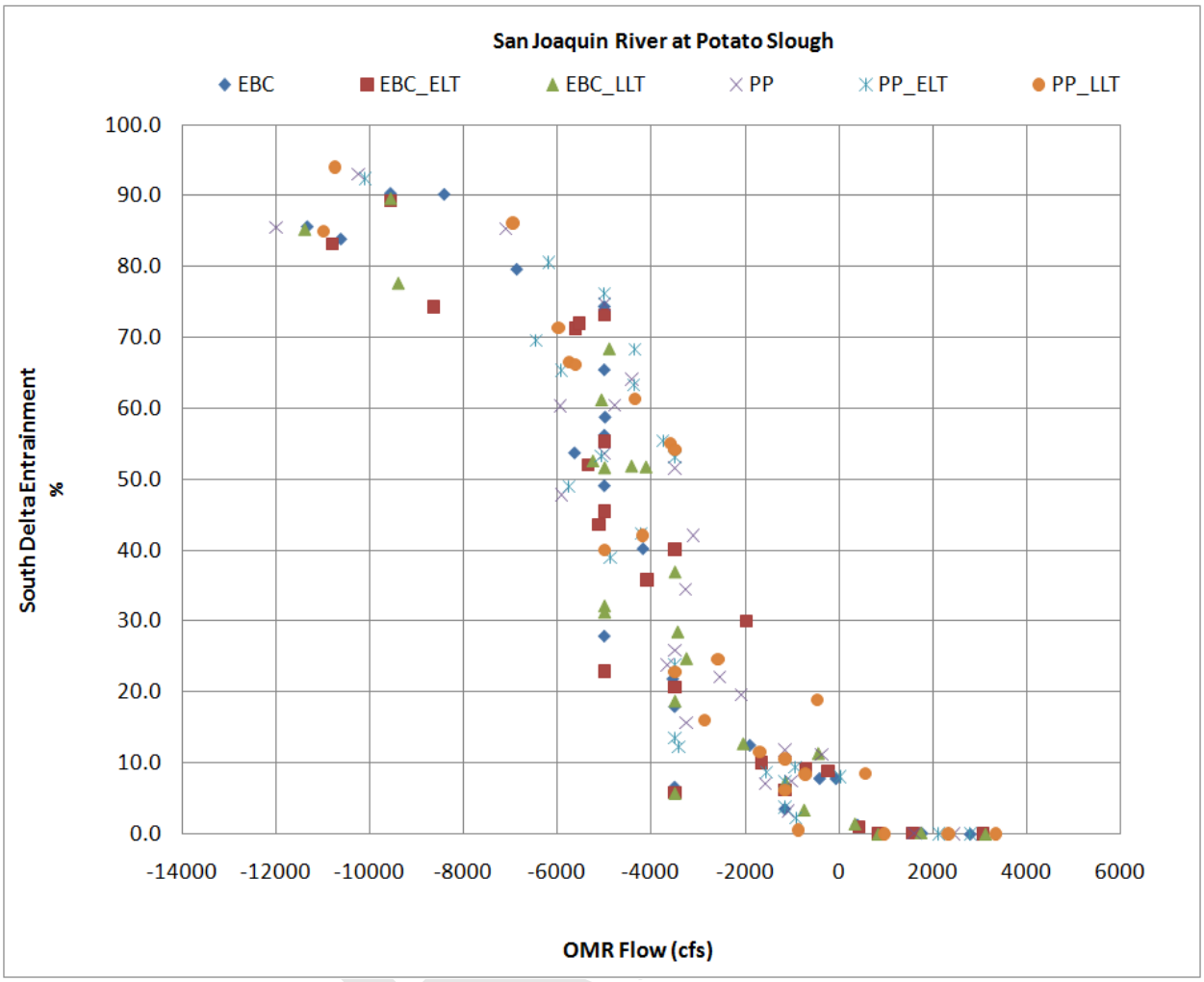

Figure A-23: An example scatter plot showing the percent entrainment of particles at south Delta pumps inserted at San Joaquin River at Potato Slough location and OMR flow, 60 days after the particles were inserted

A.7. Climate Change Scenarios

A.7.1. Selection of BDCP Climate Scenarios

A technical subgroup was formed with representatives from DWR, Reclamation, USFWS, and NMFS to review the technical merits of several approaches for incorporating climate change into BDCP analytical processes. The issues of multi-decadal variability in the sampling of any one GCM projection and the superiority of multi-model projections over any one single projection were emphasized by the group members. These and other comments received from the group members led to the recommendation of the following criteria to guide the selection of climate scenarios:

- Select a range of scenarios to reflect the uncertainty with GCM projections and emission scenarios;
- Select scenarios that reduce the "noise" inherent with any particular GCM projection due to multi-decadal variability that often does not preserve relative rank for different locations and time periods;
- Select an approach that incorporates both the mean climate change trend and changes in variability; and
- Select time periods that are consistent with the major phases used in BDCP planning.
- The selected approach for development of climate scenarios for the BDCP incorporates three fundamental elements. First, it relies on sampling of the ensemble of GCM projections rather than one single realization or a handful of individual realizations. Second, it includes scenarios that both represent the range of projections as well as the central tendency of the projections. Third, it applies a method that incorporates both changes to the mean climate as well as to the variability in climate. These elements are described further in the sections below.

A.7.2. Downscaled Climate Projections

A total of 112 future climate projections used in the IPCC AR4, subsequently bias-corrected and statistically downscaled (BCSD), were obtained from Lawrence Livermore National Laboratory (LLNL) under the World Climate Research Program's (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3). This archive of contains climate projections generated from 16 different GCMs developed by national climate centers (Table A-9) and for SRES emission scenarios A2, A1b, and B1. Many of the GCMs were simulated multiple times for the same emission scenario due to differences in starting climate system state, thus the number of available projections is greater than simply the product of GCMs and emission scenarios. These projections have been bias corrected and spatially downscaled to 1/8th degree (~12km) resolution over the contiguous United States through methods described in detail in Wood et al. 2002, Wood et al. 2004, and Maurer 2007.

TABLE A-9
General Circulation Models used in the World Climate Research Program's (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3) Database

Modeling Group, Country	WCRP CMIP3 I.D.
Bjerknes Centre for Climate Research	BCCR-BCM2.0
Canadian Centre for Climate Modeling & Analysis	CGCM3.1 (T47)
Meteo-France / Centre National de Recherches Meteorologiques, France	CNRM-CM3
CSIRO Atmospheric Research, Australia	CSIRO-Mk3.0
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.1
NASA / Goddard Institute for Space Studies, USA	GISS-ER
Institute for Numerical Mathematics, Russia	INM-CM3.0
Institut Pierre Simon Laplace, France	IPSL-CM4
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	MIROC3.2 (medres)
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA	ECHO-G
Max Planck Institute for Meteorology, Germany	ECHAM5/ MPI-OM
Meteorological Research Institute, Japan	MRI-CGCM2.3.2
National Center for Atmospheric Research, USA	CCSM3
National Center for Atmospheric Research, USA	PCM
Hadley Centre for Climate Prediction and Research / Met Office, UK	UKMO-HadCM3

A.7.3. Climate Periods

Climate change is commonly measured over a 30-year period. Changes in temperature and precipitation for any particular scenario are compared to a historical period. The historical period of 1971-2000 is selected as the reference climate since it is the currently established

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climate normal used by NOAA and represents the most recent time period. Corresponding to the long-term timelines of the BDCP analysis, in which climate change is likely to be relevant, future climate periods are identified as approximately 2025 (2011-2040) [early long-term] and 2060 (2046-2075) [late long-term]. The difference in mean annual temperature and precipitation among the two future periods and historic period were identified as the climate change metric.

A.7.4. Multi-Model Ensemble and Sub-Ensembles

The recommended approach makes use of all 112 downscaled climate projections of future climate change described in the previous section. The group of multi-model, multi-emission scenario projections is termed the ensemble. Individual model-emission scenario projections are termed "members" of the ensemble. It is often useful to characterize climate change projections in terms of the simulated change in annual temperature and precipitation compared to an historical reference period. At any selected 30-yr future climatological period, each projection represents one point of change amongst the others. This is graphically depicted in Figure A-24 for a region in Feather River watershed.

Since the ensemble is made up of many projections, it is useful to identify the median (50th percentile) change of both annual temperature and annual precipitation (dashed blue lines). In doing so, the state of climate change at this point in time can be broken into quadrants representing (1) drier, less warming, (2) drier, more warming, (3) wetter, more warming, and (4) wetter, less warming than the ensemble median. These quadrants are labeled Q1-Q4 in Figure A-24. In addition, a fifth region (Q5) can be described that samples from inner-quartiles (25th to 75th percentile) of the ensemble and represents a central region of climate change. In each of the five regions the sub-ensemble of climate change projections, made up of those contained within the region bounds, is identified. The Q5 scenario is derived from the central tending climate projections and thus favors the consensus of the ensemble.

Through extensive coordination with the State and Federal teams involved in the BDCP, the bounding scenarios Q1-Q4 were refined in April 2010 to reduce the attenuation of climate projection variability that comes about through the use of larger ensembles. A sensitivity analysis was prepared for the bounding scenarios (Q1-Q4) using sub-ensembles made up of different numbers of downscaled climate projections. The sensitivity analysis was prepared using a "nearest neighbor" (k-NN) approach. In this approach, a certain joint projection probability is selected based on the annual temperature change-precipitation change (i.e. 90th percentile of temperature and 90th percentile of precipitation change). From this statistical point, the "k" nearest neighbors (after normalizing temperature and precipitation changes) of projections are selected and climate change statistics are derived. Consistent with the approach applied in OCAP, the 90th and 10th percentile of annual temperature and precipitation change were selected as the bounding points. The sensitivity analysis considered using the 1-NN (single projection), 5-NN (5 projections), and 10-NN (10 projections) sub-ensemble of projections. These were compared to the original quadrant scenarios which commonly are made up of 25-35 projections and are based on the direction of change from 50th percentile statistic.

The very small ensemble sample sizes exhibited month by month changes that were sometimes dramatically different than that produced by adding a few more projections to the ensemble. The 1-NN approach was found to be inferior to all other methods for this reason. The original quadrant method produced a consensus direction of change of the projections,

and thus produced seasonal trends that were more realistic, but exhibited a slightly smaller range due to the inclusion of several central tending projections. The 5-NN and 10-NN methods exhibited slightly wider range of variability than the quadrant method which was desirable from the "bounding" approach. In most cases the 5-NN and 10-NN projections were similar, although they differed at some locations in representation of season trend. The 10-NN approach (Figure A-24) was found to be preferable in that it best represented the seasonal trends of larger ensembles, retained much of the "range" of the smaller ensembles, and was guaranteed to include projections from at least two GCM-emission scenario combinations (in the CMIP3 projection archive, up to 5 projections – multiple simulations – could come from one GCM-emission scenario combination). The State and Federal representatives agreed to utilize the following climate scenario selection process for BDCP:

(1) the use of the original quadrant approach for Q5 (projections within the 25th to 75th percentile bounding box) as it provides the best estimate of the consensus of climate projections and
(2) the use of the 10-NN method to developing the Q1-Q4 bounding scenarios.

An automated process has been developed that generates the monthly and annual statistics for every grid cell within the Central Valley domain and identifies the members of the sub-ensemble for consideration in each of the five scenarios.

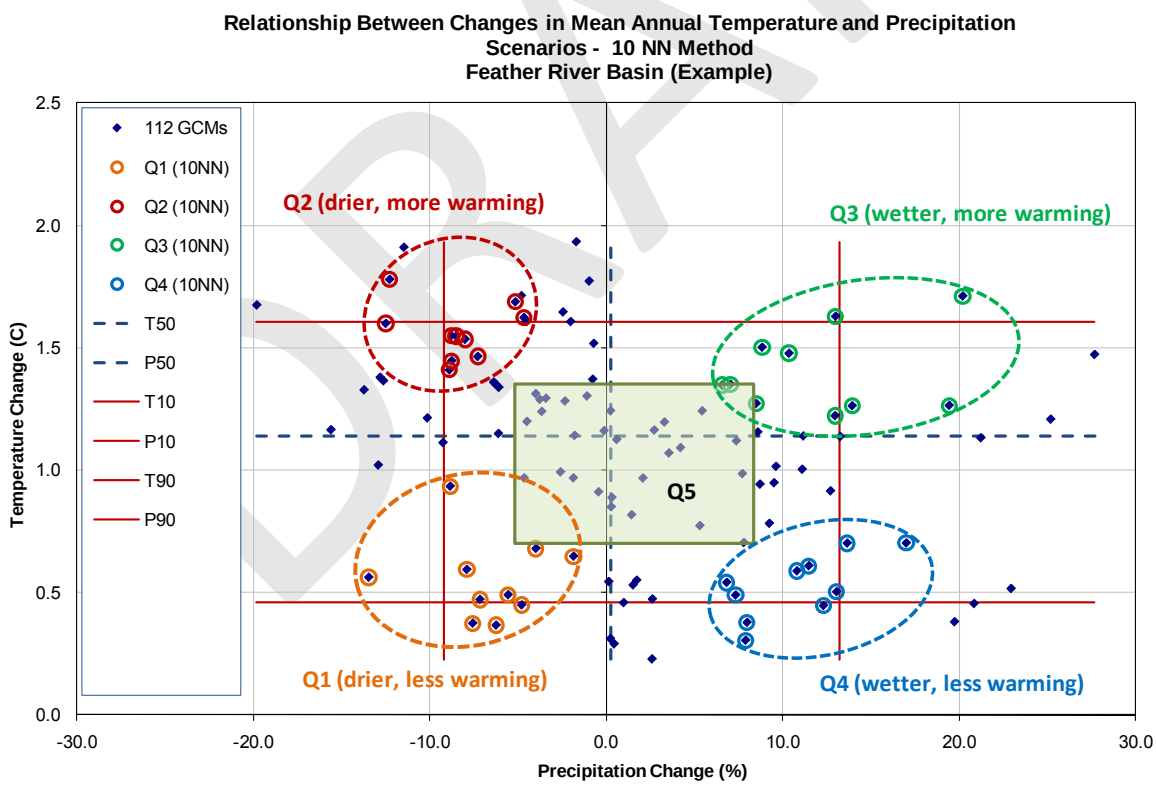

Figure A-24. Example downscaled climate projections and sub-ensembles used for deriving climate scenarios (Q1-Q5), Feather River Basin at 2025. The Q5 scenario is bounded by the 25th and 75th percentile joint temperature-precipitation change. Scenarios Q1-Q4 are selected to

reflect the results of the 10 projections nearest each of 10th and 90th joint temperature-precipitation change bounds. Note: the temperature and precipitation changes are normalized before determining the nearest neighbors.

A.7.5. Incorporating Changes in Mean Climate and Climate Variability

Climate is usually defined as the "average" condition of weather over a period of time. More rigorously, climate can be defined as the "statistical description" in terms of mean and variability of the relevant quantities over a period of time ranging from months to millions of years (IPCC TAR). The standard averaging period defined by the World Meteorological Organization (WMO) is 30 years. The parameters that are most often associated with the description of climate state are temperature, precipitation, and wind speed. Thus, climate change refers to a shift in the statistical properties of climate variables over extended periods of time.

One difficulty that arises in implementing climate change into long-term water resources planning is that the natural variability is often greater than the magnitude of change expected over several decades. In many water resource management areas, it is the extreme events (droughts and floods) that drive the decision-making and long-range planning efforts. Thus, there is a need to combine the climate change signal with the range of natural variability observed in the historical record.

In many current climate change analyses, only the mean state of climate change is analyzed through the use of the "delta" method. In this method, temperature and/or precipitation are adjusted by the mean shift from one future 30-year period to a historical 30-year period. However, climate change is unlikely to manifest itself in a uniform change in values. In fact, the climate projections indicate that the changes are nonlinear and shifts in the probability distributions are likely, not just the mean values. In other analyses, a transient 30-year depiction of climate is used and compared against a similar 30-year historical period. Hydrologic analyses are performed and summarized as the "mean" change between the future and base periods. This latter approach is roughly what has been applied in the OCAP and CAT processes. The difficulty with this approach is that the natural observed variability may be large and not fully present in the 30-year period, resulting in truncated variability. Also, because the sequence of variability is different under each period it is difficult to make comparisons between the resulting hydrologic variables beyond the mean response.

In order to incorporate both the climate change signal and the natural variability in the longer-term observed record, the recommended approach is to create an expanded time series which allows use of the long-term observed records. The approach is similar to that applied by the Climate Impacts Group for development of hydrologic scenarios for water planning in the Pacific Northwest (Wood et al 2002, Salathe et al 2007, Hamlet et al 2009), applied in the Lower Colorado River, Texas studies (CH2M HILL 2008), and recent Reclamation planning (USBR, 2010). The approach uses a technique called "quantile mapping" which maps the statistical properties of climate variables from one data subset with the time series of events from a different subset. In this fashion, the approach allows the use of a shorter period to define the climate state, yet maintains the variability of the longer historic record. The quantile mapping approach involves the following steps:

1. Extract a 30-year slice of downscaled climate projections based on the ensemble subset for the quadrant of interest and centered on the year of investigation (i.e. 2025 or 2060)
2. For each calendar month (i.e. January) of the future period, determine the statistical properties (cumulative distribution function, CDF) of temperature and precipitation at each grid cell
3. For each calendar month of the historical period (1971-2000 in our case), determine the statistical properties (CDFs) of temperature and precipitation at each grid cell
4. Develop quantile maps between the historic observed CDFs and the future downscaled climate CDFs, such that the entire probability distribution (including means, variance, skew, etc) at the monthly scale is transformed to reflect the climate scenario
5. Using the quantile maps, redevelop a monthly time series of temperature and precipitation over the observed period (1915 -2003) that incorporates the climate shift of the future period
6. Convert monthly time series to a daily time series by scaling monthly values to daily sequence found in the observed record

The result of the quantile mapping approach is a daily time series of temperature and precipitation that has the range of variability observed in the historic record, but also contains the shift in climate properties (both mean and expanded variability) found in the downscaled climate projection. Figure A-25 provides an example of this process a grid cell in the Feather River watershed. As shown in this figure, the precipitation change quantities are not expected to shift uniformly across all percentiles. For example, in this wetting climate scenario, the median (50th percentile) January precipitation is projected to exhibit almost no change from baseline conditions. However, for large precipitation events (i.e. the 90th percentile) January precipitation is projected to increase by almost 2 mm/day (more than 2 inches/month). That is, the climate shift is larger at higher precipitation events and lower at low precipitation events. While this may be different for each climate scenario, future period, spatial location, and month, the need to map the full range of statistic climate shift is important to characterize the projected effects of climate change.

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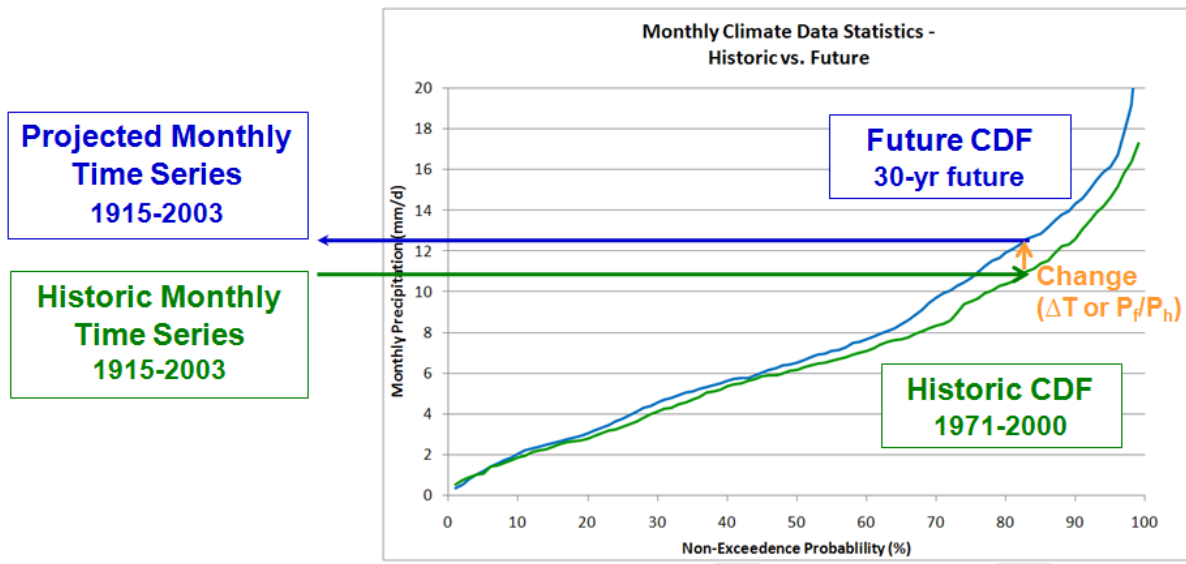


FIGURE A-25:
Historical Monthly Precipitation Statistics for a Grid Cell in Feather River Basin (January - EXAMPLE ONLY)

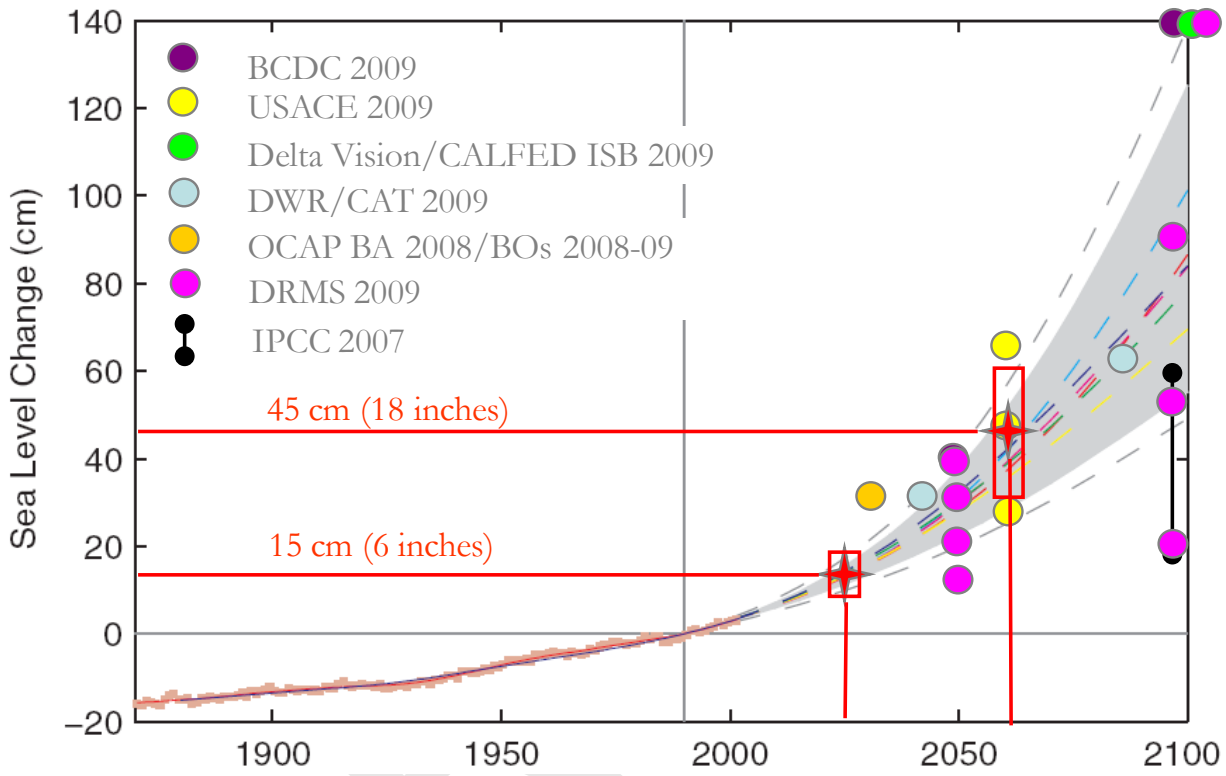
A.7.6. Sea Level Rise Scenarios

In early 2007, the IPCC released their latest assessment of the scientific assessment for projections of future climate. Included in the IPCC AR4 were revised estimates of global mean sea level rise. The IPCC estimates are based on physical models that attempt to account for thermal expansion of oceans and storage changes associated with melt of land-based ice and snowfields (Healy 2007). Since their release, the IPCC AR4 sea level rise estimates have been widely criticized for their failure to include dynamic instability in the ice sheets of Greenland and Antarctica, and for their under-prediction of recent observed increases in sea level.

Due to the limitations with the current state of physical models for assessing future sea level rise, several scientific groups, including the CALFED Independent Science Board (ISB) (Healy 2007), recommend the use of empirical models for short to medium term planning purposes. Both the CALFED ISB and CAT 2009 assessments have utilized the empirical approach developed by Ramsdorf (2007) that projects future sea level rise rates based on the degree of global warming. This method better reproduces historical sea levels and generally produces larger estimates of sea level rise than those indicated by the IPCC (2007). When evaluating all projections of global air temperature, Ramsdorf projects a mid-range sea level rise of 70 – 100 cm (28 – 40 inches) by the end of the century, and when factoring the full range of uncertainty the projected rise is 50 - 140 cm (20 – 55 inches). The CAT scenarios utilized an identical empirical approach, but limited the sea level rise estimates to the degree of warming range from 12 GCM projections selected for that study.

Using the work conducted by Ramsdorf, the projected sea level rise at the early long-term timeline for the BDCP analysis (2025) is approximately 12 - 18 cm (5 - 7 inches). At the late long-term timeline (2060), the projected sea level rise is approximately 30 – 60 cm (12 – 24 inches). These sea level rise estimates are also consistent with those outlined in the recent USACE

guidance circular for incorporating sea-level changes in civil works programs (USACE 2009). Due to the considerable uncertainty in these projections and the state of sea level rise science, it is proposed to use the mid-range of the estimates for each BDCP timeline: 15 cm (6 inches) by 2025 and 45 cm (18 inches) by 2060. In addition, sensitivity scenarios will be prepared to consider sea level rise of up to 60 cm by 2060.



A.7.7. Changes in Tidal Amplitude

As discussed previously, mean sea level has been increasing across the globe and is exhibited on all U.S. coasts and almost all long-term stations. Tidal amplitude appears to be increasing, particulary in the eastern Pacific but the trend is not consistent for all stations on the West Coast. Tidal amplitude can be significantly affected by physical changes in coasts, harbors, bays, and estuaries. At long-term open-ocean stations along the California coast (La Jolla, Los Angeles, San Francisco, and Crescent City), which are less influenced by the physical changes, Flick et al. (2003) found a statistically significant increase in tidal amplitude (MHHW - MLLW), except at Crescent City which showed a slight decreasing trend. At San Francisco, the trend in tidal amplitude was found to be around 3-5% increase per century. Jay (2009) recently completed research into changes in tidal constituents, using long-term stations. Results indicated that on average tidal amplitude along the West Coast increased by about 2.2% per century. San Francisco indicated higher increases, while some stations (Alaska/Canada) were relatively constant. Jay hypothesized that global sea level rise may be influencing the location of the amphidrominc points (locations in the ocean where there are no tides) and thus affecting tidal range. However, Jay notes that it remains unclear whether rapid evolution of tidal amplitudes can be described as a symptom of global climate change.

Inland stations such Alameda and Port Chicago showed larger increases in tidal amplitudes than open ocean stations (9% and 26%, respectively). These inland stations have both short records and may be influenced by physical changes in the Bay. The importance of long-term tide records and open-ocean stations is stressed by both Flick et al and Jay for identifying trends in tidal amplitude due to the 18.6-year periodicity and influence of physical changes. Flick et al discounts the use of these inland stations for trends in tidal amplitude. In addition, Flick et al found that other nearby stations exhibited a decreased tidal amplitude trend (Point Reyes at -12% per century and Monterey at -14% per century).

Due to the considerable uncertainty associated with the tidal amplitude increase and the evolving science relating these changes to climate change and mean sea level rise, it is recommended to include a sensitivity analysis of increased tidal amplitude. The recommendation is to evaluate the effect of an amplitude increase of 5% per century, relying on the published observed trends of Flick et al and Jay and assuming that they would continue in the future. We do not propose using the inland stations trends, adhering to guidance from Flick et al. Thus, it is proposed to include one sensitivity simulation with the UNTRIM model, which incorporates an open-ocean tidal boundary, with increased tidal amplitude of 5% per century to contribute to understanding of the relative effect of amplitude increase in comparison to mean sea level increase.

A.7.8. Analytical Process for Incorporating Climate Change

The analytical process for incorporation of climate change effects in BDCP planning includes the use of several sequenced analytical tools (Figure A-2). The GCM downscaled climate projections (DCP), developed through the process described above, are used to create modified temperature and precipitation inputs for the Variable Infiltration Capacity (VIC) hydrology model. The VIC model simulates hydrologic processes on the 1/8th degree scale to produce watershed runoff (and other hydrologic variables) for the major rivers and streams in the Central Valley. The changes in reservoir inflows and downstream accretions/depletions are translated into modified input time series for the CALSIM II model. The CALSIM II simulates the response of the river-reservoir-conveyance system to the climate change derived hydrologic patterns. The CALSIM II model, in turn, provides monthly flows for all major inflow sources to the Delta, as well as the Delta exports, for input to the DSM2 hydrodynamic model. DSM2 also incorporates the assumptions of sea level rise for an integrated assessment of climate change effects on the estuary.

At each long-term BDCP analysis timeline (Early Long-Term: 2025 and Late Long-Term: 2060), five regional climate change projections are considered for the 30-year climatological period centered on the analysis year (i.e. 2011-2040 to represent 2025 timeline). DSM2 model simulations have been developed for each habitat condition and sea level rise scenario that is coincident with the BDCP timeline. New Artificial Neural Networks (ANNs) have been developed based on the flow-salinity response simulated by the DSM2 model. These sea level rise-habitat ANNs are subsequently included in CALSIM II models. The CALSIM II model has been simulated with each of the five climate change hydrologic conditions in addition to the historical hydrologic conditions.

The CALSIM II simulations have been developed for all alternatives and Future No Project/No Action Alternatives only for the mid-range climate change scenario (Q5).

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A.8. Regional Hydrologic Modeling

Regional hydrologic modeling is necessary to understand the watershed-scale impacts of historical and projected climate patterns on the processes of rainfall, snowpack development and snowmelt, soil moisture depletion, evapotranspiration, and ultimately changes in streamflow patterns. Future projected climate change, downscaled from global climate models (GCMs), suggests substantial warming throughout California and changes in precipitation. The effect of these changes in critical to future water management. In most prior analyses of the water resources of the Central Valley, the assumptions of hydroclimatic "stationarity", the concept that variability extends about relatively unchanging mean, have been made. Under the stationarity assumption, the observed streamflow record provides a reasonable estimate of the hydroclimatic variability. However, recent observations and future projections indicate that the climate will not be stationary, thus magnifying the need to understand the direct linkages between climate and watershed processes. Hydrologic models, especially those with strong, directly linkages to climate, enable these processes to be effectively characterized and provide estimates of changes in magnitude and timing of basin runoff with changes in climate conditions.

A.8.1. Variable Infiltration Capacity (VIC) Model

The VIC model (Liang et al. 1994; Liang et al. 1996; Nijssen et al. 1997) is a spatially distributed hydrologic model that solves the water balance at each model grid cell. The VIC model incorporates spatially distributed parameters describing topography, soils, land use, and vegetation classes. VIC is considered a macro-scale hydrologic model in that it is designed for larger basins with fairly coarse grids. In this manner, it accepts input meteorological data directly from global or national gridded databases or from GCM projections. To compensate for the coarseness of the discretization, VIC is unique in its incorporation of subgrid variability to describe variations in the land parameters as well as precipitation distribution. Parameterization within VIC is performed primarily through adjustments to parameters describing the rates of infiltration and baseflow as a function of soil properties, as well as the soil layers depths. When simulating in water balance mode, as done for this California application, VIC is driven by daily inputs of precipitation, maximum and minimum temperature, and windspeed. The model internally calculates additional meteorological forcings such short-wave and long-wave radiation, relative humidity, vapor pressure and vapor pressure deficits. Rainfall, snow, infiltration, evapotranspiration, runoff, soil moisture, and baseflow are computed over each grid cell on a daily basis for the entire period of simulation. An offline routing tool then processes the individual cell runoff and baseflow terms and routes the flow to develop streamflow at various locations in the watershed. Figure A-26 shows the hydrologic processes included in the VIC model.

The VIC model has been applied to many major basins in the United States, including large-scale applications to California's Central Valley (Maurer et. al 2002; Brekke et al 2007; Cayan et al. 2009), Colorado River Basin (Christensen and Lettenmaier, 2009), Columbia River Basin (Hamlet et al 2010), and for several basins in Texas (Maurer et al 2003; CH2M HILL 2008). The VIC model application for California was obtained from Dan Cayan and Tapash Das at Scripps Institute of Oceanography (SIO) and is identical to that used in the recent Climate Action Team (2009) studies. The VIC model was simulated by CH2M HILL and comparisons were performed

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with SIO to ensure appropriate transfer of data sets. No refinements to the existing calibration was performed for the BDCP application.

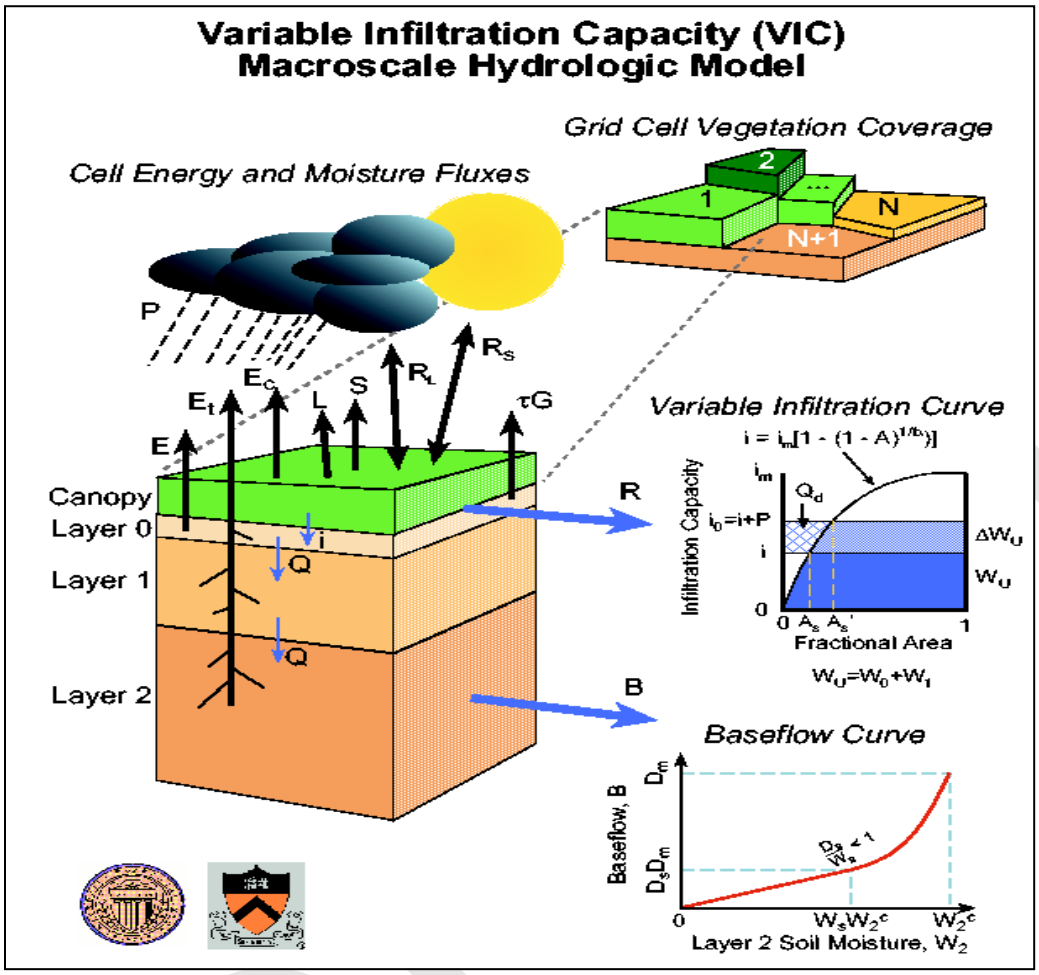

Figure A-26. Hydrologic Processes Included in the VIC Model (Source: University of Washington 2010)

A.8.2. Application of VIC Model for BDCP Evaluations

The regional hydrologic modeling is applied to support an assessment of changes in runoff associated with future projected changes in climate. These results are intended for use in comparative assessments and serve the primary purpose of adjusting inflow records in the CALSIM II long term operations model to reflect anticipated changes in climate. This section describes the regional hydrologic modeling methods used in the planning analysis for BDCP. The general flow of information is shown graphically in Figure A-2.

The GCM downscaled climate projections (DCP) are used to adjust historical California climate for the effects of climate change for each of the climate scenarios described in Section A.7. The resulting adjusted climate patterns, primarily temperature and precipitation fields are used as inputs to the VIC hydrology model. The VIC model is simulated for the each of the five climate scenarios at each BDCP long-term timeline. The VIC model simulations produce outputs of hydrologic parameters for each grid cell and daily and monthly streamflows at key locations in

the Sacramento River and San Joaquin River watersheds. The changes in "natural" flow at these locations between the observed and climate scenarios are then applied to adjust historical inflows to the CALSIM II model.

Model Domain

The VIC application for California was originally developed by University of Washington (Wood et al, 2000), but has been subsequently refined by Ed Maurer and others (Maurer et al 2002). The model grid consists of approximately 3000 grid cells at a 1/8th degree latitude by longitude spatial resolution. The VIC model domain is shown in Figure A-27 and covers all major drainages in California.

Observed Meteorology

The VIC application for the BDCP is run in water balance mode with inputs consisting of daily precipitation, minimum temperature, maximum temperature, and windspeed. The model internally calculates additional meteorological forcings such short-wave and long-wave radiation, relative humidity, vapor pressure and vapor pressure deficits. Daily gridded observed meteorology was obtained from the University of Washington (Hamlet and Lettenmaier 2005) for the period of 1915-2003. This data set adjusts for station inhomeniety (station length, movement, temporal trends) and is comparable to a similar observed data set developed by Maurer et al (2002) for the 1950-99 overlapping period. The longer sequence of this observed meteorology data set allow for improved simulation techniques and integration with CALSIM II model with commensurate time coverage. In addition, this observed data set is currently being applied by Cayan et al (2010) for the recent study on Southwest drought and Hamlet et al (2010) in their study of climate change in the Pacific Northwest. To better understand the sensitivity of the VIC modeling to different observed meteorology, comparative simulations using both the Hamlet data set and the Maurer data set were performed. The resulting simulated streamflows were comparable between the two data sets with relatively minor differences in individual months and years.

Daily Meteorology for Future Climate Scenarios

Scenarios of future climate were developed through methods as described in Section A.7. These ensemble informed scenarios consist of daily time series and monthly distribution statistics of temperature and precipitation for each grid cell for the entire state of California. Historical daily time series of temperature and precipitation are converted to representative future daily series through the process of quantile mapping which applies the change in monthly statistics derived from the climate projection information onto the input time series. The result of this process (described in detail in Section A.7.) is a modified daily time series that spans the same time period as the observed meteorology (1915-2003). Daily precipitation and temperature are adjusted based on the derived monthly changes and scaled according to the daily patterns in the observed meteorology. Wind speed was not adjusted in these analyses as downscaling of this parameter was not available, nor well-translated from global climate models to local scales.

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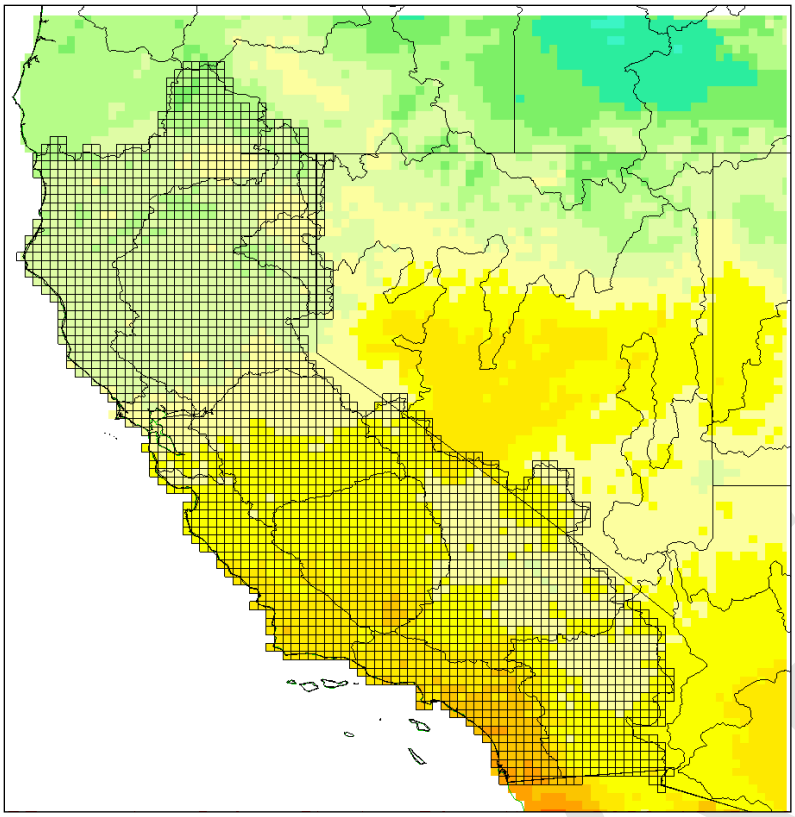

Figure A-27: VIC model domain and grid as applied for the BDCP application.

Grid Cell Characterization and Water Balance

As described previously, the VIC model was simulated in water balance mode. In this mode, a complete land surface water balance is computed for each grid cell on a daily basis for the entire model domain. Unique to the VIC model is its characterization of sub-grid variability. Sub-grid elevation bands enable more detailed characterization of snow-related processes. Five elevation bands are included for each grid cell. In addition, VIC also includes a sub-daily (1 hour) computation to resolve transients in the snow model. The soil column is represented by three soil zones extending from land surface in order to capture the vertical distribution of soil moisture. The VIC model represents multiple vegetation types as uses NASA's Land Data Assimulation System (LDAS) databases as the primary input data set.

For each grid cell, the VIC model computes the water balance over each grid cell on a daily basis for the entire period of simulation. For the simulations performed for the BDCP, water balance variables such as precipitation, evapotranspiration, runoff, baseflow, soil moisture, and snow water equivalent are included as output. In order to facilitate understanding of these watershed process results, nine locations throughout the in the watershed were selected for more detailed review. These locations are representative points within each of the following hydrologic basins: Upper Sacramento River, Feather River, Yuba River, American River, Stanislaus River, Tuolumne River, Merced River, and Upper San Joaquin River. The flow in these main rivers are included in the Eight River Index which is the broadest measure of total flow contributing to the Delta. A ninth location was selected to represent conditions within the Delta itself.

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Routing of Streamflows

The runoff simulated from each grid cell is routed to various river flow locations using VIC's offline routing tool. The routing tool processes individual cell runoff and baseflow terms and routes the flow based on flow direction and flow accumulation inputs derived from digital elevation models (Figure A-28). For the simulations performed for the BDCP, streamflow was routed to 21 locations that generally align with long-term gauging stations throughout the watershed. For the VIC application for the BDCP, several additional streamflow routing locations were added to ensure that all major watersheds contributing to Delta inflow were considered. The primary additions were the smaller drainages in the upper Sacramento Valley consisting of Cottonwood Creek and Bear River and the Eastside streams consisting of Cosumnes, Mokelumne, and Calaveras Rivers. Table A-10 lists these 21 locations. The flow at these locations also allows for assessment of changes in various hydrologic indices used in water management in the Sacramento-San Joaquin Delta. Flows are output in both daily and monthly time steps. Only the monthly flows were used in subsequent analyses. It is important to note that VIC routed flows are considered "naturalized" in that they do not include effects of diversions, imports, storage, or other human management of the water resource.

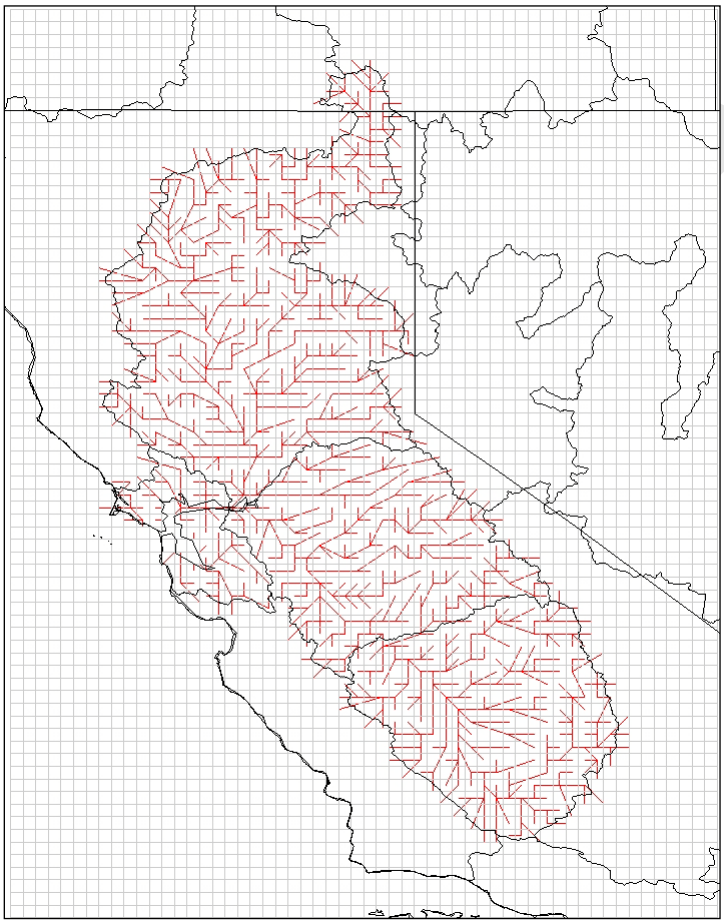

Figure A-28: VIC model routing network as applied for the BDCP application.

Table A-10: Listing of flow routing locations included in the VIC modeling.

Abbr	Name	Lat	Lon	VIC Lat	VIC Lon
SMITH	Smith River at Jed Smith SP	41.7917	-124.075	41.8125	-124.063
SACDL	Sacramento River at Delta	40.9397	-122.416	40.9375	-122.438
TRINI	Trinity River at Trinity Reservoir	40.801	-122.762	40.8125	-122.813
SHAST	Sacramento River at Shasta Dam	40.717	-122.417	40.6875	-122.438
SAC_B	Sacramento River at Bend Bridge	40.289	-122.186	40.3125	-122.188
OROVI	Feather River at Oroville	39.522	-121.547	39.5625	-121.438
SMART	Yuba River at Smartville	39.235	-121.273	39.1875	-121.313
NF_AM	North Fork American River at North Fork Dam	39.1883	-120.758	39.1875	-120.813
FOL_I	American River at Folsom Dam	38.683	-121.183	38.6875	-121.188
CONSU	Cosumnes River at Michigan Bar	38.5	-121.044	38.3125	-121.313
PRD_C	Mokelumne River at Pardee	38.313	-120.719	38.3125	-120.813
N_HOG	Calaveras River at New Hogan	38.155	-120.814	38.1875	-120.813
N_MEL	Stanislaus River at New Melones Dam	37.852	-120.637	37.9375	-120.563
MERPH	Merced River at Pohono Bridge	37.7167	-119.665	37.9375	-119.563
DPR_I	Tuolumne River at New Don Pedro	37.666	-120.441	37.6875	-120.438
LK_MC	Merced River at Lake McClure	37.522	-120.3	37.5625	-120.313
MILLE	San Joaquin River at Millerton Lake	36.984	-119.723	36.9375	-119.688
KINGS	Kings River - Pine Flat Dam	36.831	-119.335	37.1875	-119.438
COTTONWOOD	Cottonwood Creek near Cottonwood	40.387	-122.239		
CLEARCREEK	Clear Creek near Igo	40.513	-122.524		
BEARCREEK	Bear River near Wheatland	39.000	-121.407		

A.8.3. Output Parameters

As discussed previously the following key output parameters are produced on a daily and monthly time-step:

- Temperature, precipitation, runoff, baseflow, evapotranspiration, soil moisture, and snow water equivalent on grid-cell and watershed basis

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- Routed streamflow at major flow locations to the Sacramento Valley and San Joaquin Valley

A.8.4. Critical Locations for Analysis

The watershed hydrologic process information can be characterized for each of the approximately 3,000 grid cells, but the nine locations described above provide a reasonable spatial coverage of the changes anticipated in Central Valley. The routed streamflows at all 21 locations identified in Table A-10 are necessary to adjust the inflow timeseries and hydrologic indices in the CALSIM II model. Analysis of flows for watersheds much smaller than what is included here should be treated with caution given the current spatial discretization of the VIC model domain. The streamflows included in this analysis and used to adjust hydrology in the CALSIM II model account for over 95% of the total natural inflow to the Delta.

A.8.5. Modeling Limitations

The regional hydrologic modeling described using the VIC model is primarily intended to generate changes in inflow magnitude and timing for use in subsequent CALSIM II modeling. While the model contains several sub-grid mechanisms, the coarse grid scale should be noted when considering results and analysis of local scale phenomenon. The VIC model is currently best applied for the regional scale hydrologic analyses. The model is only as good as its inputs. There are several limitations to long-term gridded meteorology related to spatial-temporal interpolation and bias correction that should be considered. In addition, the inputs to the model do not include any transient trends in the vegetation or water management that may affect streamflows; they should only be analyzed from a "naturalized" flow change standpoint. Finally, the VIC model includes three soil zones to capture the vertical movement of soil moisture, but does not explicitly include groundwater. The exclusion of deeper groundwater is not likely a limiting factor in the upper watersheds of the Sacramento and San Joaquin River watersheds that contribute approximately 80-90 percent of the runoff to the Delta, however, in the valley floor groundwater management and surface water regulation is considerable. Water management models such as CALSIM II should be utilized to characterize the heavily "managed" portions of the system.

A.8.6. Linkages to Other Physical Models

The VIC hydrology model requires input related to historic and future meteorological conditions. Long-term historical gridded datasets have been obtained to characterize past climate. Future estimates of meteorological forcings are derived from downscaled climate projections incorporating the effects of global warming. The changes in routed streamflows between historic and future VIC simulations are used to adjust inflows and hydrologic indices for use in the CALSIM II model.

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example, installation of sedimentation barriers and other stormwater protections during grading—in contrast to mitigation measures that would be necessary to be included as part of project approval to offset the environmental effects of the proposed action. The rationale behind including environmental commitments is that the BCDP proponents commit to undertake and implement these measures as part of the project in advance of impact findings and determinations in good faith to improve the quality and integrity of the project, streamline the environmental analysis, and demonstrate responsiveness and sensitivity to environmental quality. .Environmental commitments that are incorporated into the alternatives are detailed in Appendix 3B.

4.3 Overview of Tools, Analytical Methods, and Applications

Several modeling tools and analytical methods were used to characterize and analyze the operational changes in water operations in the SWP and CVP systems under each alternative. These tools represent the best available technical tools for purposes of conducting the analyses at issue. The overall flow of information between the models and the general application and use of outputs for the resource evaluations are shown in Figure 4-1. Table 4-1 provides a description of the various modeling tools and an overview of how they may be applied for the environmental consequences analyses.

The models were used to compare and contrast the effects among various operating scenarios. The models incorporated a set of base assumptions; the assumptions were then modified to reflect the operations associated with each of the alternatives. The output of the models is used to show the comparative difference in the conditions among the different alternative scenarios. The model output does not predict absolute conditions in the future; rather, the output is intended to show what type of changes would occur. This type of model is described as comparative rather than predictive. Because of the comparative nature of these models, these results are best interpreted using various statistical measures such as long-term and year-type averages and probability of exceedance.

In general, CALSIM II is used to simulate the operations of the SWP and CVP. The output of this model is then used by the DSM2 model to simulate the hydrodynamics, water quality, and particle tracking. With the information generated from these models, the water supply, flows, and water quality can be compared under different operating scenarios. The output from these models are then used by a variety of other models to support the comparative analysis of various other resources, such as land use, economics, energy, temperature, and other water quality characteristics. Additional detailed discussions of the modeling tools and assumptions are provided in Appendix 4B, *Modeling Tools* .

[*Note to Lead Agencies: Table 4-1 in preparation*]

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Table 4-1. Overview of BDCP EIR/EIS Modeling Tools

Model Name	Description of Model
Artificial Neural Network (ANN)	ANN mimics the flow-salinity relationships as modeled in DSM2, and provides a rapid transformation of this information into a form usable by the Statewide CALSIM II model. ANN is implemented in CALSIM II to inform the operations of the upstream reservoirs and the Delta export pumps to satisfy particular salinity requirements.
CALSIM II	CALSIM II simulates operations of the SWP, CVP, and other facilities in the Central Valley and approximates changes in river flows and exports from the Delta. The principal results of interest for this phase of evaluation are changes to: (1) Sacramento River flows, (2) exports and south Delta flows, and (3) reservoir storage conditions associated with the assumed operation of the BDCP simulated scenarios.
Central Valley Hydrologic Model (CVHM)	CVHM is a three-dimensional numerical groundwater flow model that simulates subsurface and limited surface hydrologic processes over the entire Central Valley at a uniform grid-cell spacing of 1 mile.
Central Valley Hydrologic Model - Delta (CVHM-D)	CVHM-D simulates hydrologic processes in the Delta region at a more refined grid-cell spacing of 0.25 mile (compared to the grid-cell spacing of 1 mile with CVHM).
Central Valley Production Model (CVPM)	CVPM is a multi-regional model of irrigated agricultural production and economics that simulates the decisions of agricultural producers in California's Central Valley. The model includes up to 22 crop production regions in the Central Valley and 26 categories of crops. Surface water supplies are estimated by hydrologic models and groundwater use and pumping lift are estimated iteratively with a groundwater simulation model. CVPM model versions consider responses under average hydrologic conditions and responses during drought. The model maximizes the producer and consumer surplus to determine an optimal market solution. Output from CALSIM II surface water and groundwater models provide key modeling inputs to the CVPM agricultural production model.
Delta Simulation Model II (DSM2)	DSM2 is a one-dimensional hydrodynamic and water quality simulation model used to simulate hydrodynamics, water quality, and particle tracking. It describes the existing conditions in the Delta, as well as performs simulations for the assessment of incremental environmental impacts caused by facilities and operations. DSM2 uses flow data generated from CALSIM II outputs. DSM2 is simulated on a 15-minute time step to address the changing tidal dynamics of the Delta system.
IMPLAN	IMPLAN develops input-output estimates of the economic impacts of various activities. For water resources planning, IMPLAN estimates the income and employment effects upon local communities from water project construction and the regional effects of water transfers. Key modeling inputs for IMPLAN include output from the recreation economics analysis, CVPM, LCPSIM, and LCRBWQM.
Least Cost Planning SIMulation (LCPSIM)	LCPSIM is a simulation/optimization model that assesses the economic benefits and costs of increasing urban water service reliability at the regional level. The primary objective of LCPSIM is to develop a regional water management plan based on the principle of least-cost planning.

Administrative Draft

Note to Reader: This administrative draft document is being released prior to the public draft that will be released for formal public review and comment later in 2012. It incorporates comments by the Lead Agencies on prior versions, but has not been reviewed or approved by the Lead Agencies for adequacy in meeting the requirements of CEQA or NEPA. All members of the public will have an opportunity to provide comments on the public draft. Responses will be prepared only on comments submitted in the formal public review and comment period.

Model Name	Description of Model
Lower Colorado River Basin Water Quality Model (LCRBWQM)	LCRBWQM covers nearly the entire urban coastal region of southern California and assesses the regional economic effects of water salinity within the SWP system and Colorado River Aqueduct. The LCRBWQM salinity model assesses the average annual regional salinity benefits or costs based on demographic data; water deliveries; TDS concentration; and costs for typical household, agricultural, industrial, and commercial water uses. LCRBWQM uses mathematical functions that define the relationship between TDS and items in each affected category, such as the useful life of appliances, specific crop yields, and costs to industrial and commercial customers. The key model inputs into LCRBWQM are CALSIM II and DSM2 estimates of SWP East and West Branch deliveries and the concentration of TDS in these deliveries.
Reclamation Long Term-GEN (LT_GEN)	LT-GEN is a CVP power model that estimates the CVP power generation, capacity, and project use based on the operations defined by a CALSIM II simulation. The LT-GEN Model computes monthly power generation, capacity, and project use (pumping plant demand) for each CVP power facility for each month of the CALSIM II simulation.
Particle Tracking Model (PTM) (DSM2)	DSM2 PTM generates a weighted average entrainment risk of smelt from stations throughout the Delta based on an assumed starting distribution of smelt within the Delta and PTM results. This weighting is performed through post-processing of the PTM results to represent the proportion of fish that would occur in different parts of the Delta or starting distributions. The analysis focuses on the total proportion or percent of the population that would move to the different endpoints after 30 or 60 days under a project relative to existing conditions.
Reclamation Monthly Temperature Model - Sacramento River Basin (Reclamation Temperature)	This model predicts the effects of operations on water temperatures in the Sacramento, Feather, Stanislaus, and American river basins and upstream reservoirs. The model simulates monthly reservoir and stream temperatures used for evaluating the effects of SWP and CVP operations on mean monthly water temperatures in the basin based on hydrologic and climatic input data. The model uses CALSIM II output to simulate mean monthly vertical temperature profiles and release temperatures for five major reservoirs (Trinity, Whiskeytown, Shasta, Oroville, Folsom, and New Melones), four downstream regulating reservoirs (Lewiston, Keswick, , Natoma, and Goodwin), and four main river systems (Sacramento, Feather, American, and Stanislaus).
RMA	RMA2 is a surface hydrodynamic model that computes two-dimensional depth-averaged velocity and water surface elevation. RMA11 is a two-dimensional depth-averaged water quality model that computes a temporal and spatial description of conservative and non-conservative water quality parameters. RMA11 uses the results from RMA2 to describe the flow field. The model uses a depth-averaged approximation in the western Delta and Suisun Bay where substantial vertical gradients in salinity are often present. The model uses CALSIM outputs as inputs and produces results at a 15-minute time step.
State Water Project Power Model (SWP POWER)	SWP Power is an SWP power model that estimates the SWP power generation, capacity, and project use based on the operations defined by a CALSIM II simulation. The SWP Power Model computes monthly power generation, capacity, and project use (pumping plant demand) for each SWP power facility for each month of the CALSIM II simulation.
UnTRIM San Francisco Bay Delta Model (UnTRIM)	UnTRIM assesses the effects of sea level rise on Bay-Delta hydrodynamics and water quality. UnTRIM is a three-dimensional hydrodynamic model of the San Francisco Bay and Delta. Model outputs from UnTRIM are used to retrain ANN models with climate change and are corroborated with CALSIM II and DSM2.

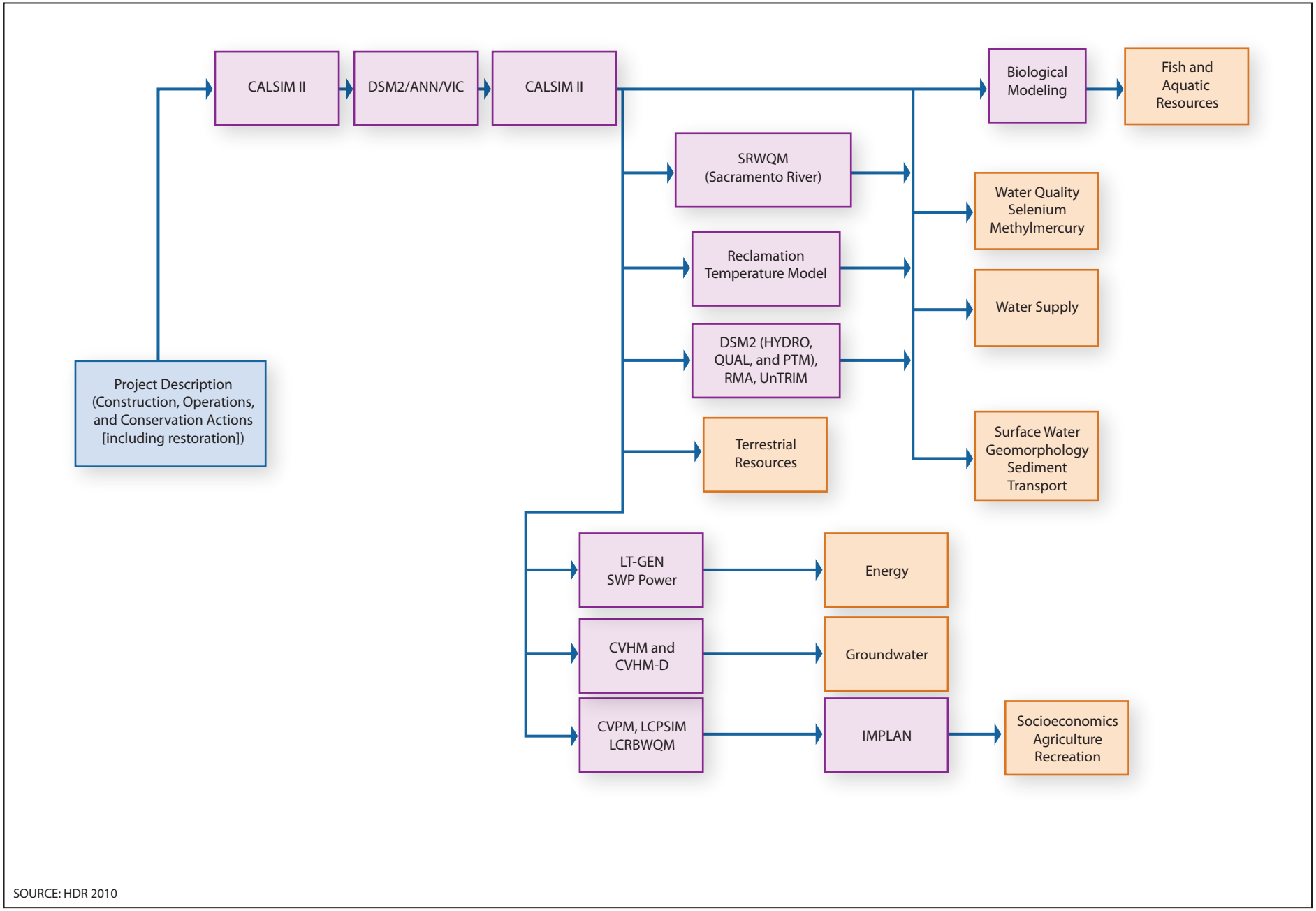
Administrative Draft

Note to Reader: This administrative draft document is being released prior to the public draft that will be released for formal public review and comment later in 2012. It incorporates comments by the Lead Agencies on prior versions, but has not been reviewed or approved by the Lead Agencies for adequacy in meeting the requirements of CEQA or NEPA. All members of the public will have an opportunity to provide comments on the public draft. Responses will be prepared only on comments submitted in the formal public review and comment period.

Model Name	Description of Model
Upper Sacramento River Water Quality Model (SRWQM)	SRWQM predicts the effects of operations to water temperature in the Sacramento River and Shasta and Keswick reservoirs. The model is a daily time step and provides water temperatures for each day of the 82-year hydrologic period used in CALSIM II.
Variable Infiltration Capacity (VIC)	VIC is a spatially distributed hydrologic model that solves water balance. Changes in routed stream flows from VIC simulations adjust inflows to the CALSIM II model. VIC incorporates spatially distributed parameters describing topography, soils, land use, and vegetation classes. The VIC model is driven by daily inputs of precipitation, maximum and minimum temperature, and wind speed.
CCHE2D	CCHE2D model is a two-dimensional depth-averaged, unsteady, flow and sediment transport model. The flow model is based on depth-averaged Navier-Stokes equations. The sediment transport module is used to simulate non-uniform sediment (both non-cohesive and cohesive) using non-equilibrium transport models.
Land Evaluation Site Assessment Model (LESA)	In the LESA system, the land evaluation rating is combined with the site assessment rating to determine the total rating of a specific site. The higher the total value of a site, the more likely the site is suited for long term agricultural production.
Other Municipal Water Economics Model (OMWEM)	
Statewide Agricultural Production Model (SWAP)	SWAP is an optimization model for major crops and agricultural regions in California and uses Positive Mathematical Programming (or PMP). SWAP has been used to estimate economic losses due to salinity in the Central Valley and economic losses to agriculture in the San Joaquin Delta
Bay Area Water Quality Economics Model (BAWQEM)	
OFFROAD2007	The OFFROAD Model estimates the relative contribution of gasoline, diesel, compressed natural gas, and liquefied petroleum gas powered vehicles to the overall emissions inventory of the state.
Emissions & Generation Resource Integrated Database (eGRID)	The eGRID is a comprehensive source of data on the environmental characteristics of almost all electric power generated in the United States. These environmental characteristics include air emissions for nitrogen oxides, sulfur dioxide, carbon dioxide, methane, and nitrous oxide; emissions rates; net generation; resource mix; and many other attributes.
URBan EMISsions (URBEMIS 2007)	URBEMIS 2007 estimates air pollution emissions from a wide variety of land use projects. The model uses the California Air Resources Board's EMFAC2007 model for on-road vehicle emissions and the OFFROAD2007 model for off-road vehicle emissions.
EMission FACtors (EMFAC 2007)	The EMFAC model is used to calculate emission rates from all motor vehicles, such as passenger cars to heavy-duty trucks, operating on highways, freeways and local roads in California
AERMOD Modeling System	A steady-state plume model that incorporates air dispersion based on planetary boundary layer turbulence structure and scaling concepts, including treatment of both surface and elevated sources, and both simple and complex terrain.

Administrative Draft

BDCP Figure 4-1



SOURCE: HDR 2010

BDCP EIR/EIS (12-6-2011)

DRAFT

Note: this figure will be updated for the public draft.

Figure 4-1

Use of Modeling Tools and Results in Analysis of BDCP Alternatives

BDCP Table 1

Table 1. Model Utilization in BDCP Effects Analysis

Model	Description	Applicable Effects Analysis Appendix								
		A	B	C	D	E	F	G	H	I
Conceptual Models	Conceptual models organize factors and relationships to explain phenomena. They are a starting point for development of quantitative models and stand on their own as a way to structure discussion and analyses.	X	X	X	X	X	X	X	X	
CALSIM II	The CALSIM II planning model simulates the operation of the CVP and SWP over a range of hydrologic conditions. CALSIM II produces key outputs that include river flows and diversions, reservoir storage, Delta flows and exports, Delta inflow and outflow, deliveries to project and non-project users, and controls on project operations.		X	X	X	X	X	X		
DSM 2	DSM2 is a one-dimensional hydrodynamic and water quality simulation model used to simulate hydrodynamics, water quality, and particle tracking in the Sacramento-San Joaquin Delta. The DSM2 model has three separate components, or modules: HYDRO, QUAL, and PTM.		X	X	X		X			
DSM 2 Hydro	DSM2-HYDRO predicts changes in flow rates and depths as a result of the BDCP and climate change. Outputs are used to determine the effects of these hydrodynamic parameters on covered terrestrial and fish species and as inputs to other biological models.			X	X					
DSM 2 Qual	The DSM-QUAL module simulates fate and transport of conservative and non-conservative water quality constituents, including salts, given a flow field simulated by HYDRO. Outputs are used to estimate changes in salinity and their effects on covered species as a result of the BDCP and climate change.			X			X			
DSM 2 PTM	The DSM-PTM module simulates fate and transport of neutrally buoyant particles through space and time. Outputs are used to estimate the effect of hydrodynamic changes on the fate and transport of larval fish and toxics through the Delta, as well as entrainment of larval fish at various locations.		X	X	X		X			
RMA	The RMA model output is used to evaluate the effects of tidal habitat restoration on flows throughout the Delta and the subsequent effects on covered species, aquatic and terrestrial. It is also used to calibrate CALSIM II and DSM 2.						X		X	
SRWQM	Output from the Sacramento River Water Quality Model is used as an input to a number of biological models for upstream lifestages of salmonids and sturgeon.			X	X					

Key to Appendices:

A: Conceptual Foundation and Analytical Framework	B: Entrainment	C: Flow, Salinity, Passage and Turbidity	D: Toxics	E: Habitat Restoration
F: Ecological	G: Fish Population	H: Terrestrial	I: Analyses Not Used	

Model	Description	Applicable Effects Analysis Appendix								
		A	B	C	D	E	F	G	H	I
USBR Temp Model	The USBR Temp Model is used to predict the effects of operations on water temperatures in the Feather, Stanislaus, Trinity, and American river basins, which are then used as inputs to the Reclamation Salmon Mortality Model and species-specific habitat evaluations.			X	X		X			
MIKE-21	Outputs of MIKE-21 are used to predict the area of inundated habitat in the Yolo Bypass for species such as splittail and Chinook salmon			X						
DRERIP	The Delta Regional Ecosystem Restoration Implementation Plan conceptual models and scientific evaluation process were developed to aid in planning and decision making for potential ecosystem restoration actions in the Delta. The 2009 DRERIP assessment of BDCP provided qualitative rankings for the effects on covered fish species from the conservation measures proposed at that time.	X	X	X	X	X	X			
Striped Bass Bioenergetics Model	The bioenergetics model is used to estimate predation rates of striped bass on covered fish species at the proposed North Delta diversion intakes. Results of the model are also used as inputs to the Delta Passage Model and Interactive Object-Oriented Salmon Simulation (IOS) Model.			X			X			
Delta Passage Model (DPM)	The Delta Passage Model is used to predict relative reach-specific survival estimates for winter, spring, and fall-run juvenile Chinook salmon passing through the Delta, as well as estimates of salvage in the south Delta export facilities.		X	X						
IOS	The Interactive Object-Oriented Salmon Simulation model is used to evaluate the effects of multiple aspects of the BDCP on survival of winter-run Chinook salmon and population viability.							X		
OBAN	Complementary to IOS, the Oncorhynchus Bayesian Analysis (OBAN) model is used to predict the effects of multiple BDCP actions on winter-run and spring-run Chinook salmon survival and population dynamics and population viability.			X				X		
SacEFT	The Sacramento River Ecological Flows Tool (SacEFT) is used to predict the effects of flow changes in the Sacramento River on a set of physical (spawning area, juvenile rearing area, redd scour, and redd dewatering) and biological (egg survival, juvenile stranding, and juvenile growth) parameters for all races of Chinook salmon and steelhead. The model also predicts flow-based effects on green sturgeon egg survival.			X	X					

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Model	Description	Applicable Effects Analysis Appendix								
		A	B	C	D	E	F	G	H	I
SALMOD	SALMOD is used to predict the effects of flows in the Sacramento River on habitat quality and quantity and ultimately on juvenile production of all races of Chinook salmon.			X						
USBR Salmon Mortality Model	This model is used to predict temperature-related proportional losses of eggs and fry for each race of Chinook salmon in the Trinity, Sacramento, Feather, American, and Stanislaus rivers.			X						
Fall X2 Model	Calculates surface area of water at 2 ppt salinity as related to the position of X2 during the fall (September-December).			X						
Covered Wildlife and Plant Species Habitat Models	Habitat models were developed for each of the covered wildlife and plant species based on vegetation/land cover associations that support each species' habitat type modified by parameters such as soil type, elevation, topography, spatial distribution, and proximity to aquatic habitats, as relevant.								X	
Salvage-Density Method	Uses historical salvage and flow data to predict entrainment		X							
Old and Middle River Flow Proportional Entrainment Regressions (delta smelt)	Uses linear regression (based on estimates from Kimmerer [2008], as well as estimates adjusted based on the rationale provided by Miller [2011]) and CALSIM data to estimate the proportion of delta smelt population that would be entrained		X							
Manly (2011) Salvage Estimation Equation (delta smelt)	Uses multiple regression to estimate salvage of adult delta smelt as a function of OMR flows, turbidity, and population size		X							
Effectiveness of Nonphysical Barriers	Discusses results of recent studies at Georgiana Slough and Old River as well as literature studies to determine potential effectiveness of barriers in other Delta locations		X	X						
Screening Effectiveness Analysis (North Delta Intake)	Estimate of potential for screening based on different sizes of fish approaching the north Delta intakes		X							

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Model	Description	Applicable Effects Analysis Appendix								
		A	B	C	D	E	F	G	H	I
Origin-of-flow analyses	Estimates the number of adult anadromous fish ending up at Fremont Weir.			X						
Fry-rearing benefit for Yolo Bypass	Quantifies fry benefits			X						
Habitat Suitability Indices	Quantifies the value of habitat for a particular covered species. Variables used depend on the species and available data.					X			X	
Maunder-Deriso delta smelt life cycle model	A state-space multi-stage lifecycle model that evaluates population impacts on delta smelt by allowing density dependence and environmental factors to impact different life stages.							X		
Kimmerer et al. X2-abundance Regression (longfin smelt)	Regression relationships using X2 to estimate annual abundance indices of longfin smelt in fall midwater trawls, bay midwater trawls, and bay otter trawls.			X						
Glibert Foodweb Regression	Regressions that estimate relative change in abundance of total chlorophyll, diatoms and dinoflagellates, and several copepod and fish species based on changes in individual nutrients and nutrient ratios, the latter having been derived from DSM2-QUAL modeling.									X
Copper Loading	Uses DSM 2 and the calculated total load of the contaminant within each watershed to estimate the diluted concentration of contaminant in the Plan Area.									X
Pyrethroid/EDC Loading	Uses DSM 2 and the calculated total load of the contaminant within each watershed to estimate the diluted concentration of contaminant in the Plan Area.									X
Selenium Loading	Uses DSM 2 and the calculated total load of the contaminant within each watershed to estimate the diluted concentration of contaminant in the Plan Area.									X
Mercury/Methylmercury Loading	Uses DSM 2 and the calculated total load of the contaminant within each watershed to estimate the diluted concentration of contaminant in the Plan Area.									X
Ammonia Loading	Uses DSM 2 and the calculated total load of the contaminant within each watershed to estimate the diluted concentration of contaminant in the Plan Area.									X
	Total Models	**2**	**12**	**22**	**10**	**5**	**10**	**6**	**5**	**6**

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Estimating California Central Valley Unimpaired Flows

Francis Chung, Ph.D., P.E.
Messele Ejeta, Ph.D., P.E

Modeling Support Branch
Bay-Delta Office
Department of Water Resources

January 6, 2011

Outline

- Key Points
- Definition of Unimpaired Flow (UF)
- Assumptions
- History
- Geographic Extent
- Data Sources for Estimating UF
- Sample Estimation Procedure
- Summary of Estimated UFs
- Limitations
- Closing

Key Points

- The unimpaired flows (UF) can be significantly different from the natural flows.
- UF is a conceptual quantity estimated through various means.
- UF is an imprecise estimate, and will require further improvement before being used as an operational flow criterion. This improvement can be made with careful design, time, and expert effort.
- Implementing the proposed flow criteria in real time operations will require timely acquisition of field data needed to estimate the UF.
- Timely acquisition of field data, and, under certain circumstances, forecasting certain components of the UF will pose extra challenges to the project operations.

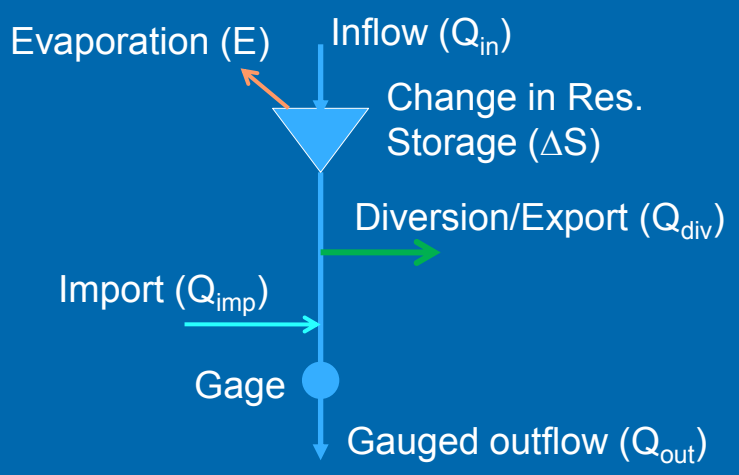
Definition of UF

- The following terms are (have been) used by DWR for UF
  - Full natural flow
  - Natural flow
  - Natural runoff
  - Unimpaired flow
  - Unimpaired runoff
- However, revised Bay-Delta Office Reports make distinctions between “Natural flow” and “Unimpaired flow”
  - Natural flow is a theoretical flow in pre-development or virgin state.
  - UF is an estimated flow for natural flow, not natural flow. The estimation assumes:
    - the existence of the current river configuration.
    - the same groundwater accretion and depletion as in historical condition.

Definition of UF (cont.)

- California Data Exchange Center (CDEC) Definition
  - "Full Natural Flow" or "Unimpaired Runoff" represents the natural water production of a river basin, unaltered by upstream diversions, storage, or by export or import of water to or from other watersheds.
- State Water Resources Control Board
  - Unimpaired flow is the total volume of water that would flow past a particular point of interest if no diversions (impairments) were taking place in the watershed above that point (taken from annual and seasonal unimpaired flow definitions).

Conceptual UF Estimation Procedure



$$UF = Q_{out} - Q_{imp} + Q_{div} + \Delta S + E$$

Assumptions

- Observed (gage) data is reliable.
- Change in stream groundwater interaction due to flow regulation is not included.
- Change in surface retention of precipitation (such as swamps) due to land use development is not included.
- Change in flow due to change in channel reconfiguration is not included.
- Water flow from upstream to downstream of the Sacramento and San Joaquin valleys are instantaneous (no routing).

History of UF Development

- First Edition (DWR, Apr 1980): California Central Valley Natural Flow Data
- Second Edition (DWR, Division of Planning, Feb 1987): California Central Valley Unimpaired Flow Data
  - (WY 1921 – 1983)
- Third Edition (DWR, Division of Planning, Aug 1994):
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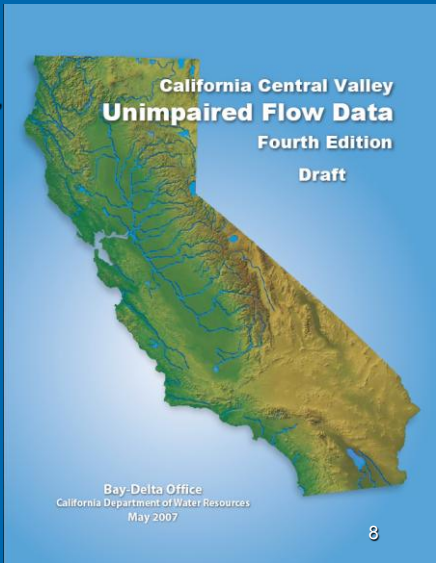
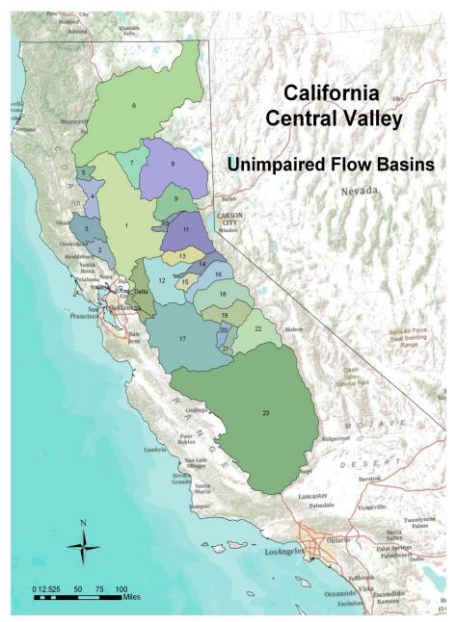


Geographic Extent

- Unimpaired flows are estimated for 24 river basins that are tributary to the Sacramento Valley, Eastside Streams, and San Joaquin Valley.



Data Sources

- USGS gages adjusted for upstream reservoir operations
- Proportionality between UF of unknown basin using UF of known basin in terms of area or precipitation
- Regression analysis (correlation between nearby watersheds)
- Depletion studies

Example : San Joaquin River at Millerton Reservoir (UF 22)

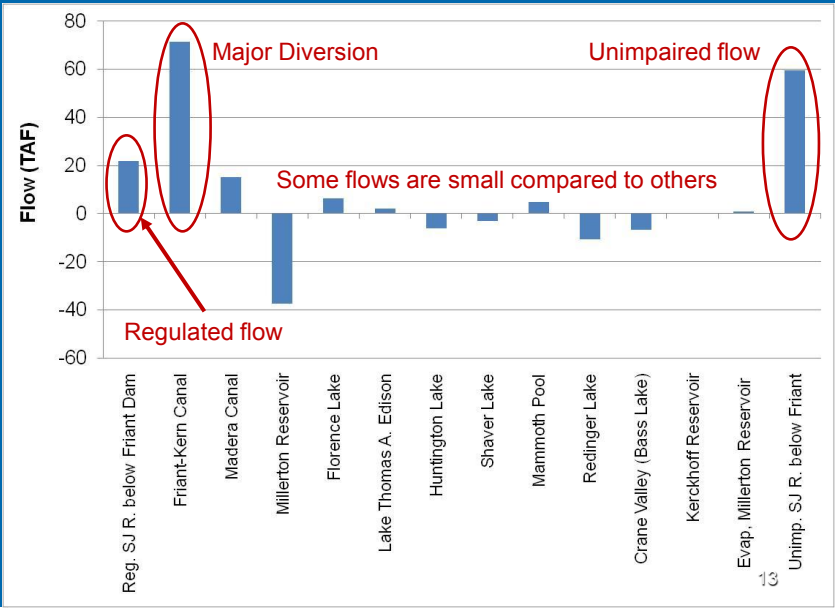
Example (cont.)

Example: San Joaquin River at Millerton Reservoir

Flow category	Adjustment	Flow description	Source
Observed flow	+	San Joaquin River below Friant Dam	USGS gage
Diversion	+	Friant-Kern Canal	MI2
	+	Madera Canal	MI1
Storage gain	+	Millerton Lake	MIL (RECL.)
	+	Florence Lake	FLR
	+	Lake Thomas A. Edison	TAE
	+	Huntington Lake	HNT
	+	Shaver Lake	SHV
	+	Mammoth Pool	MPL
	+	Redinger Lake	RDN
	+	Crane Valley (Bass Lake)	CNV
	+	Kerckhoff Reservoir	KRH
Evaporation	+	Millerton Lake	MIL (RECL.)
Unimpaired flow	Sum	San Joaquin River below Friant Dam	SJF

Example (cont.)

Example: San Joaquin River at Millerton Reservoir (October 2010 Data)



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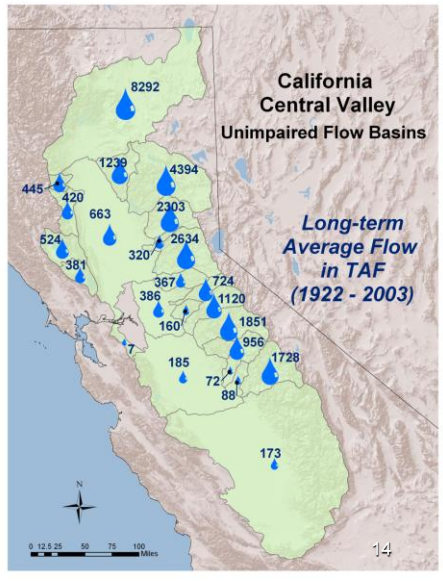
Summary of Estimated UFs in the Central Valley

Region	Long-term annual average flow volume (MAF)
Sac Valley	21.6
Eastside Streams	1.6
San Joaquin Valley	6.2
Delta Inflow	29.4



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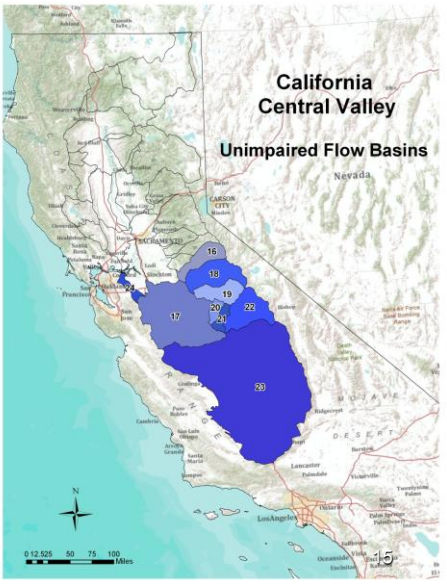
Components of the SJ Valley UF.

San Joaquin Valley outflow to the Delta

- 9 River basins (UF Basin 16 – 24)
- Contributes ~21% of flow to the Delta



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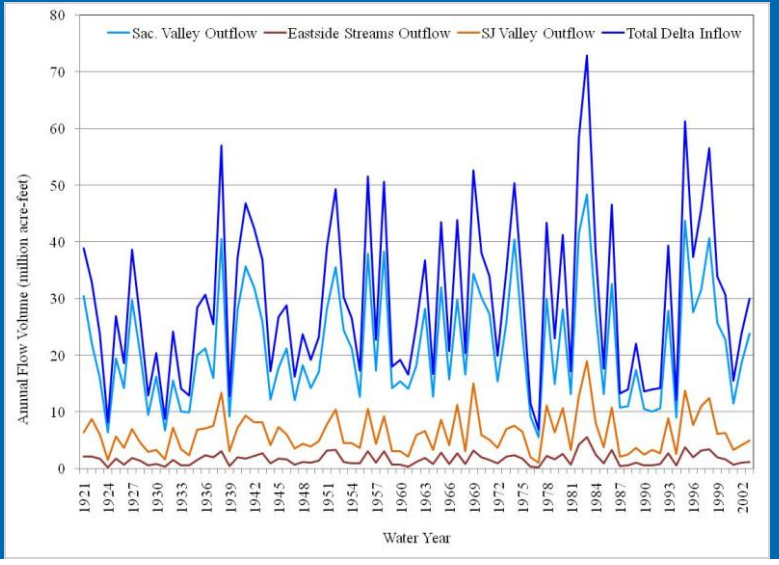
Summary of Estimated UFs to the Delta (cont.)



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Limitations

- Mixed use as natural flow
- Inconsistency of estimation approaches
- Access to proprietary data
- No flow routing
- Some estimates are based on expert judgment; hence not precise
- Data for early periods are poorly documented
- Groundwater use – recent studies show a significant level of stream-groundwater interaction shift in the Sac Valley

In Closing …

- The UF is viewed as a close surrogate to the natural flow. These two quantities, however, must be distinguished as they can be significantly different depending on the timing and location.
- UF is a conceptual quantity estimated through various means. Direct field measurement of the UF is not possible. UF has been used as an index in D1641 year classification.
- UF is an imprecise estimate requiring further improvement before being used as an operational flow criterion. Refinement is possible given careful design, time, resources and expert effort.
- Applying the proposed flow criteria to real time operations will require timely acquisition of field data that are necessary to estimate the UF. Timely acquisition of needed field data and, under certain circumstances, forecasting certain components of the UF can pose extra challenges to the project operations.

Acknowledgements

Robert H. Zettlemoyer
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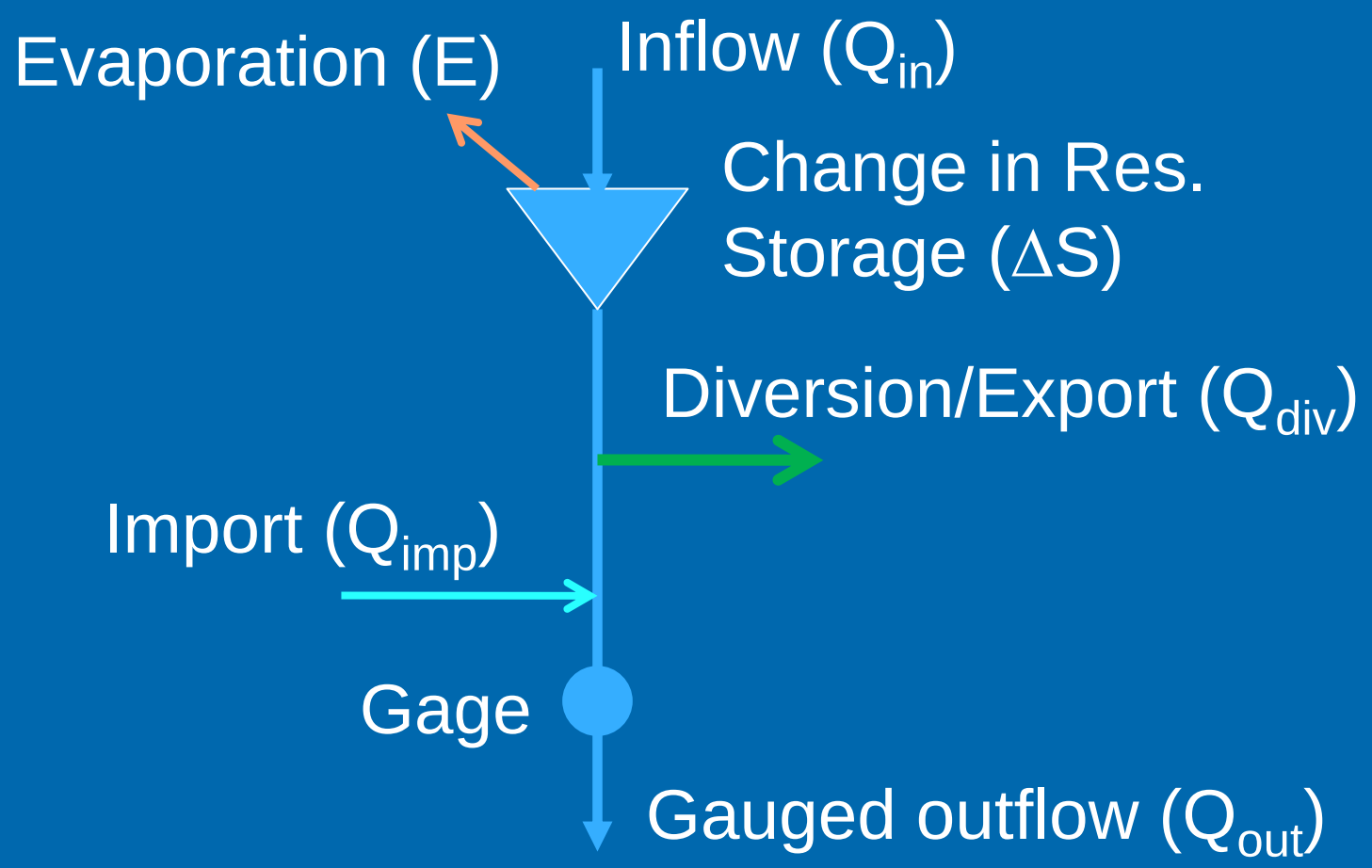

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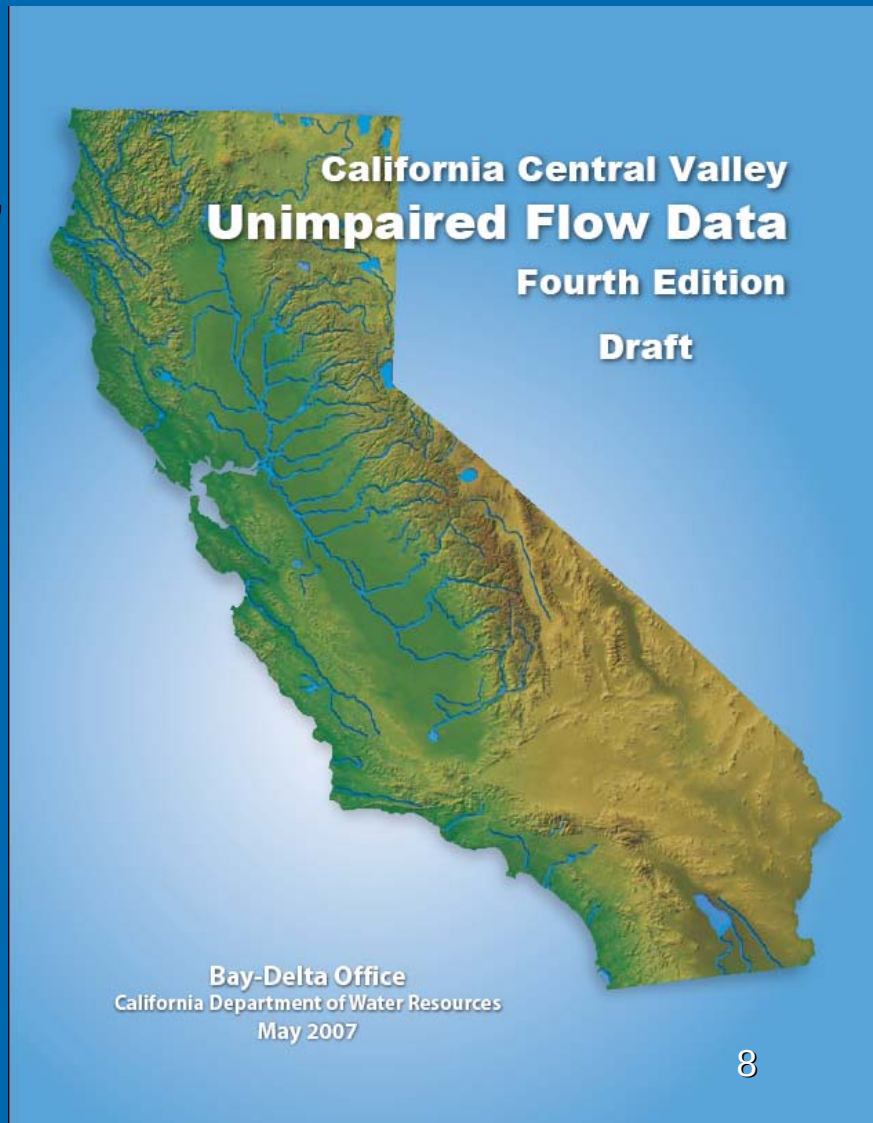
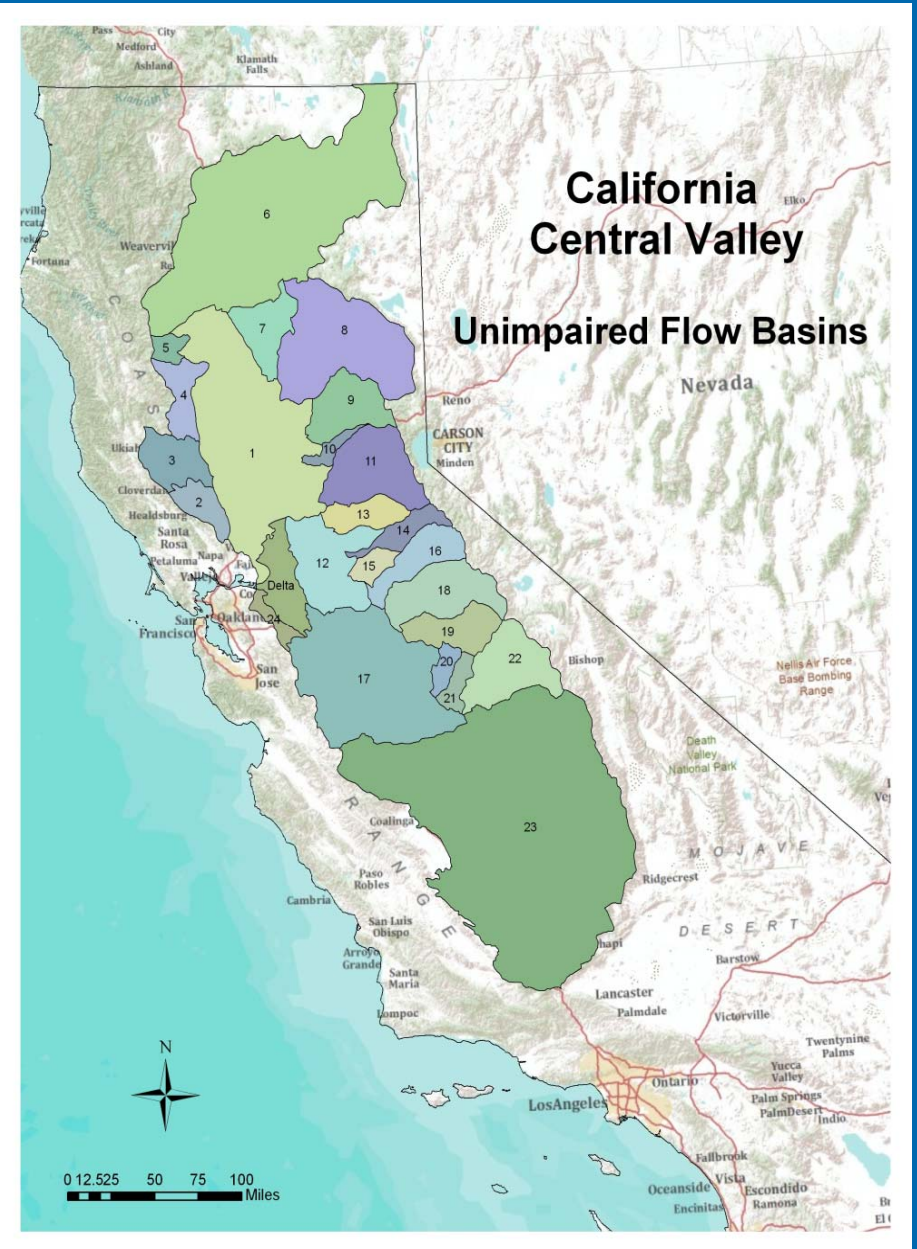


Geographic Extent

- Unimpaired flows are estimated for 24 river basins that are tributary to the Sacramento Valley, Eastside Streams, and San Joaquin Valley.



Data Sources

- USGS gages adjusted for upstream reservoir operations
- Proportionality between UF of unknown basin using UF of known basin in terms of area or precipitation
- Regression analysis (correlation between nearby watersheds)
- Depletion studies

Example : San Joaquin River at Millerton Reservoir (UF 22)

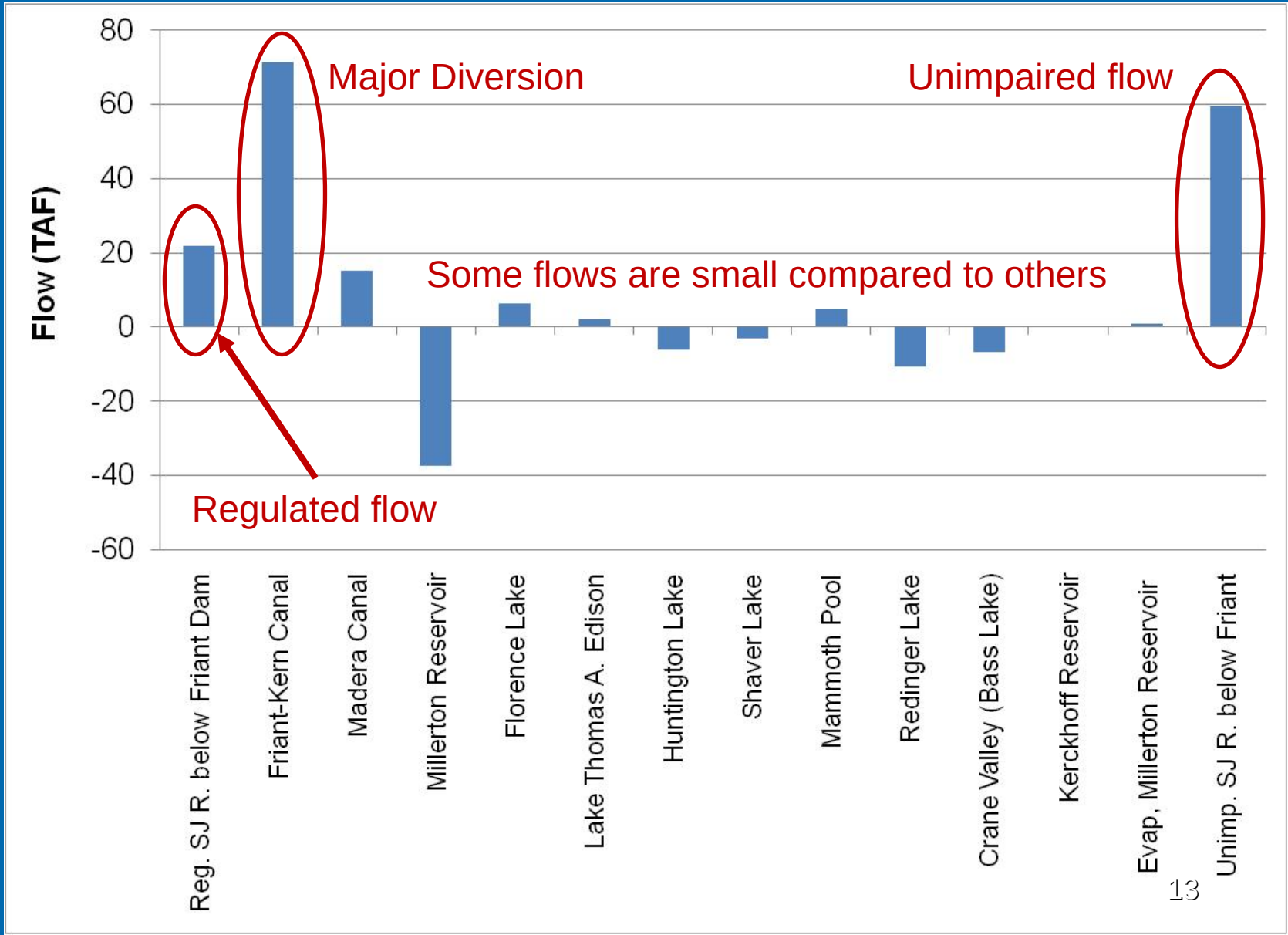
Example (cont.)

Example: San Joaquin River at Millerton Reservoir

Flow category	Adjustment	Flow description	Source
Observed flow	+	San Joaquin River below Friant Dam	USGS gage
Diversion	+	Friant-Kern Canal	MI2
	+	Madera Canal	MI1
Storage gain	+	Millerton Lake	MIL (RECL.)
	+	Florence Lake	FLR
	+	Lake Thomas A. Edison	TAE
	+	Huntington Lake	HNT
	+	Shaver Lake	SHV
	+	Mammoth Pool	MPL
	+	Redinger Lake	RDN
	+	Crane Valley (Bass Lake)	CNV
	+	Kerckhoff Reservoir	KRH
Evaporation	+	Millerton Lake	MIL (RECL.)
Unimpaired flow	Sum	San Joaquin River below Friant Dam	SJF

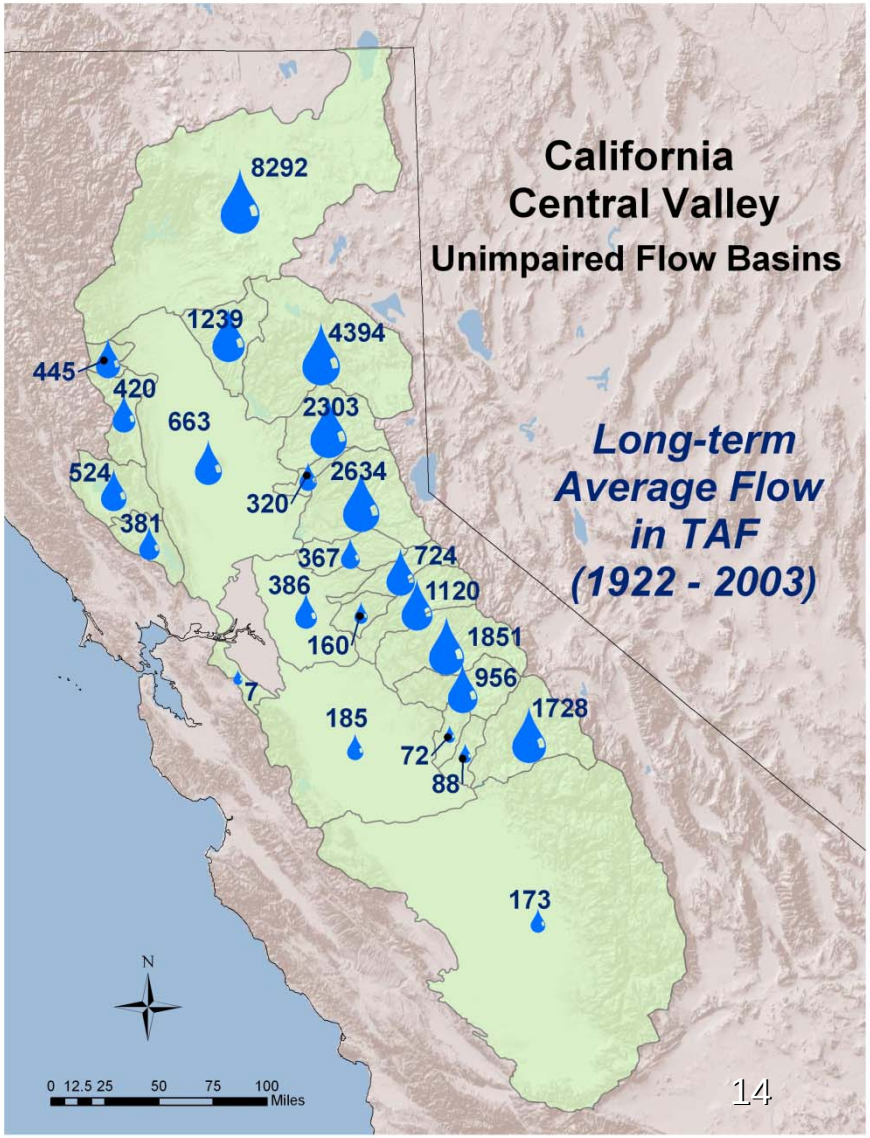
Example (cont.)

Example: San Joaquin River at Millerton Reservoir (October 2010 Data)



Summary of Estimated UFs in the Central Valley

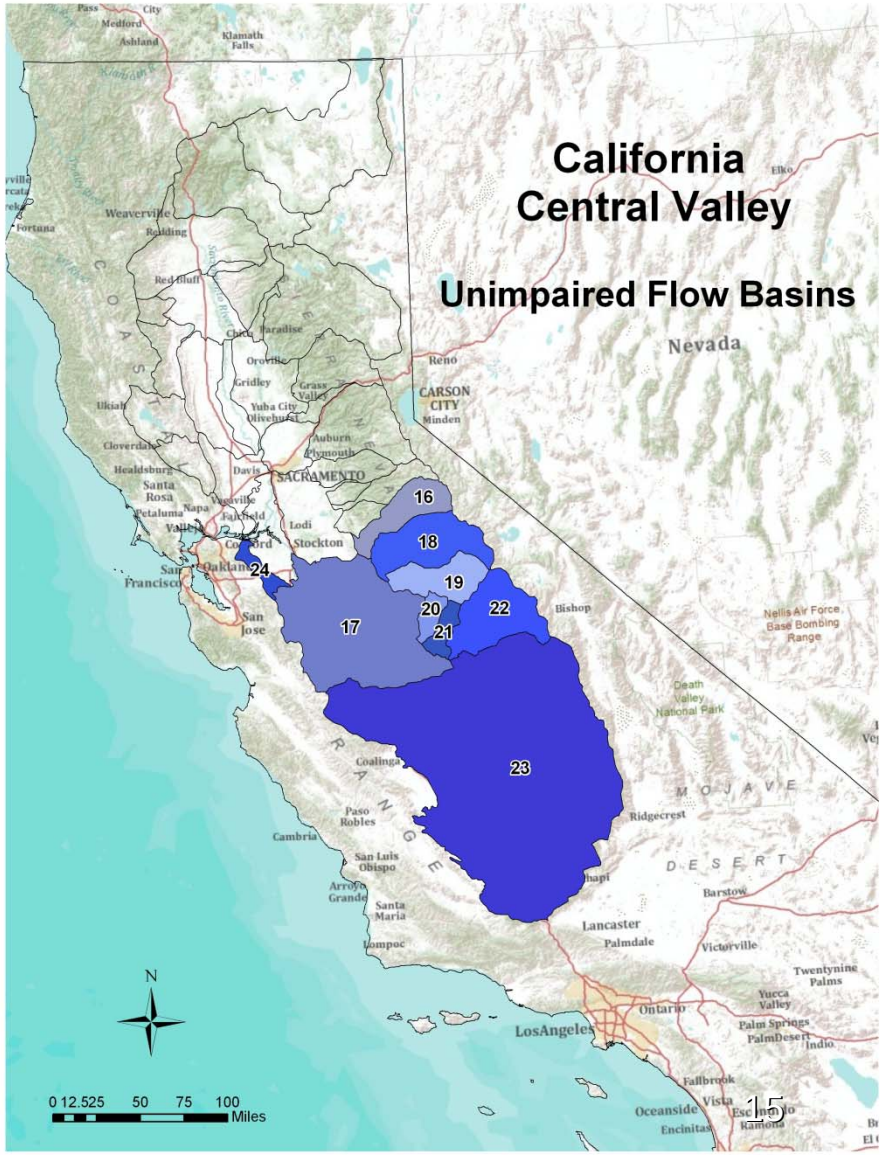
Region	Long-term annual average flow volume (MAF)
Sac Valley	21.6
Eastside Streams	1.6
San Joaquin Valley	6.2
Delta Inflow	29.4



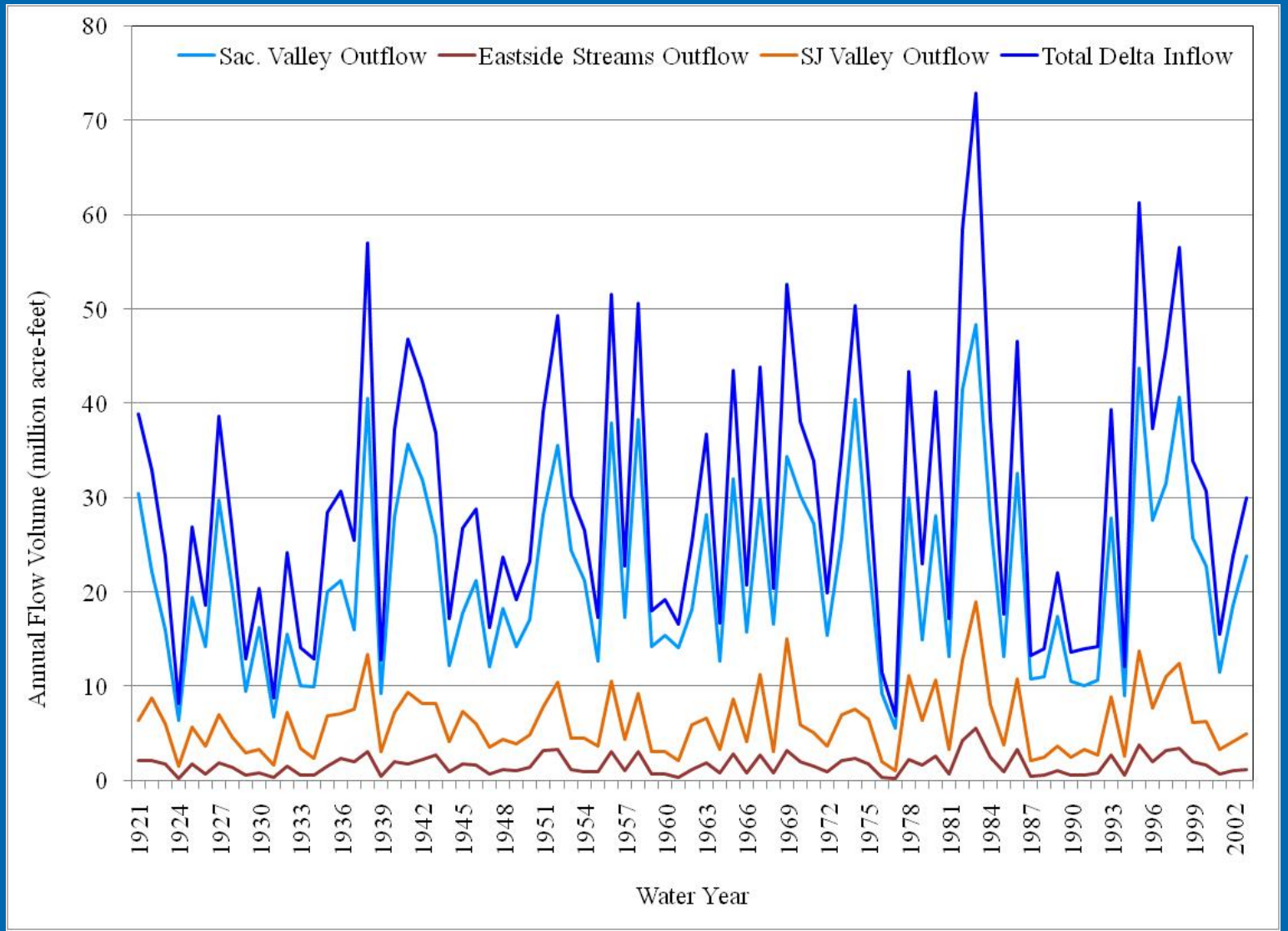
Components of the SJ Valley UF.

San Joaquin Valley outflow to the Delta

- 9 River basins (UF Basin 16 – 24)
- Contributes ~21% of flow to the Delta



Summary of Estimated UFs to the Delta (cont.)



Limitations

- Mixed use as natural flow
- Inconsistency of estimation approaches
- Access to proprietary data
- No flow routing
- Some estimates are based on expert judgment; hence not precise
- Data for early periods are poorly documented
- Groundwater use – recent studies show a significant level of stream-groundwater interaction shift in the Sac Valley

In Closing …

- The UF is viewed as a close surrogate to the natural flow. These two quantities, however, must be distinguished as they can be significantly different depending on the timing and location.

- UF is a conceptual quantity estimated through various means. Direct field measurement of the UF is not possible. UF has been used as an index in D1641 year classification.

- UF is an imprecise estimate requiring further improvement before being used as an operational flow criterion. Refinement is possible given careful design, time, resources and expert effort.

- Applying the proposed flow criteria to real time operations will require timely acquisition of field data that are necessary to estimate the UF. Timely acquisition of needed field data and, under certain circumstances, forecasting certain components of the UF can pose extra challenges to the project operations.

Acknowledgements

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Jane Schafer-Kramer

Thank you!

Natural Delta Outflow Water Balance

CWEMF Annual Meeting
February 25, 2014

J. Phyllis Fox, Consultant
Dan Howes, CSU San Luis Obispo
Andy Draper, MWH
Paul Hutton, Metropolitan Water District

Natural Delta Outflow Water Balance

Methods

Analysis & Results

Conclusions

What do we mean by "natural" conditions?

Water Balance Model

Long-Term Average Annual Natural Delta Outflow
Water Years 1922-2009

Delta Outflow = Water Supply – Water Use

where:

Water Supply = Rim Inflows + Valley Floor Precipitation

Water Use = $\Sigma\ (ET_v * A_v)$

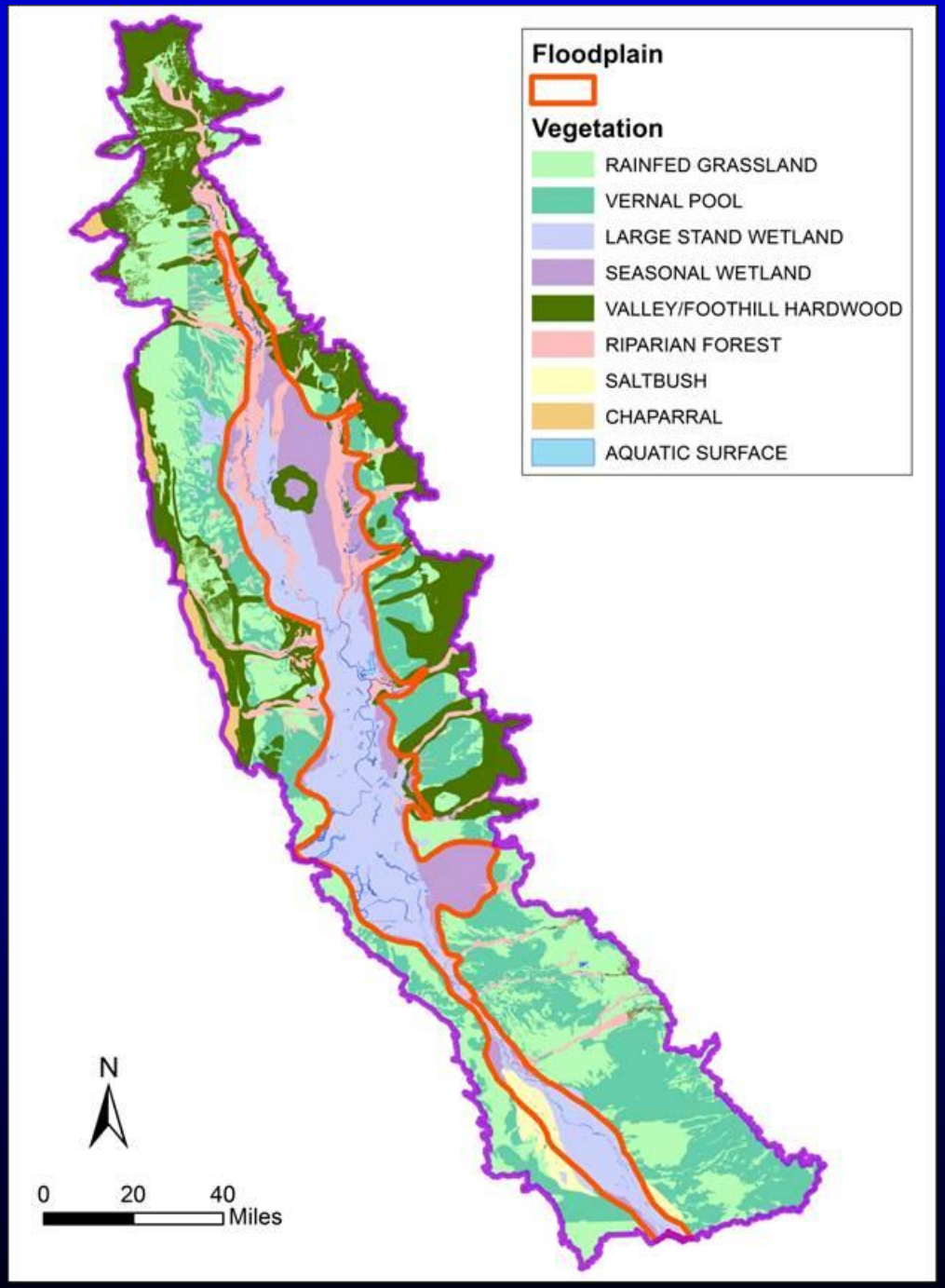
Basins
Sacramento
Delta
San Joaquin
Planning Area Boundary
Floodplain
503
504
506
507
511
509
510
603
602
607
608
606
609
N
0
20
40
Miles
Sacramento
San Francisco
Los Angeles

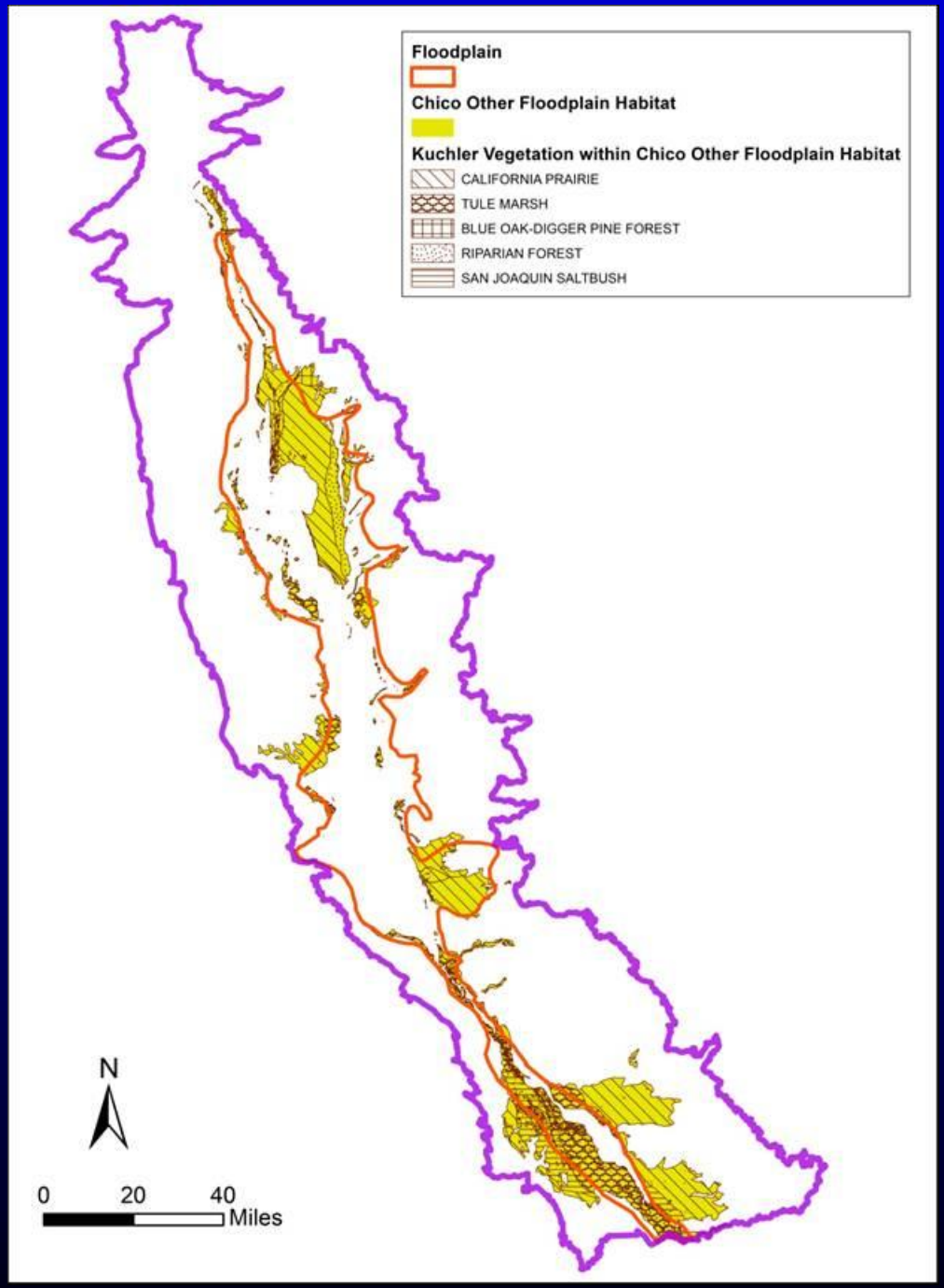
Natural Delta Outflow Water Balance

Methods

Analysis & Results

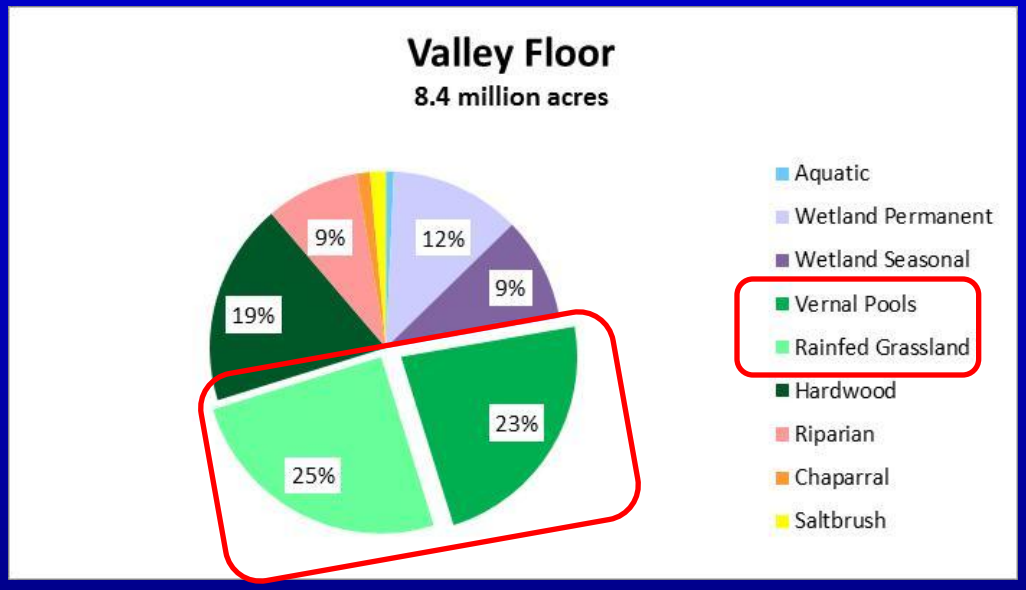
Conclusions

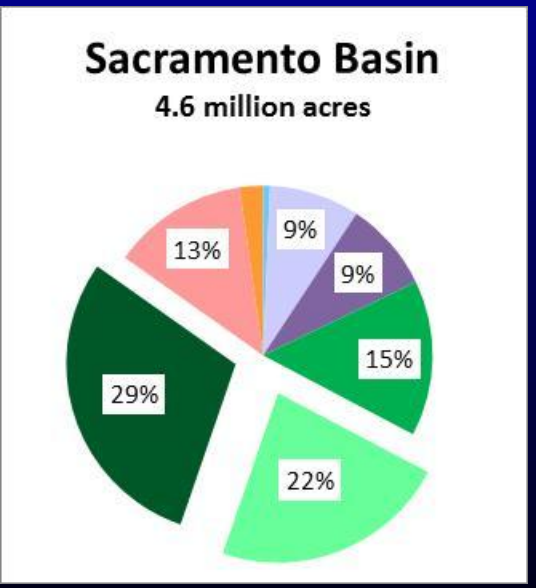

Floodplain
Vegetation
RAINFED GRASSLAND
VERNAL POOL
LARGE STAND WETLAND
SEASONAL WETLAND
VALLEY/FOOTHILL HARDWOOD
RIPARIAN FOREST
SALTBUSH
CHAPARRAL
AQUATIC SURFACE
N
0
20
40
Miles

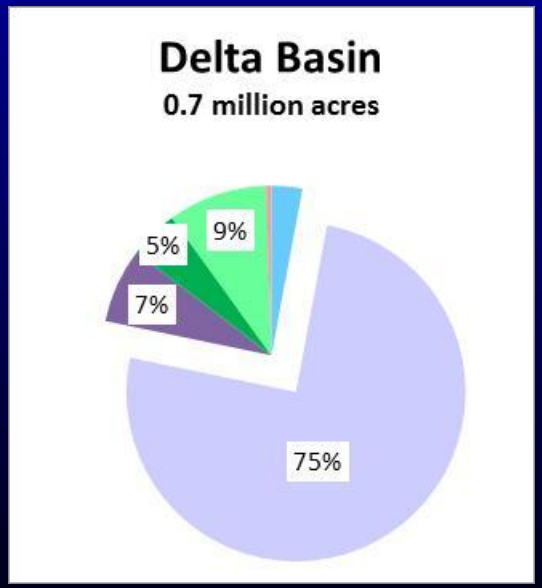

Floodplain
Chico Other Floodplain Habitat
Kuchler Vegetation within Chico Other Floodplain Habitat
CALIFORNIA PRAIRIE
TULE MARSH
BLUE OAK-DIGGER PINE FOREST
RIPARIAN FOREST
SAN JOAQUIN SALTBUSH
N
0
20
40
Miles

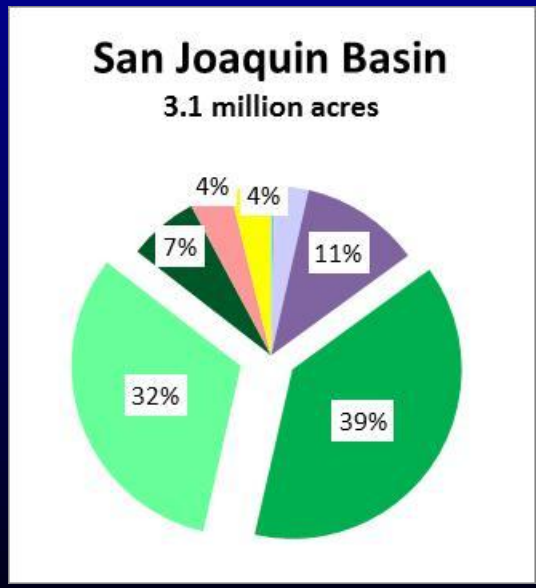
Natural Vegetation Distribution

Scenario 1: Grasslands as a Static Mix of Rainfed & Vernal Pools









Evapotranspiration Rates (ET_v)

88-Year Average (feet per year)

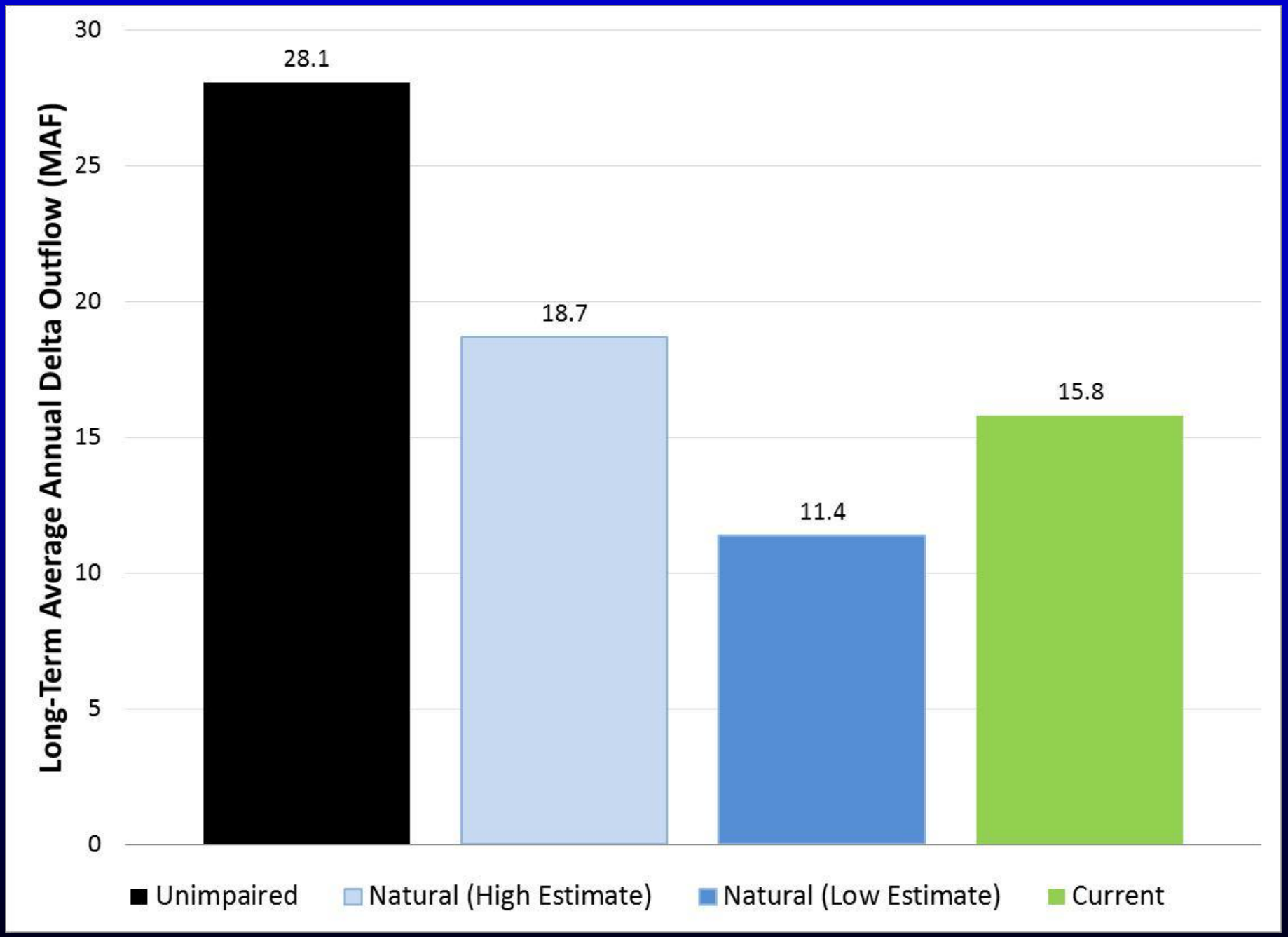
		Grasslands (48%)			Wetlands (21%)		Forest (28%)			Other (3%)		
Basin	Planning Area	Rainfed	Perennial	Vernal Pools	Permanent	Seasonal	Foothill Hardwood	Valley Oak Savanna	Riparian	Saltbrush	Chaparral	Aquatic Surface
Sacramento	503	1.3	4.3	2.5	4.6	4.2	1.5	2.2	4.4	2.0	1.0	4.2
	504	1.1	4.2	2.4	4.6	4.2	1.3	2.1	4.3	2.0	0.9	4.1
	506	1.1	4.4	2.6	4.8	4.4	1.3	2.2	4.5	2.0	0.8	4.3
	507	1.2	4.6	2.6	4.9	4.5	1.4	2.3	4.7	2.1	0.9	4.5
	509	1.1	4.5	2.6	4.8	4.4	1.3	2.2	4.6	2.1	0.8	4.3
Delta	510	1.0	4.5	2.6	4.9	4.4	1.3	2.2	4.6	2.1	0.8	4.4
	602	0.9	4.0	2.3	4.3	3.9	1.1	1.9	4.1	1.8	0.6	3.9
San Joaquin	511	1.1	4.7	2.7	5.1	4.6	1.4	2.4	4.8	2.2	0.9	4.6
	601	0.9	3.7	2.2	4.0	3.7	1.1	1.8	3.8	1.7	0.6	3.6
	603	1.1	4.7	2.7	5.1	4.6	1.4	2.3	4.8	2.2	0.8	4.6
	606	0.8	4.4	2.6	4.8	4.4	1.0	2.0	4.6	2.1	0.6	4.3
	607	1.0	4.6	2.7	5.0	4.5	1.2	2.2	4.7	2.1	0.7	4.5
	608	0.9	4.7	2.8	5.1	4.7	1.2	2.3	4.9	2.2	0.7	4.6
	609	1.0	5.0	2.9	5.4	4.9	1.2	2.3	5.1	2.3	0.7	4.9
Range		0.9-1.2	3.7-5.0	2.2-2.9	4.0-5.4	3.7-4.9	1.0-1.5	1.8-2.4	3.8-5.1	1.7-2.3	0.6-1.0	3.6-4.9

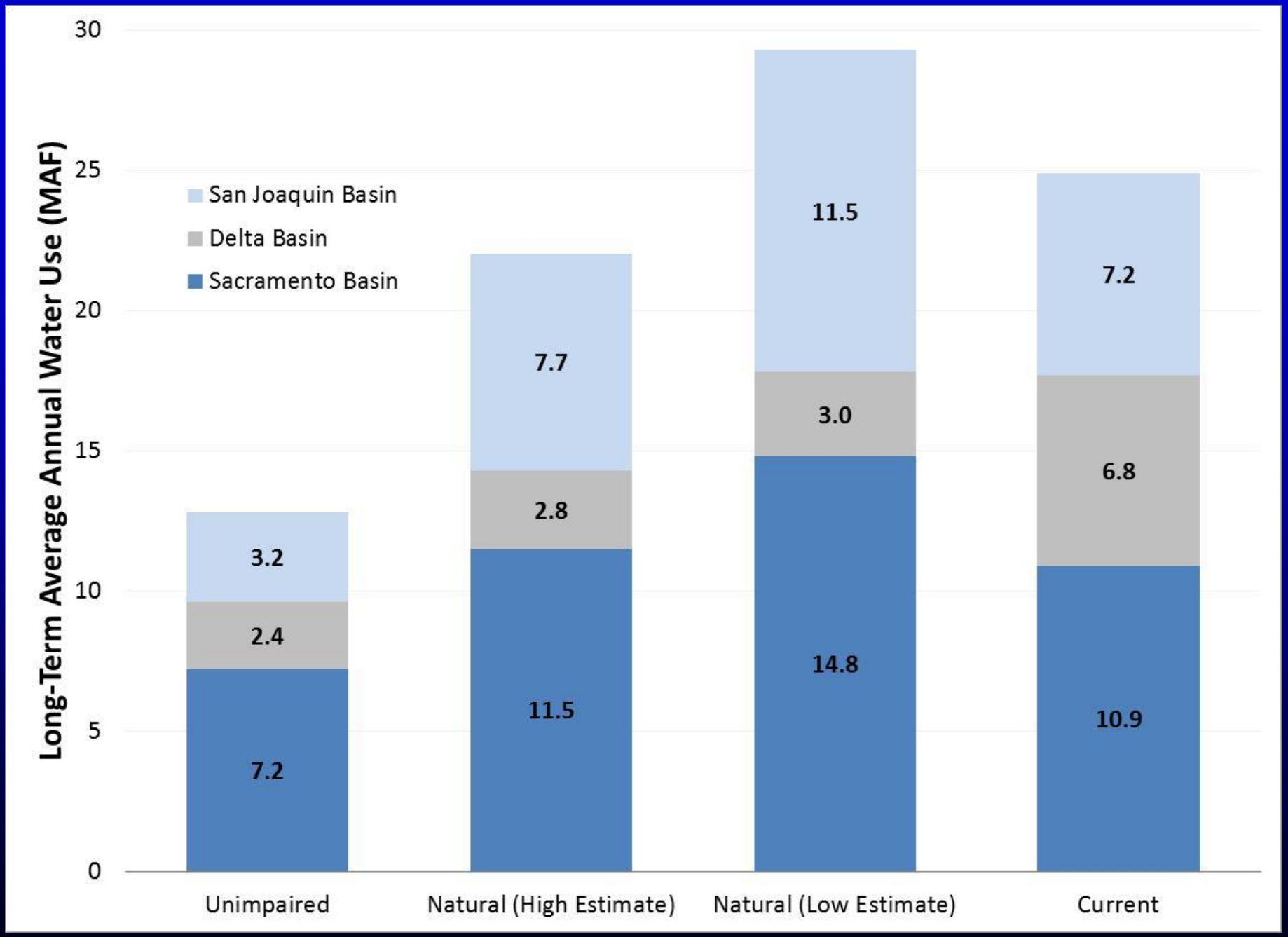
#	Scenario Category	Deviation from Scenario 1
2	Constant Area Grassland Scenarios	Grassland vegetation assumed as “Vernal Pools”
3		Grassland vegetation assumed as mix of “Vernal Pools” and “Perennial”
4		Grassland vegetation assumed as mix of “Vernal Pools” and “Perennial” in Sacramento & Delta Basins & assumed as “Rainfed” in San Joaquin Basin
5	Variable Area Grassland Scenarios	Grassland vegetation (except “Vernal Pools”) assumed as mix of “Perennial” and “Rainfed” that varies annually with Valley Floor natural inflow
6		Grassland vegetation assumed as mix of “Perennial” and “Rainfed” that varies annually with Valley Floor natural inflow
7	Other Scenarios	Hardwood vegetation assumed as “Valley Oak Savanna”
8		Same as Scenario 5 except “Seasonal Wetlands” assumed as “Rainfed Grasslands” in San Joaquin Basin floodplain

Natural Water Balance

Water Years 1922-2009
MAF per year

Water Supply								
Rim Inflow	**27.7**							
Precipitation	**12.9**							
Total	**40.6**							
Water Use	#1	#2	#3	#4	#5	#6	#7	#8
Sacramento Basin	11.5	12.9	14.8	14.8	12.7	12.6	12.6	14.8
Delta Basin	2.8	2.9	3.0	3.0	2.8	2.8	2.8	3.0
San Joaquin Basin	7.7	9.5	11.5	5.4	9.1	8.6	7.9	4.1
Total	21.9	25.2	29.2	23.2	24.7	24.1	23.2	21.9
Delta Outflow	**18.7**	**15.4**	**11.4**	**17.4**	**15.9**	**16.5**	**17.4**	**18.7**


Long-Term Average Annual Delta Outflow (MAF)
30
25
20
15
10
5
0
28.1
18.7
11.4
15.8
Unimpaired
Natural (High Estimate)
Natural (Low Estimate)
Current


Long-Term Average Annual Water Use (MAF)
30
25
20
15
10
5
0
San Joaquin Basin
Delta Basin
Sacramento Basin
3.2
2.4
7.2
7.7
2.8
11.5
11.5
3.0
14.8
7.2
6.8
10.9
Unimpaired
Natural (High Estimate)
Natural (Low Estimate)
Current

Natural Delta Outflow Water Balance

Methods

Analysis & Results

Conclusions

Conclusions

- Long-term average annual Delta outflow is approximately 16 MAF under natural conditions, roughly the same as current LOD outflow.
- Unimpaired outflow calculations should not be used to represent natural conditions, as they do not account for the natural landscape and vegetation water use.
- Natural grassland composition poses the most significant area of uncertainty and is thought to be strongly influenced by groundwater conditions and flood frequency and duration.

Paul Hutton, Ph.D., P.E.
phutton@mwdh2o.com

Unimpaired Water Balance for the Valley Floor 1922-2003 (MAF/year)		
Water Supply		
Inflow (from rim watersheds)	27.7	
Precipitation (on Valley Floor)	12.9	
Total Water Supply		40.6
Water Use		
Sacramento Basin	7.2	
Delta	2.4	
San Joaquin Basin	3.2	
Total Water Use		12.8
Delta Outflow		27.8

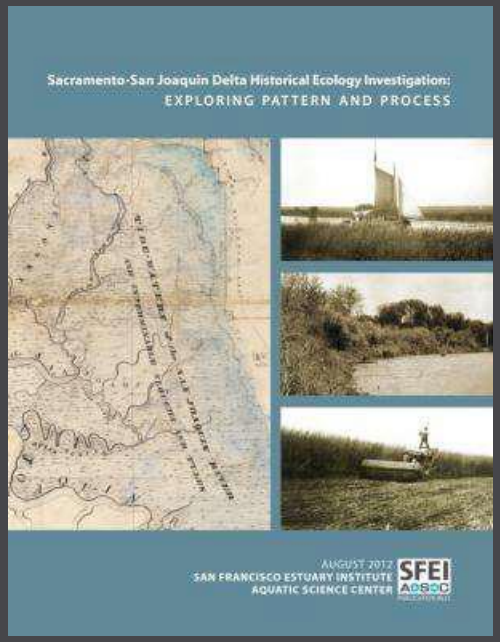
Current LOD Water Balance for the Valley Floor 1922-2003 (MAF/year)		
Water Supply		
Inflow (from rim watersheds)	27.7	
Precipitation (on Valley Floor)	12.9	
Total Water Supply		40.6
Water Use		
Sacramento Basin	10.9	
Delta	6.8	
San Joaquin Basin	7.2	
Total Water Use		24.8
Delta Outflow		15.8

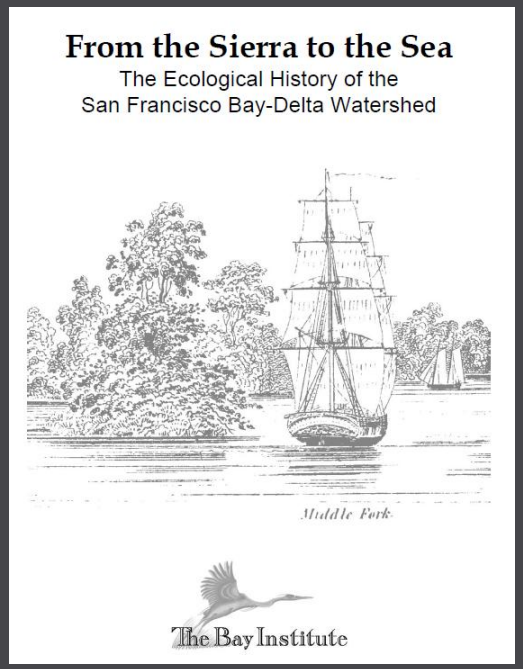
Overview of Recent Efforts to Characterize Natural Delta Outflow

Paul Hutton, Ph.D., P.E.
Metropolitan Water District
Curt Schmutte, P.E.
Consultant

Purpose

- Gain Insights into Natural Hydrologic Conditions
  - A return to natural conditions is not a realistic goal.
  - However, understanding the biological functions provided under natural conditions is necessary for effective restoration efforts.
- Demonstrate that Unimpaired Outflow Does Not Provide a Reasonable Approximation of Natural Hydrologic Conditions





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Guobiao Huang, DWR

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UC Davis

DWR

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Sam Safran, SFEI

Julie Beagle, SFEI

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Alison Whipple, UC Davis

Andy Bell, UC Davis

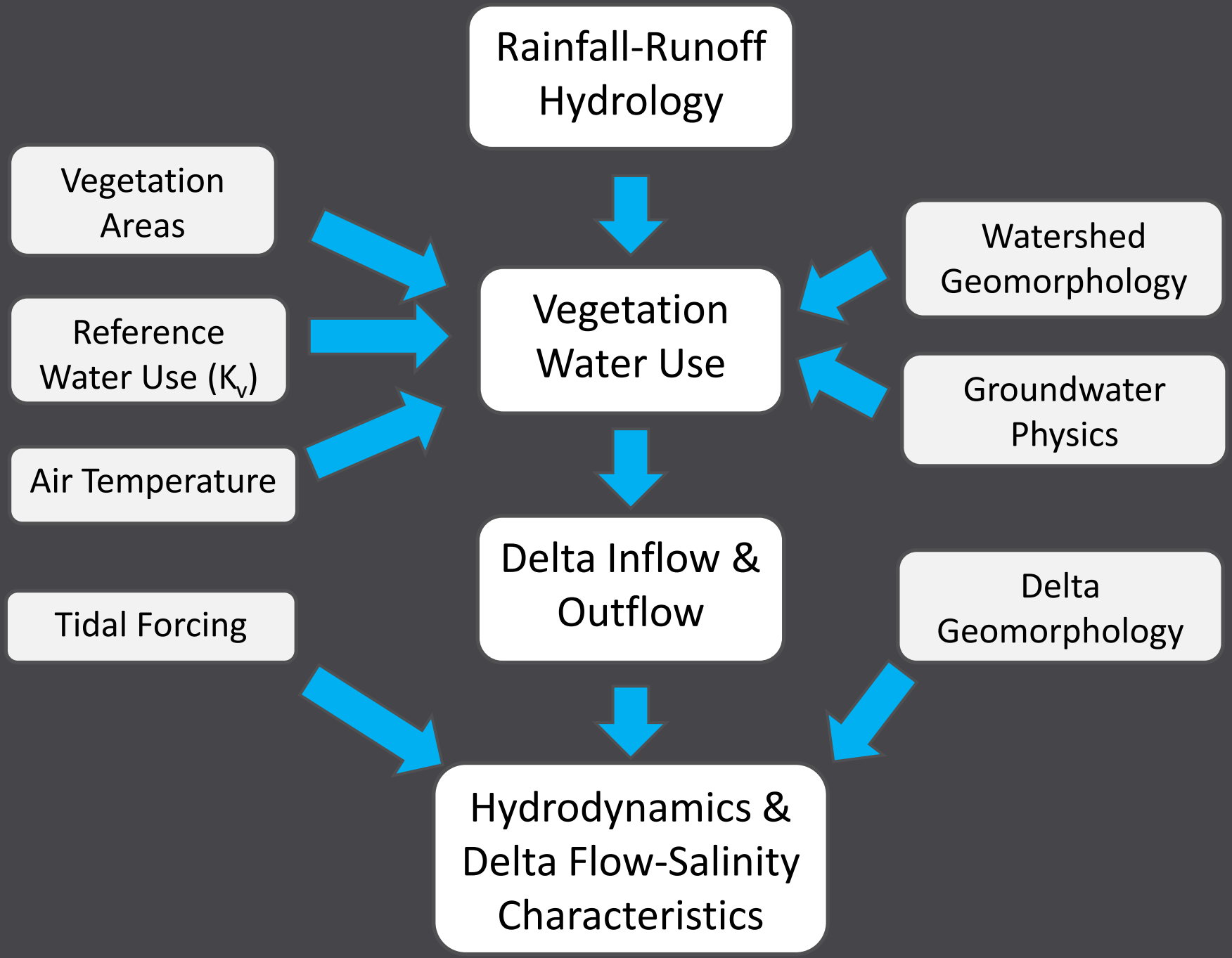
Mui Lay, UC Davis

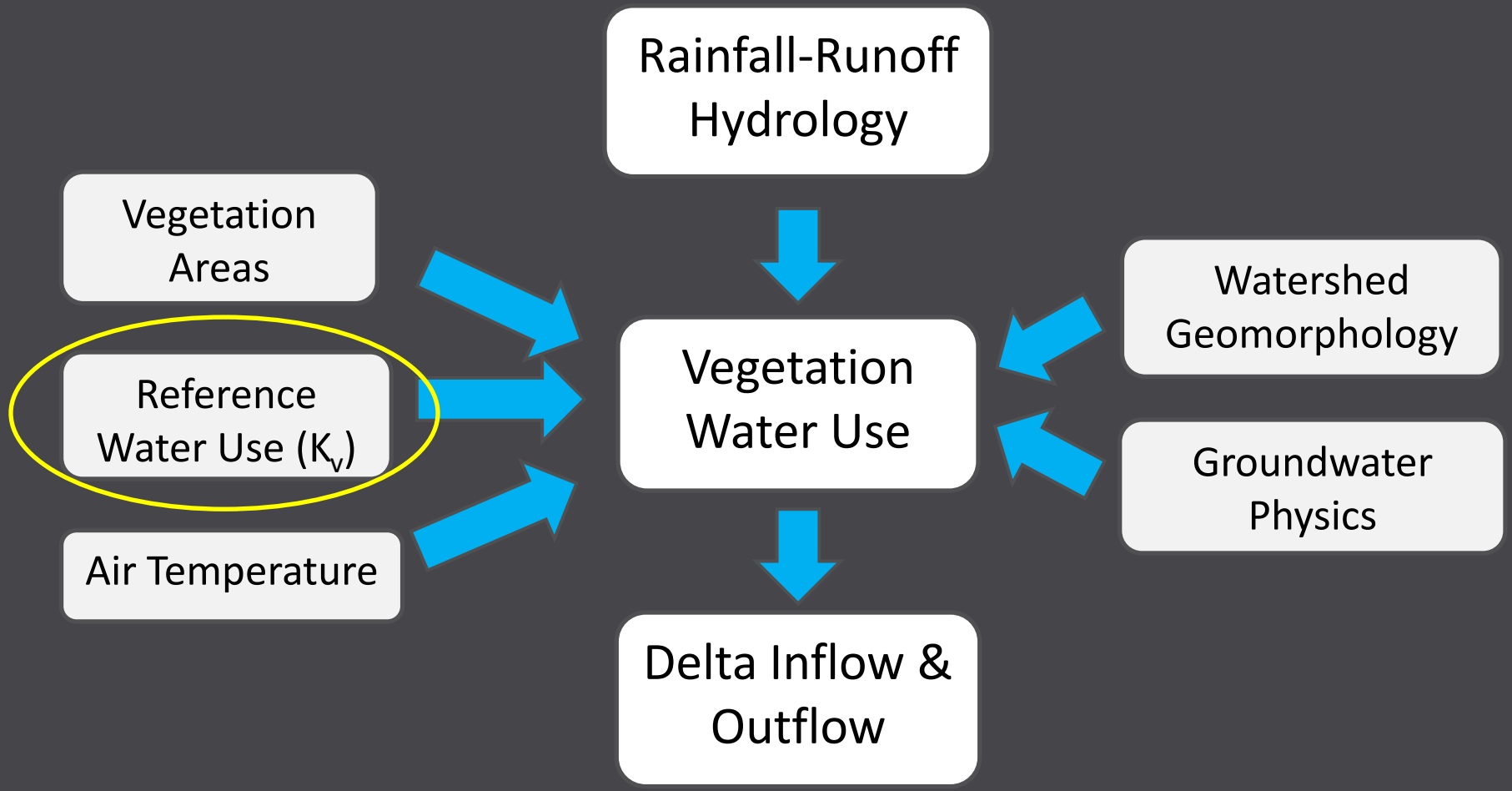
John DeGeorge, RMA

Edward Gross, RMA

Stephen Andrews, RMA

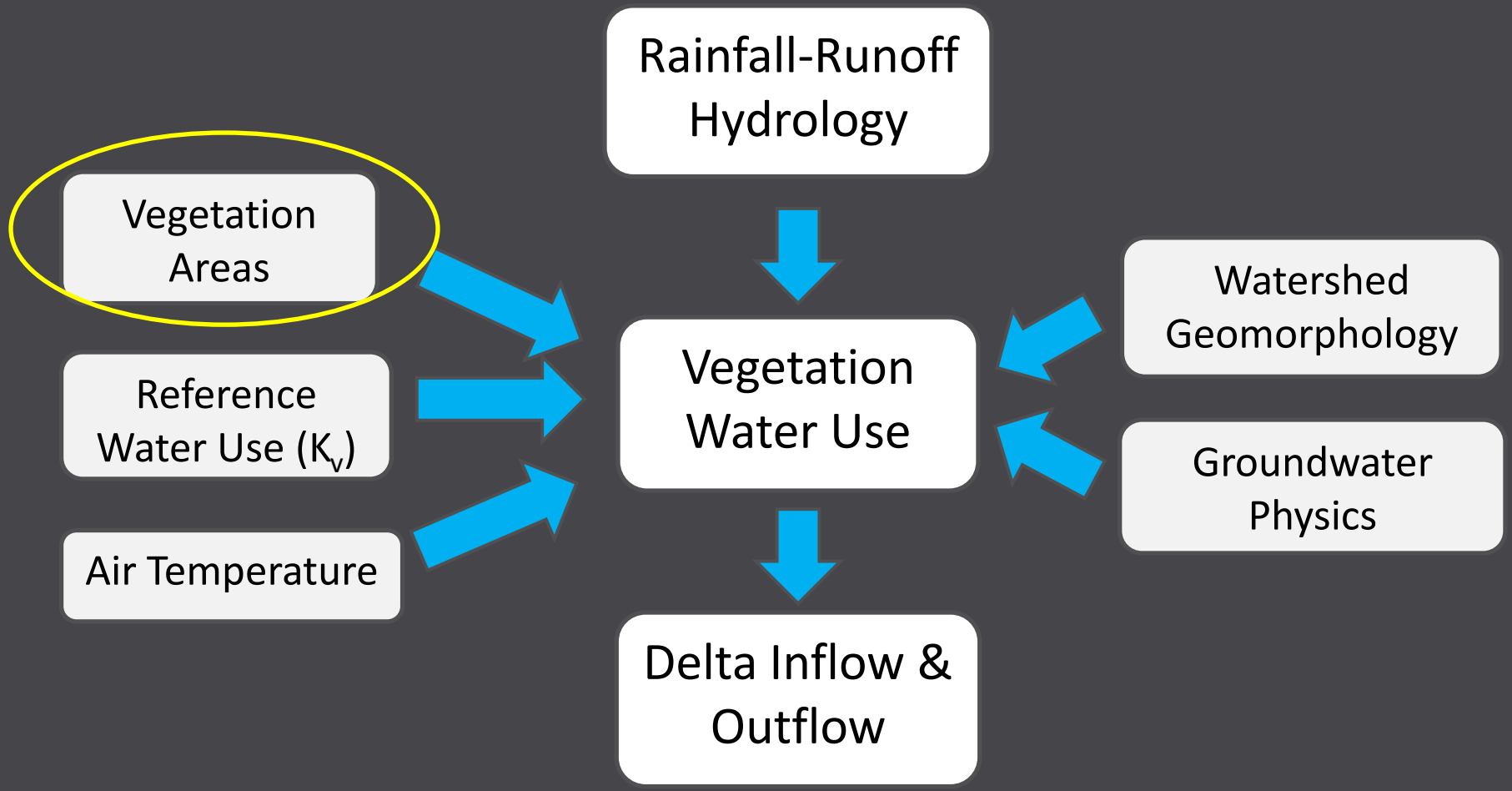
Stacie Grinbergs, RMA


Rainfall-Runoff Hydrology
Vegetation Areas
Reference Water Use (K_v)
Air Temperature
Tidal Forcing
Vegetation Water Use
Watershed Geomorphology
Groundwater Physics
Delta Inflow & Outflow
Delta Geomorphology
Hydrodynamics & Delta Flow-Salinity Characteristics



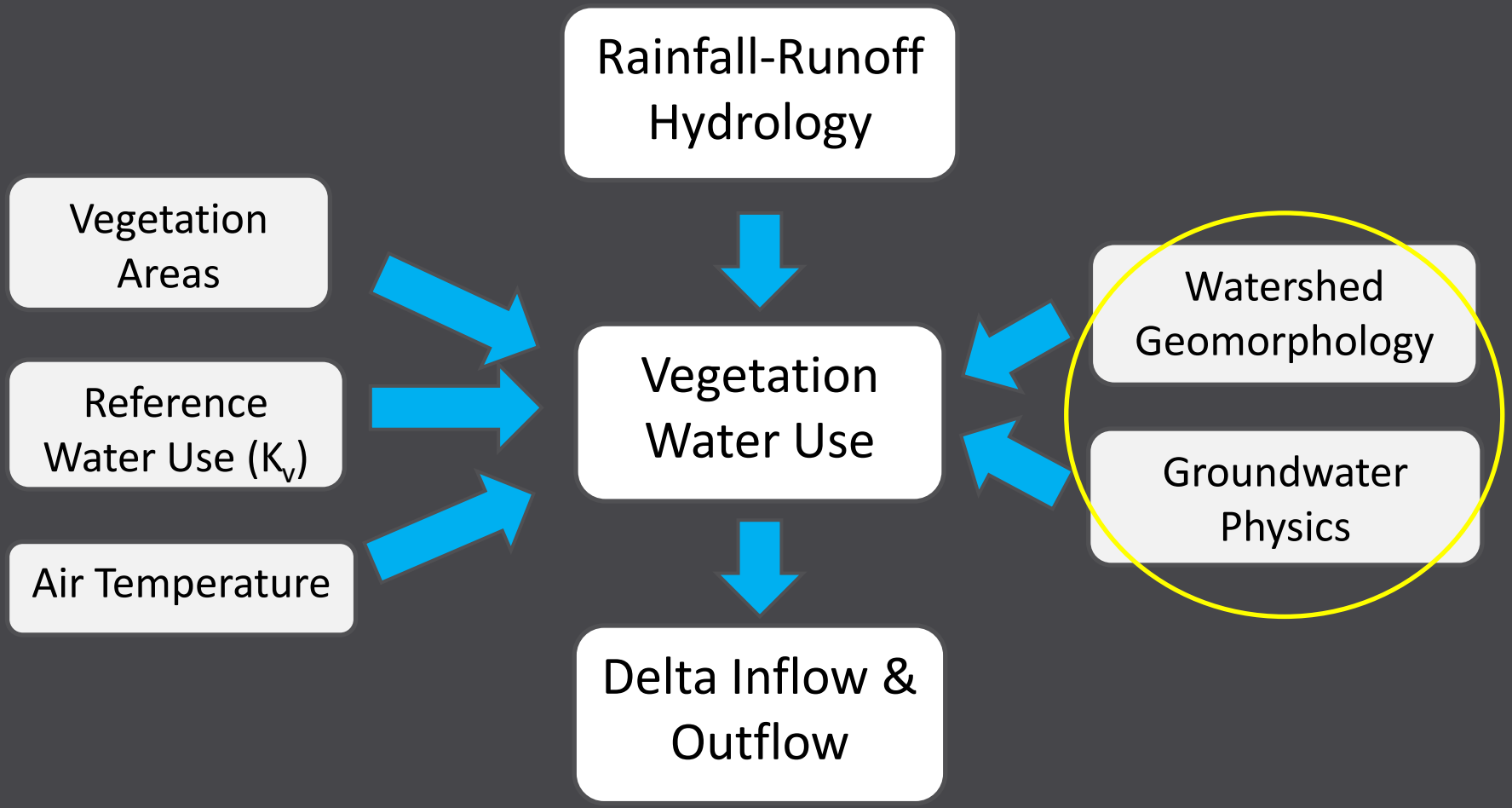
Dan Howes, CSU San Luis Obispo

ET from Natural Vegetation in the Central Valley of California: Monthly Grass Reference Based Vegetation Coefficients and the Dual Crop Coefficient Approach



J. Phyllis Fox

Natural Delta Outflow Water Balance



Andy Draper, MWH

Natural Flow Monthly Routing Model

Tariq Kadir, DWR

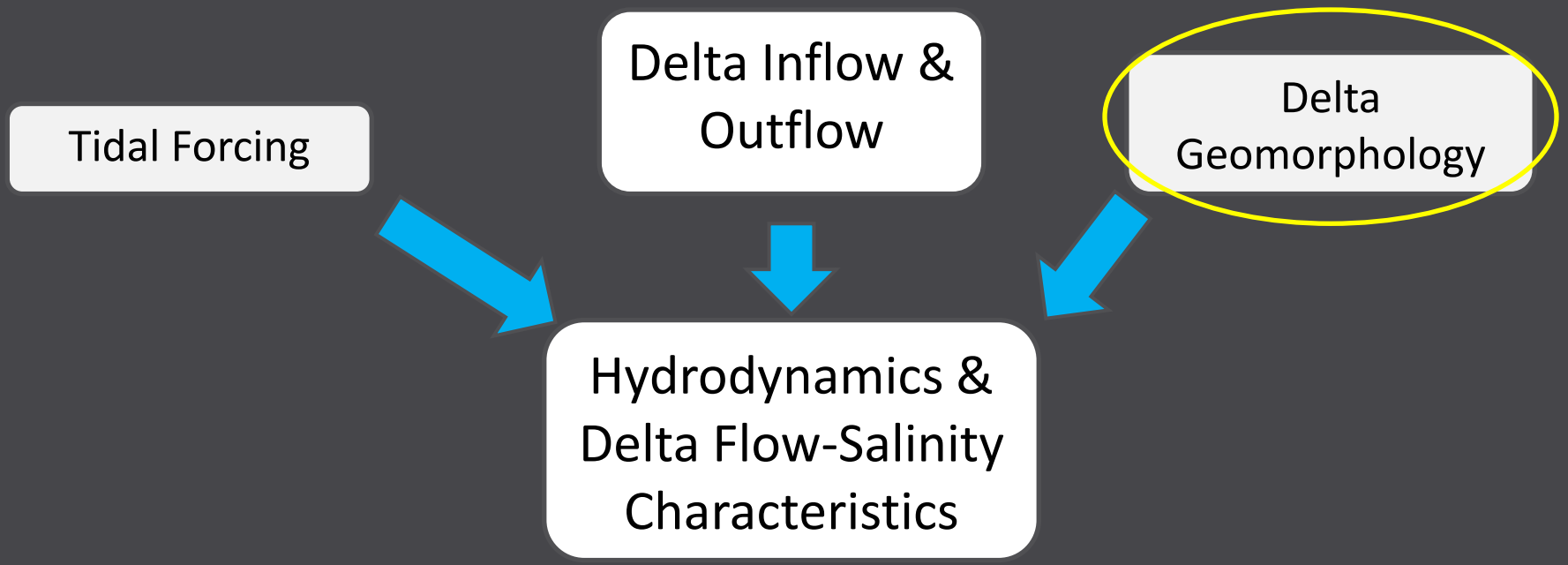
Simulated 1922-2009 Daily Inflows to the Sacramento – San Joaquin Delta under Predevelopment Conditions Using Precipitation-Runoff Models and C2VSIM: Preliminary Results

Robin Grossinger, SFEI

Generating a Historical Bathymetric-Topographic Digital Elevation Model (Part 1): Data Collection and Development

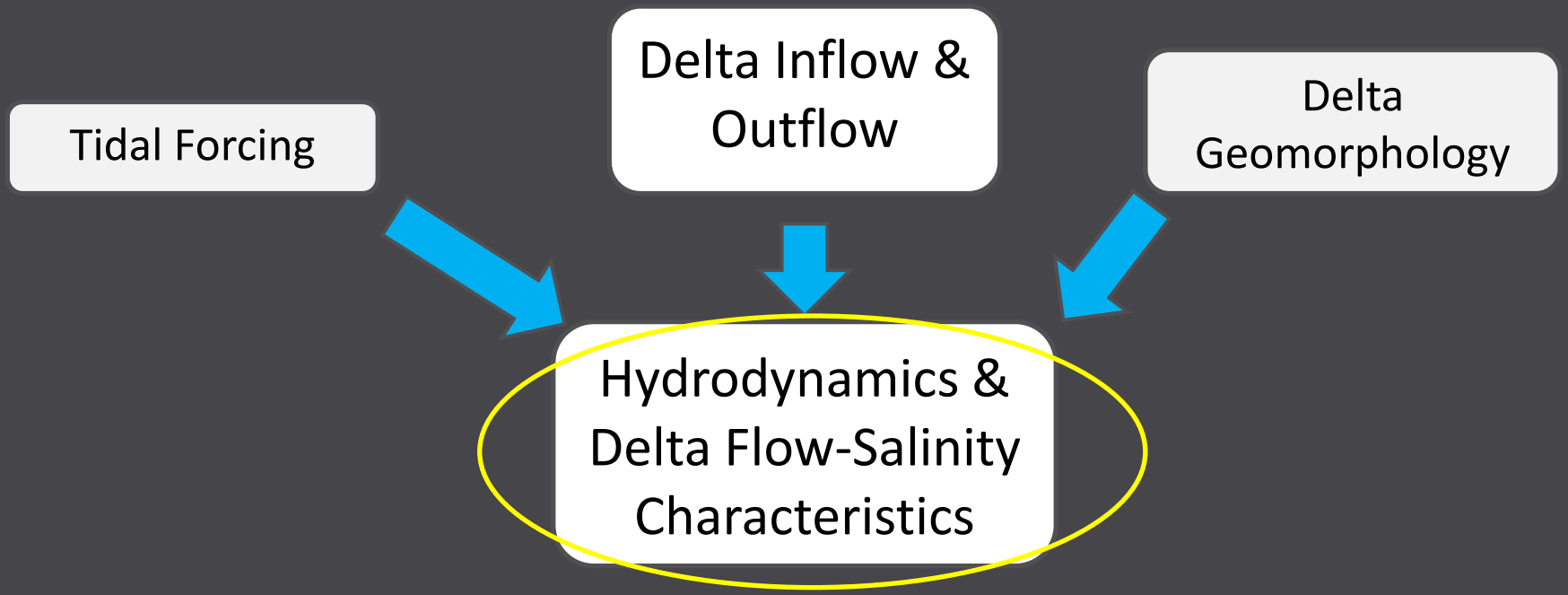
Bill Fleenor, UC Davis

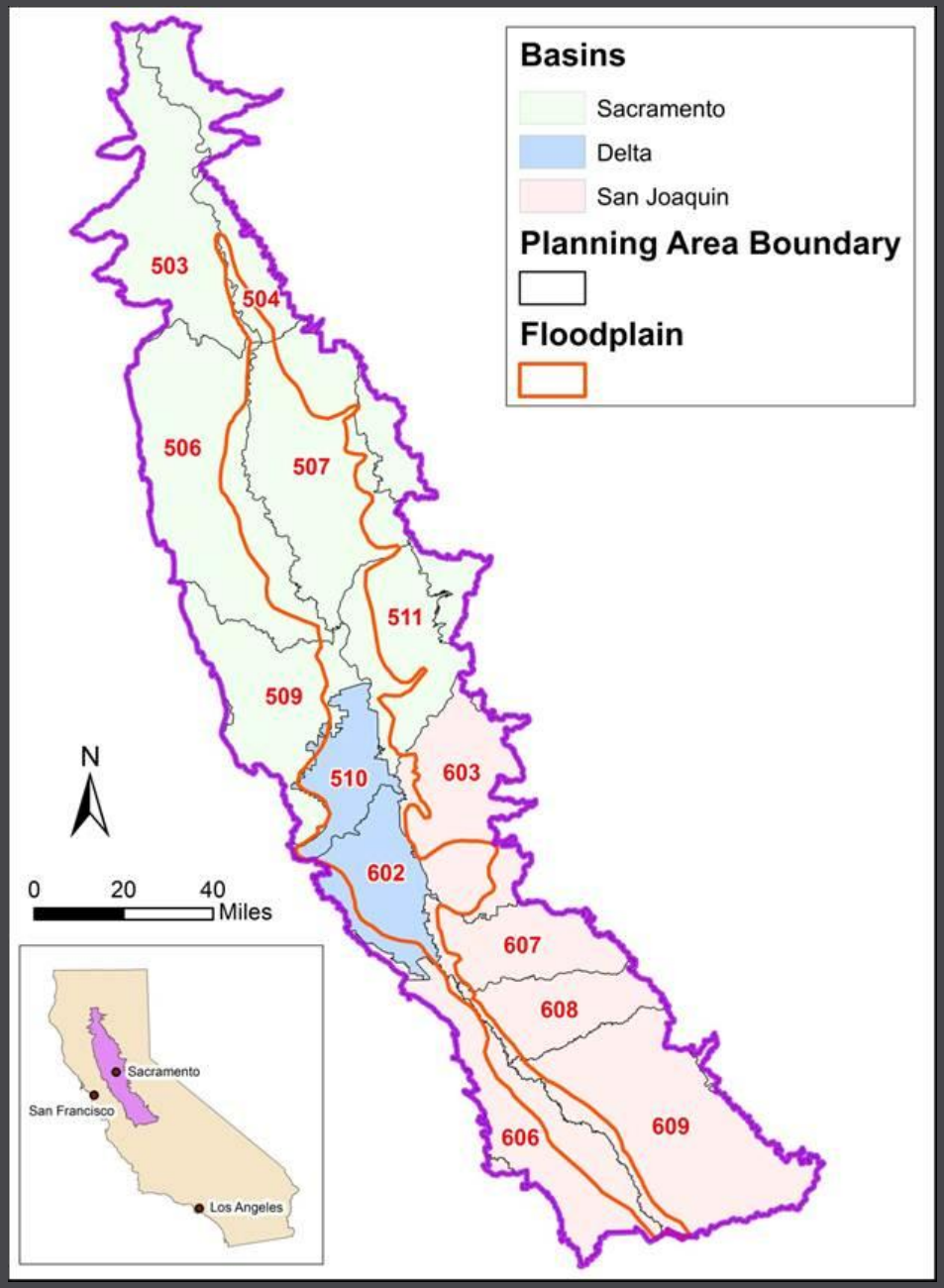
Generating a Historical Bathymetric-Topographic Digital Elevation Model (Part 2): Data Interpolation



John DeGeorge, RMA

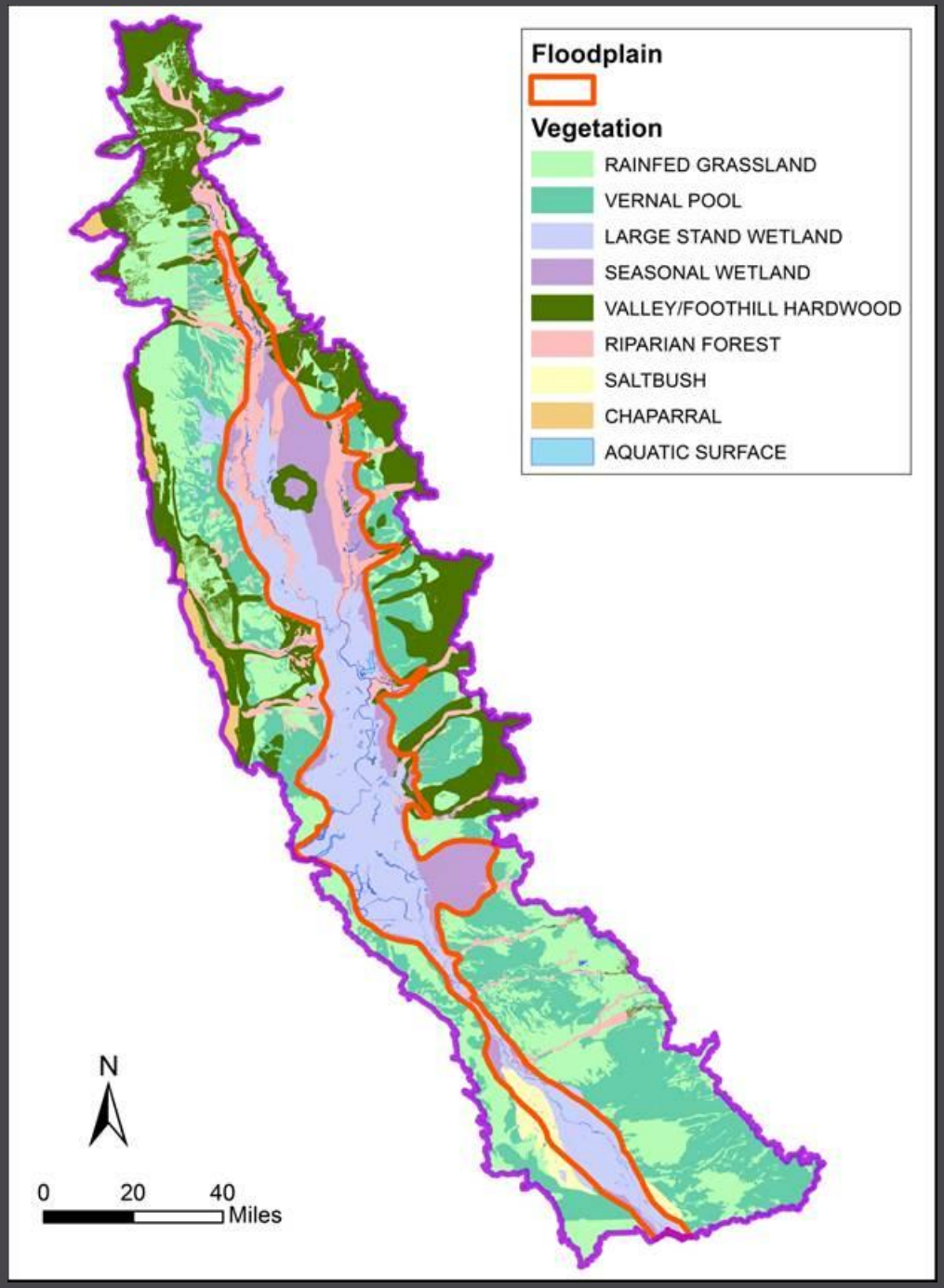
Development of a Three-Dimensional, Stratified Flow Model of the Natural Delta





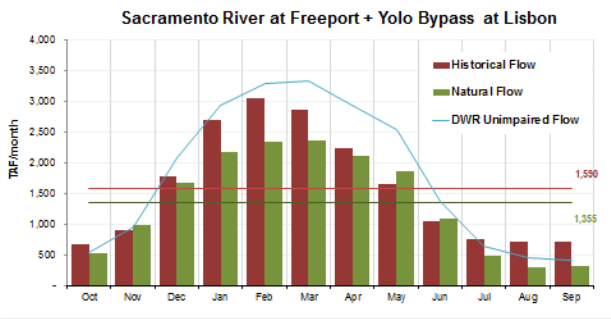
Vegetation Class	Area (%)	Et_v (ft/yr)
Rainfed Grassland	48	0.9-1.2
Perennial Grassland		3.7-5.0
Vernal Pools		2.2-2.9
Permanent Wetlands	12	4.0-5.4
Seasonal Wetlands	9	3.7-4.9
Foothill Hardwood	19	1.0-1.5
Valley Oak Savanna		1.8-2.4
Riparian Forest	9	3.8-5.1
Saltbrush	3	1.7-2.3
Chaparral		0.6-1.0
Aquatic		3.6-4.9

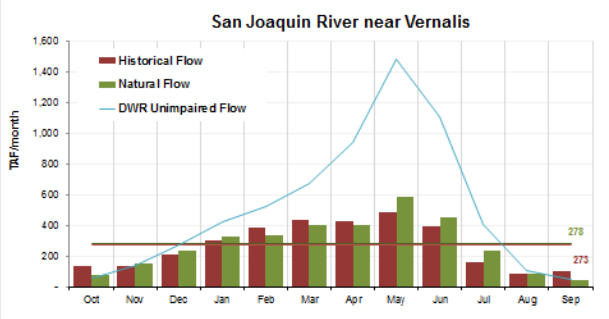
Vegetation Areas

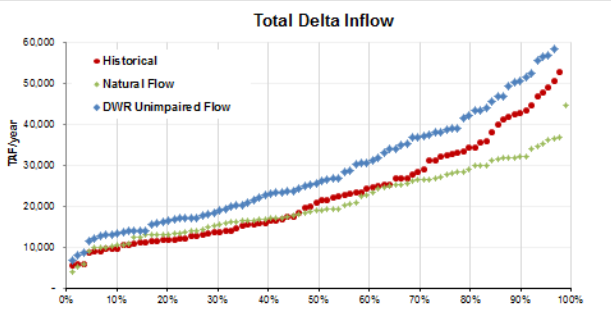


Monthly Routing Model

USER DEFINED INPUTS



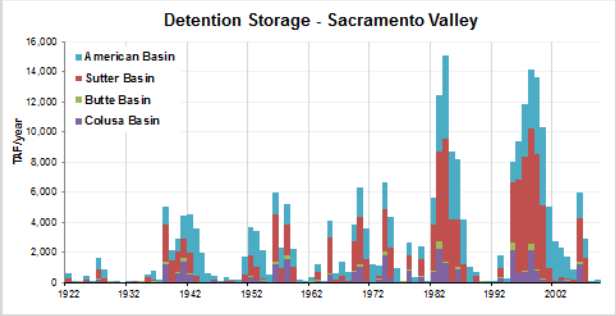


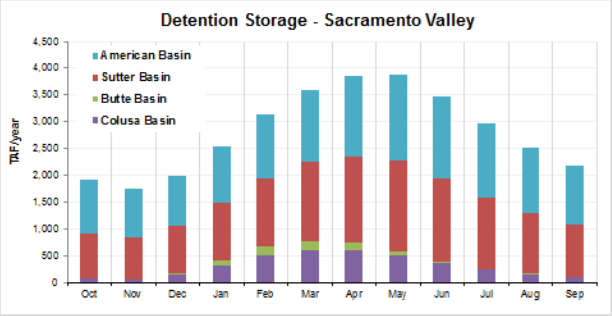


Detention Storage

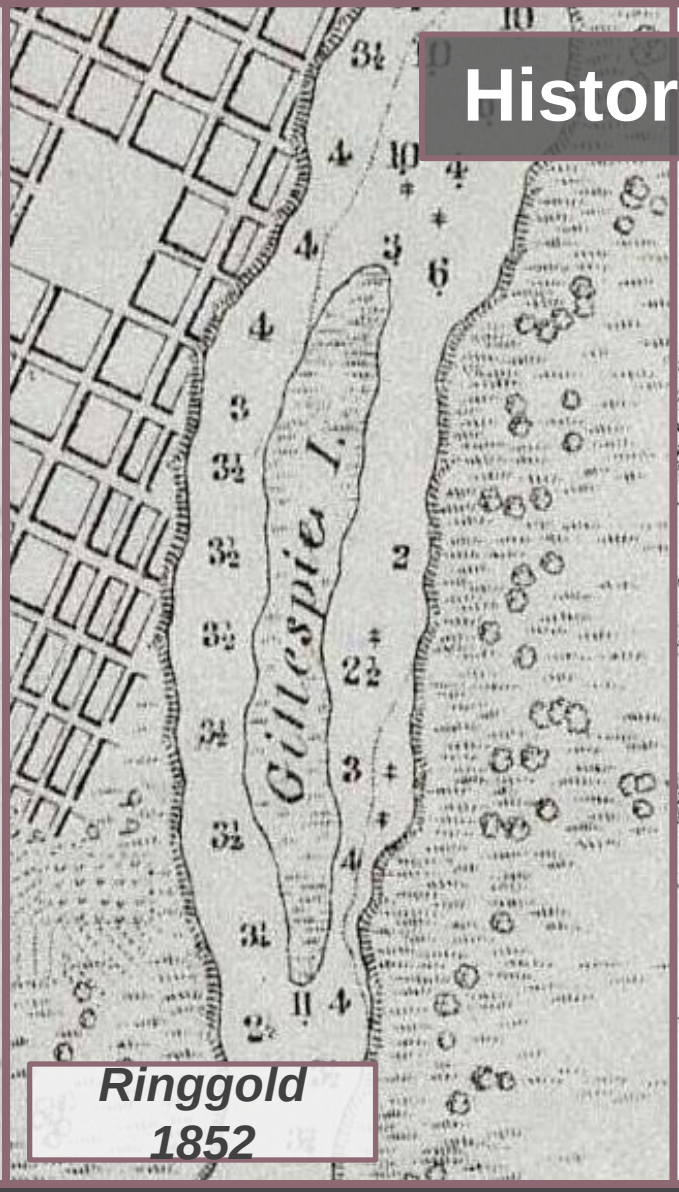
Basin	Discharge Coefficient	Where Referenced in Routing Calculations Worksheet
Default value	2.0	
Butte Basin	0.5	row= 2, column = 27
Colusa Basin	2.0	row= 2, column = 42
Sutter Basin	2.0	row= 2, column = 67
American Basin	0.5	row= 2, column = 88

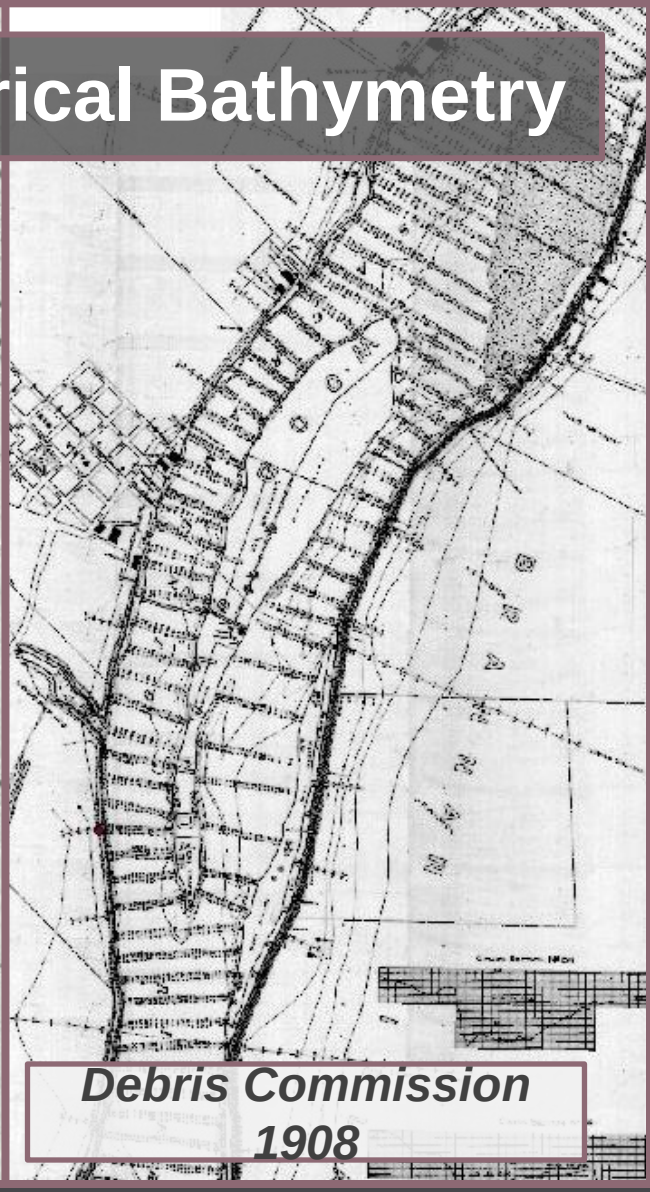
This table defines the stage-discharge relationship for the detention basins of the Sacramento Valley. The outflow from these basins is assumed to be proportional to the square-root of the head difference between the stage in the detention basin and the stage in the downstream channel. For the outflow from the Butte Basin, the downstream stage is assumed to be zero. No detention storage is modeled for the Yolo Basin.



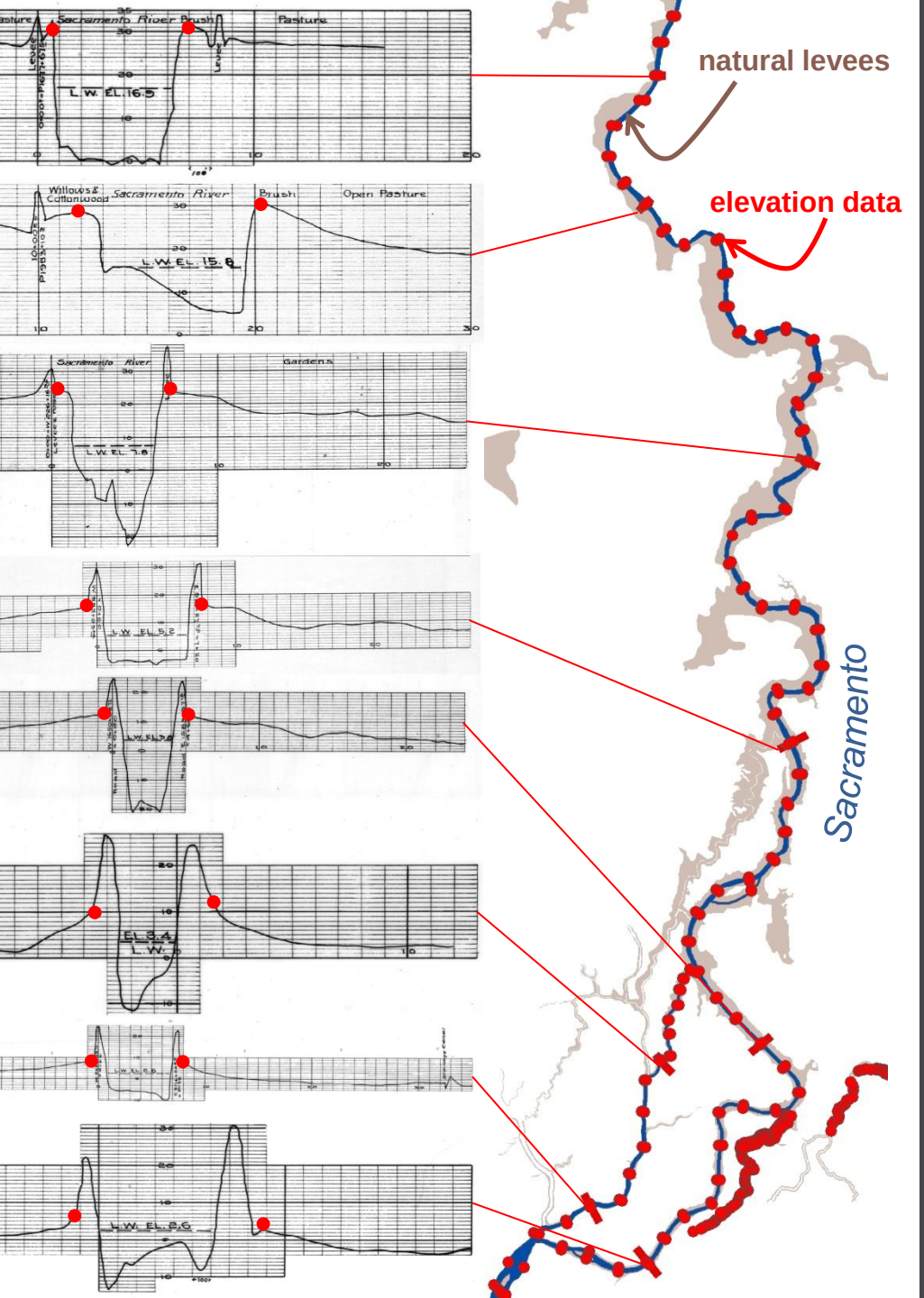


Historical Bathymetry





Historical bathymetry data compiled from **multiple sources** with variation **in time period, spatial accuracy, coverage, and sounding density**



Historical Topography

Natural levees

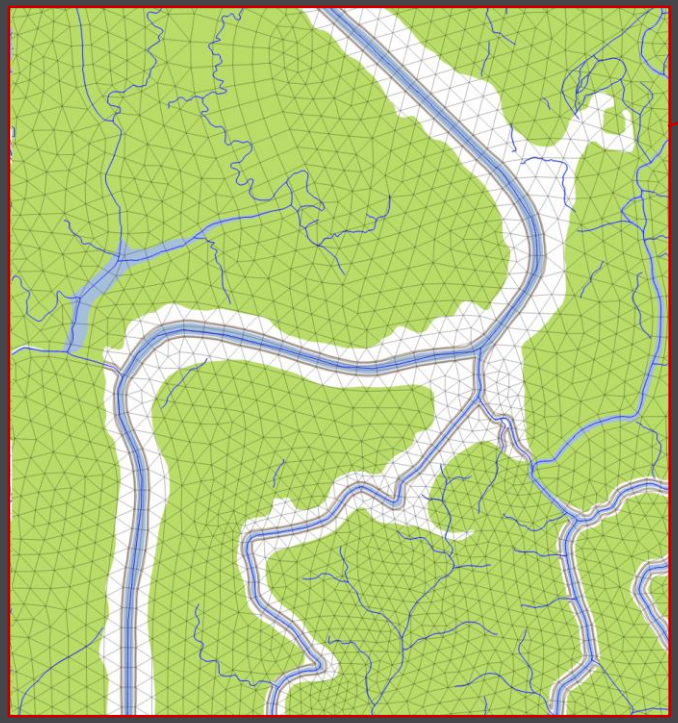
- extent from Historical Ecology layers
- elevations derived from early detailed topographic surveys
- Sacramento River levees ranged from 30 ft. (near Feather River) to 4 ft. NAVD88 (near Rio Vista)
- corroborated with historical written record
- will compare against modern LiDAR

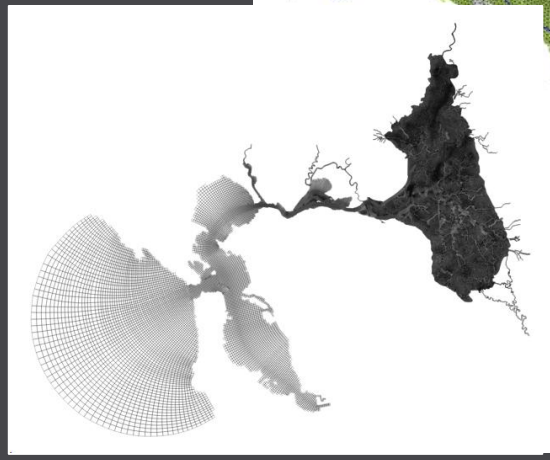
Marsh surface

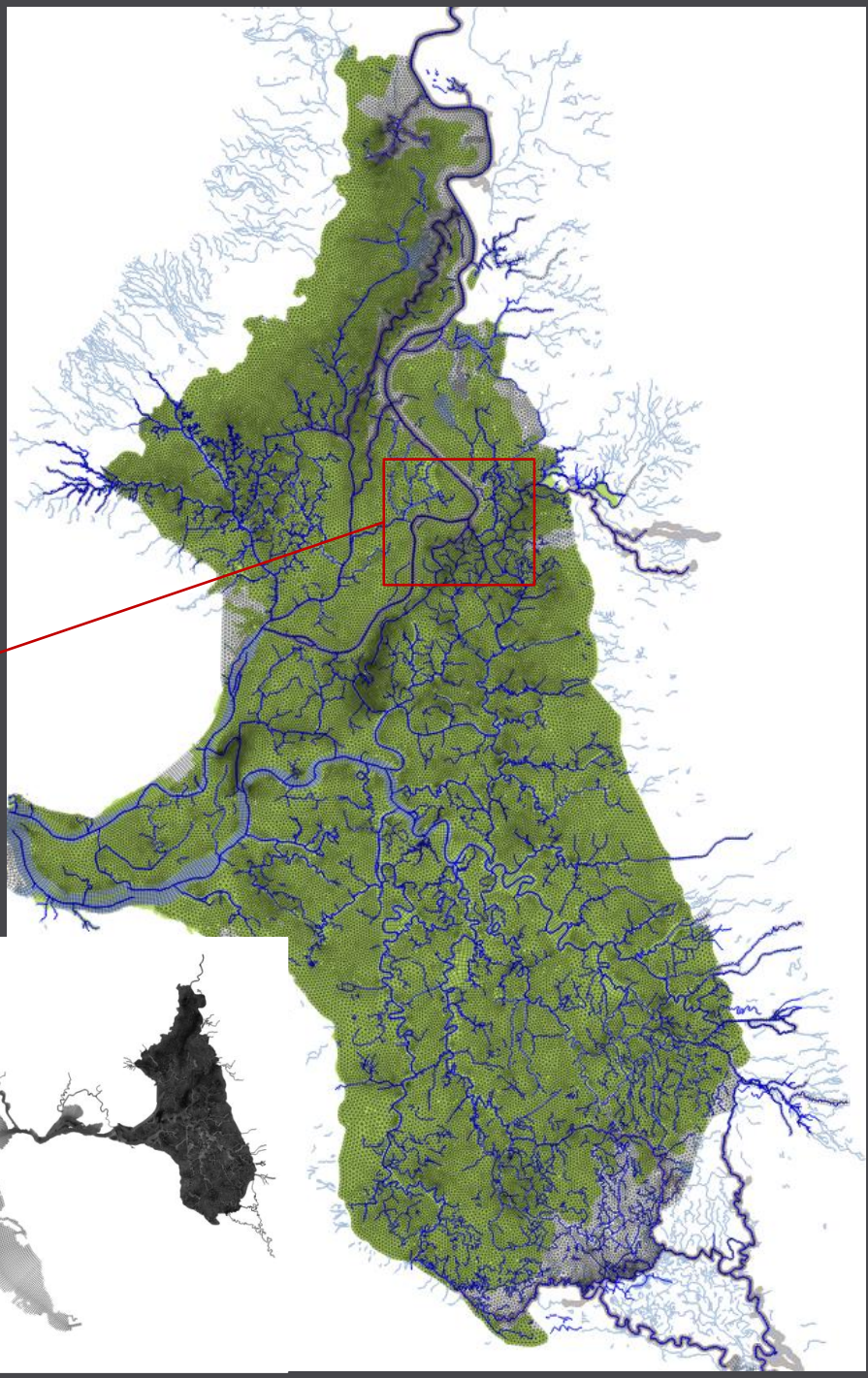
- extent from Historical Ecology layers
- elevation relative to MSL

UnTRIM3D Model of the Natural Delta (RMA)

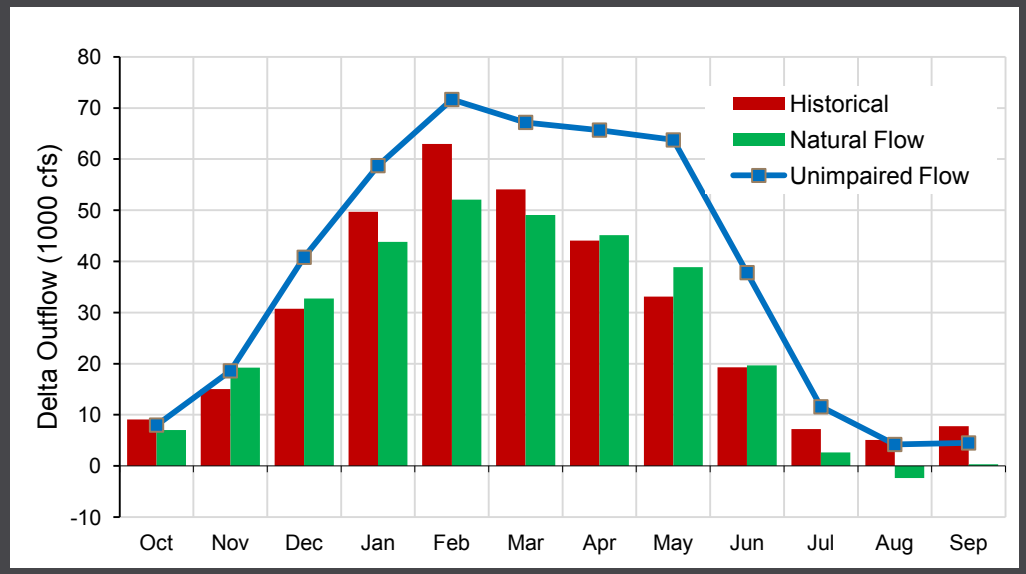
- Flow aligned quadrilateral elements follow levee crests in main channels
- Triangular elements fill adjacent tidal plains
- Low-order channels captured implicitly using subgrid in 3D model
- ~125,000 elements, 54 vertical layers (max)
- 60:1 ratio of simulation time to run time

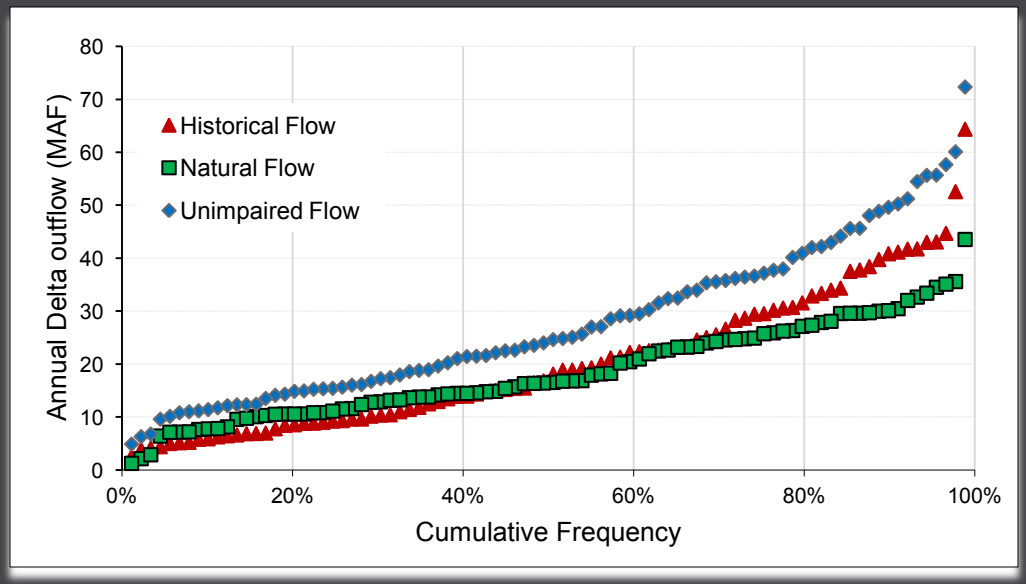


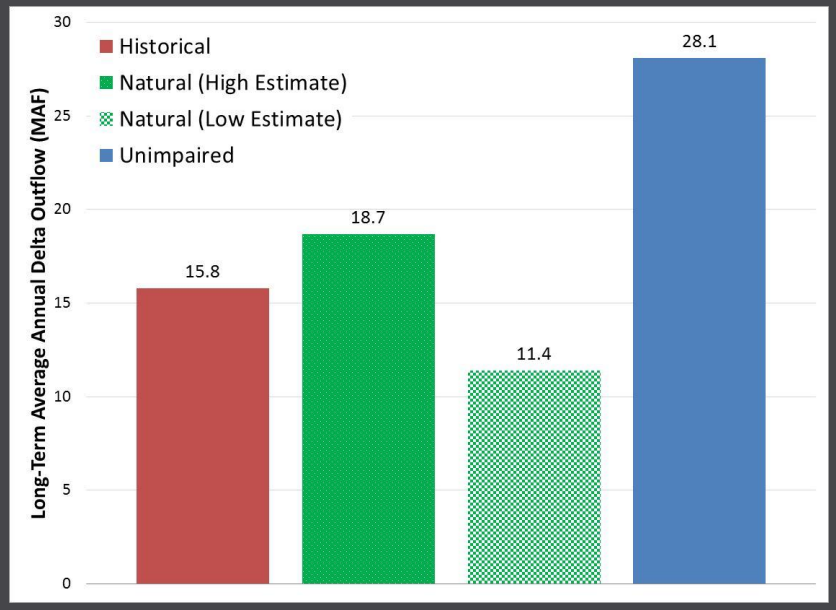




Project Status: Hydrology







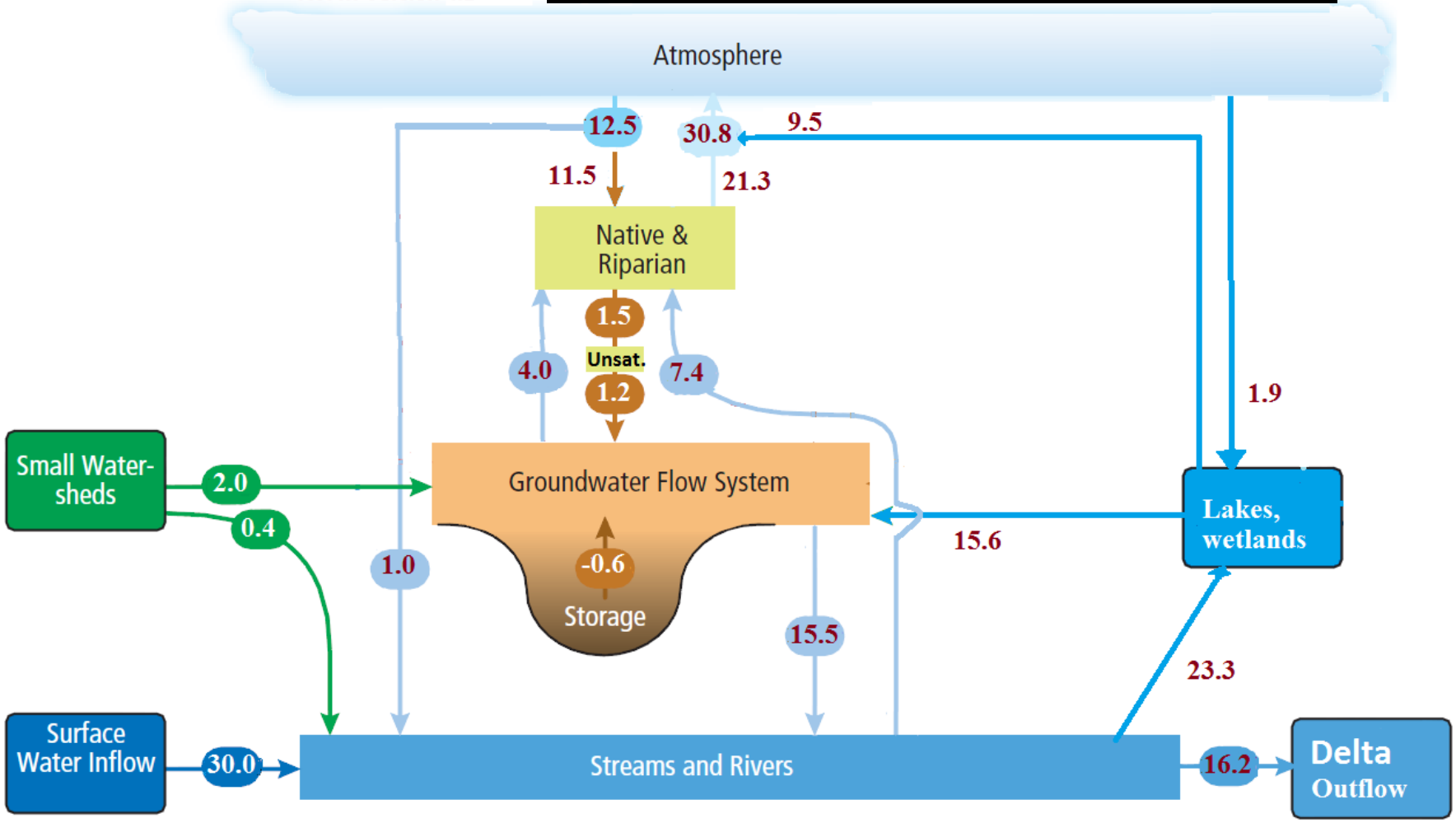
Simulated Annual Water Budget

Pre-Development condition

Average Flows for water years **1922-2009**
[Million Acre-Feet/Year]

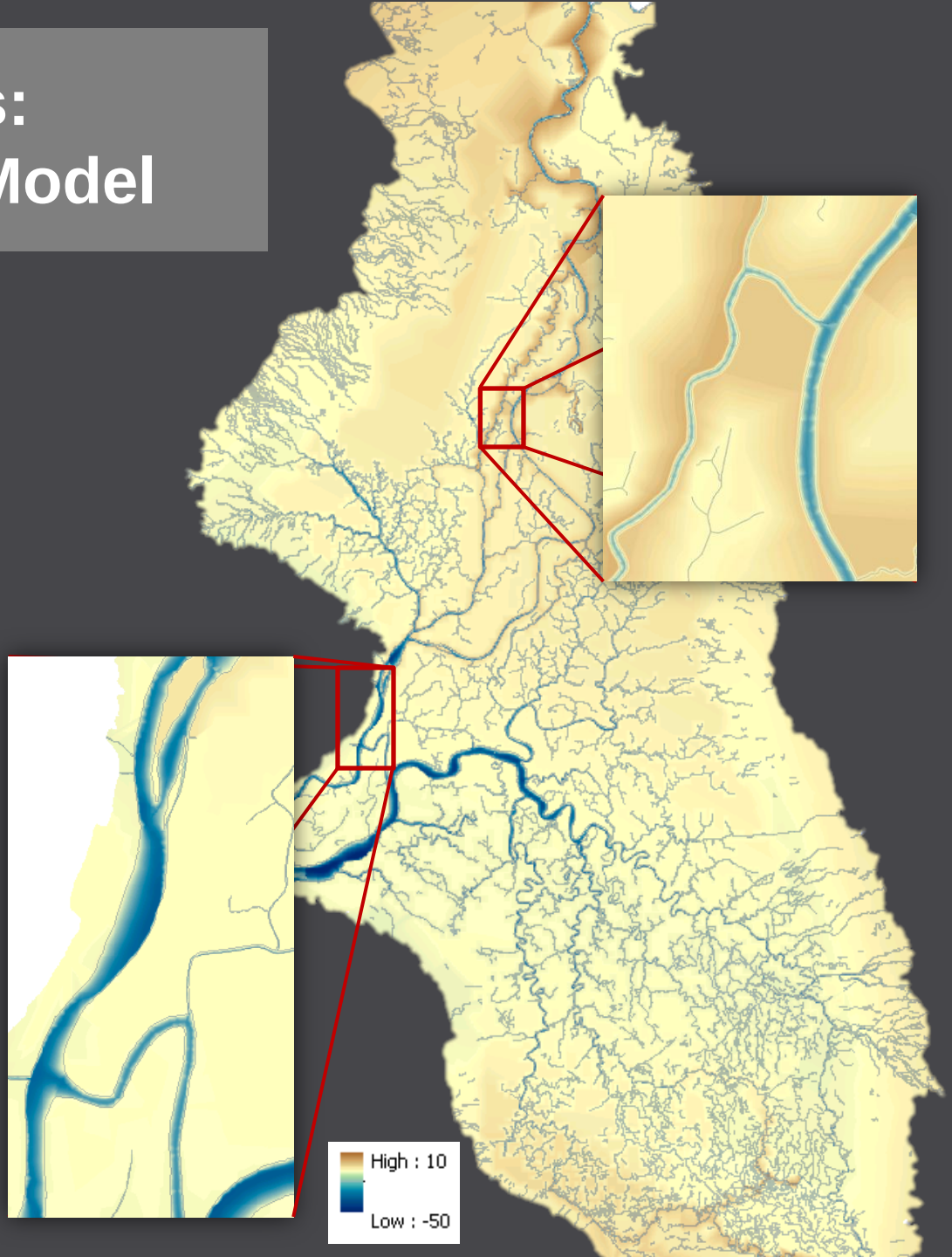
IWFM Version 4.1

Sacramento-San Joaquin Valley and Delta



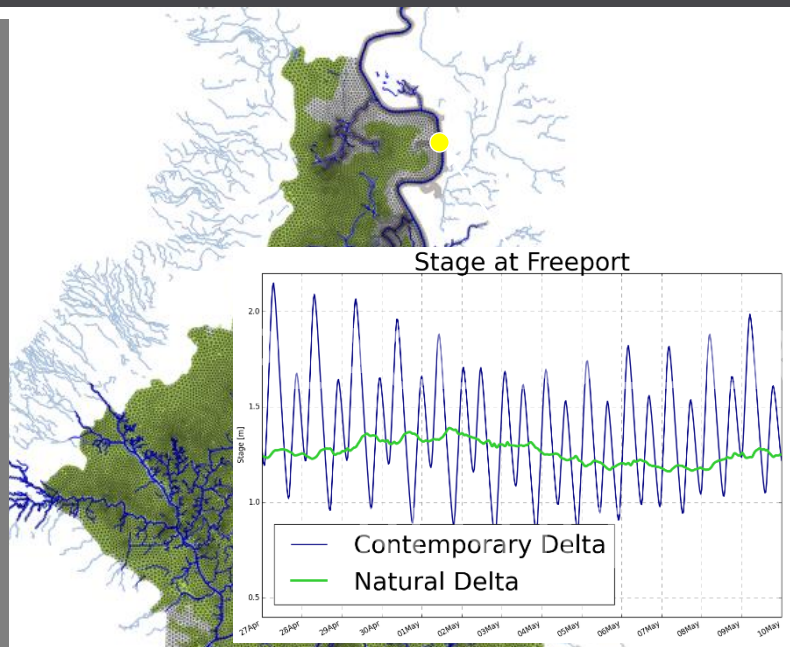
Project Status: Digital Elevation Model

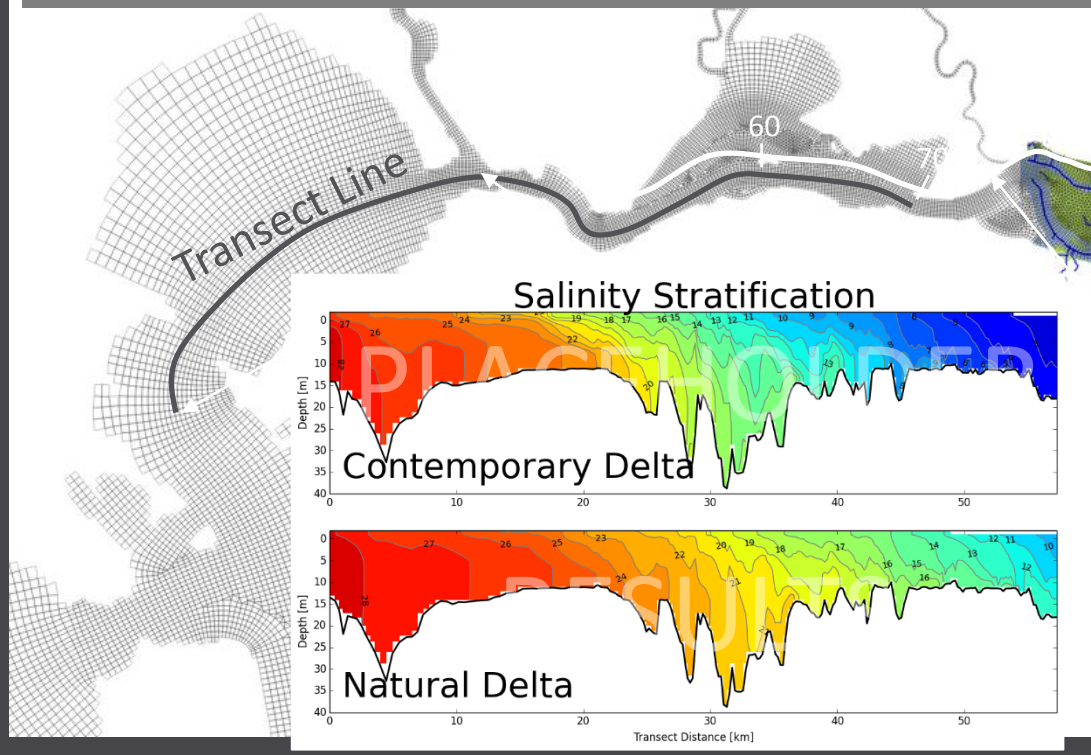
- Interim DEM includes channel bathymetry plus approximations of natural levees and marsh elevation

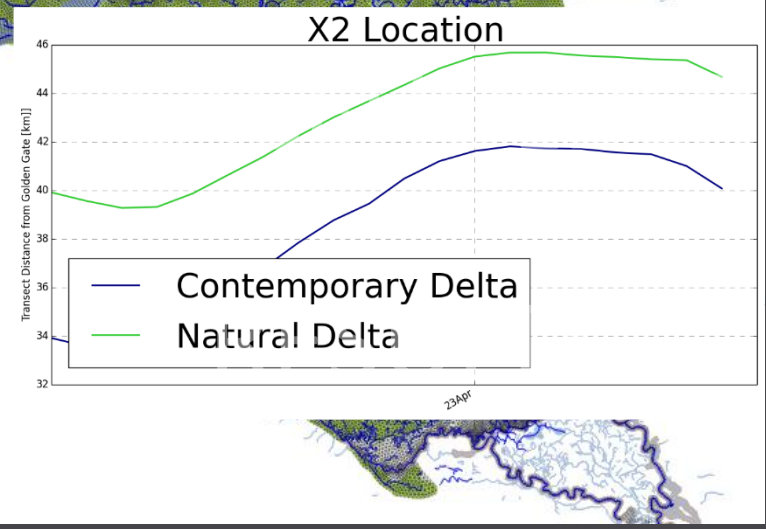


Project Status: Hydrodynamics

- Iterative tuning of DEM and hydrodynamic model to achieve expected tidal range
- Comparison of natural and contemporary Delta using natural hydrology
  - Stratification
  - X2 location
  - Tidal Range







PLACEHOLDER RESULTS

Next Steps

- Hydrology
  - Refinement of groundwater-surface water modeling by DWR
- DEM & Hydrodynamic Model Development
  - Second phase of model development to be funded by Metropolitan Water District
  - Continued collaboration with UC Davis

Evapotranspiration from Natural Vegetation in the Central Valley of California

CWEMF 2014 Annual Meeting

Folsom, CA

February 25, 2014

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moving water in new directions

Irrigation Training and Research Center (ITRC)

California Polytechnic State University

San Luis Obispo, California

www.itrc.org

(805) 756-2434

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Introduction

- Evapotranspiration estimates for natural vegetation are important for:
  - Restoration activities
  - Hydrologic evaluations/modeling
    - Historical water consumption
    - Potential future water consumption
- Concurrent evaluation of pre-developed natural flow out of the Delta
  - Requires ET estimates of vegetation in pre-developed CA (area that flows to the Delta)

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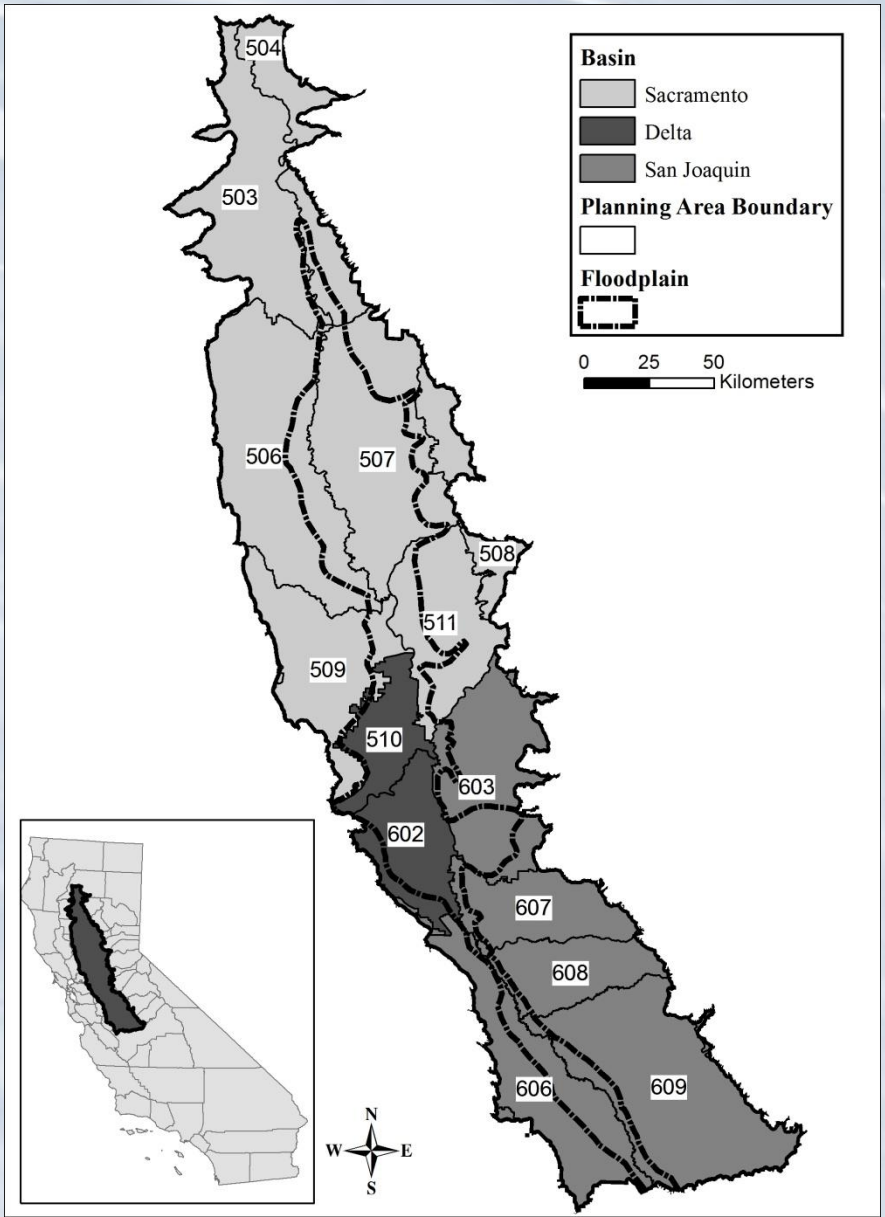
Central Valley Floor

Planning Areas
(CDWR, 2005)



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Introduction

- Direct measurement of plant evapotranspiration is challenging and there is a need to estimate ET in different time periods and locations

- Measurements in one location are not directly transferable to another (climate, management, soils, etc.)

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Issues

- Agriculture has standardized on the use of reference evapotranspiration/crop coefficient methodology to achieve transferability
  - (standard equations for reference crop evapotranspiration: ASCE 2005 Modified Penman-Monteith)
- Same standardization is not found for estimating ET of natural or native vegetation
- Researchers base the reference on:
  - Evaporation pans
  - Priestley-Taylor
  - Blaney-Criddle
  - Jensen-Haise
  - One of the Penman-Monteith versions

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Issues Continued

- Quality of the reference data, lack of standardization, and issues with transferability limits the direct use of research measurements by other users
- Quality E pan data for example can be very limited
- With the increase in weather station networks and standards for site maintenance, following the agriculture standards seems like a logical step forward for natural vegetation
  - Spatial ETo estimates (e.g. SpatialCIMIS)
- This will promote further work and use of existing research for modeling and computation of natural vegetation ET

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ETc for Ag Crops

- Standard Reference Crops
  - Alfalfa or tall crop (ETr)
  - Grass or short crop (ETo) (*California*)

- Special reference evapotranspiration weather station networks are proliferating
  - CIMIS
  - Agrimet
  - CoAgMet and others

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Objectives of This Study

- Estimate the evapotranspiration from natural vegetation in California's Central Valley using:
  - Estimated grass reference based vegetation coefficients (Kv's) for non-water stressed vegetation based on past research
  - For vegetation relying on rainfall, a daily soil water balance with the dual crop coefficient method
  - Daily and monthly ETo and precip for each planning area from 1922-2009 (CDWR – Orang et al. 2013)

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Methodology – Kv approach

- Reviewed over 120 references on evapotranspiration from a variety of natural vegetation types
- Limited results to data:
  - presented monthly or more frequently
  - measured within surrounding vegetation using a standard/verified approach
  - most were from 1950 to present
  - focused on studies in the western U.S. (arid/semi-arid environments)

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Methodology - Kv (cont.)

- Computed vegetation coefficients on a monthly basis

$$Kv = \frac{ETc}{ETo}$$

- ETo = grass reference evapotranspiration
- In some cases, ETo weather stations were not available in the area where the study was conducted
- Used a calibrated Hargreaves Equation to compute ETo for those cases

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Methodology – Soil Water Balance

- Vegetation relying on rainfall
- ETv depends on rainfall and is low in summer
- Soil water balance using the FAO 56 dual crop coefficient approach
- Model calibrated based on measured data from other studies
  - Rainfed grasses and foothill oak savannas (Baldocchi et al. 2004)
  - Chaparral (Claudio et al. 2006)

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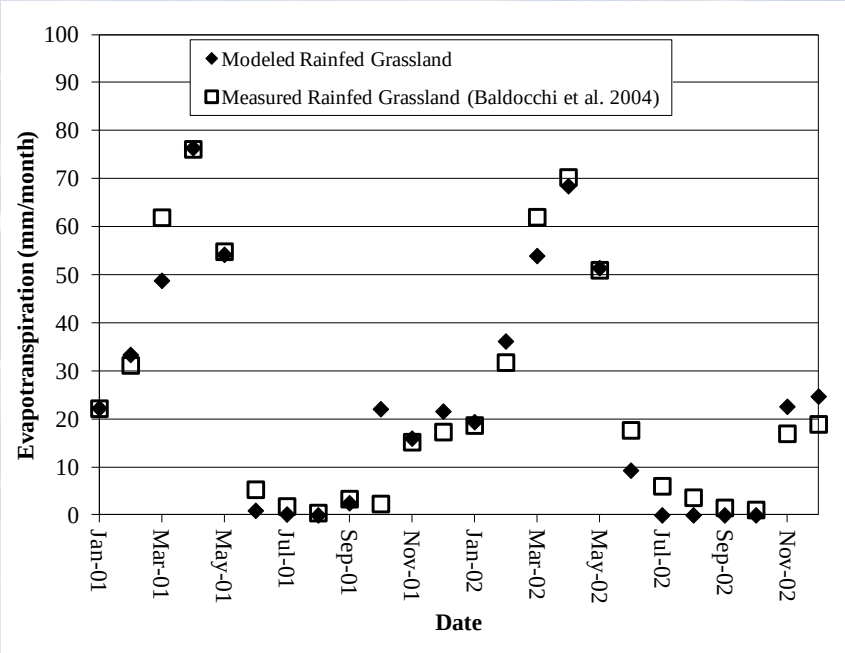
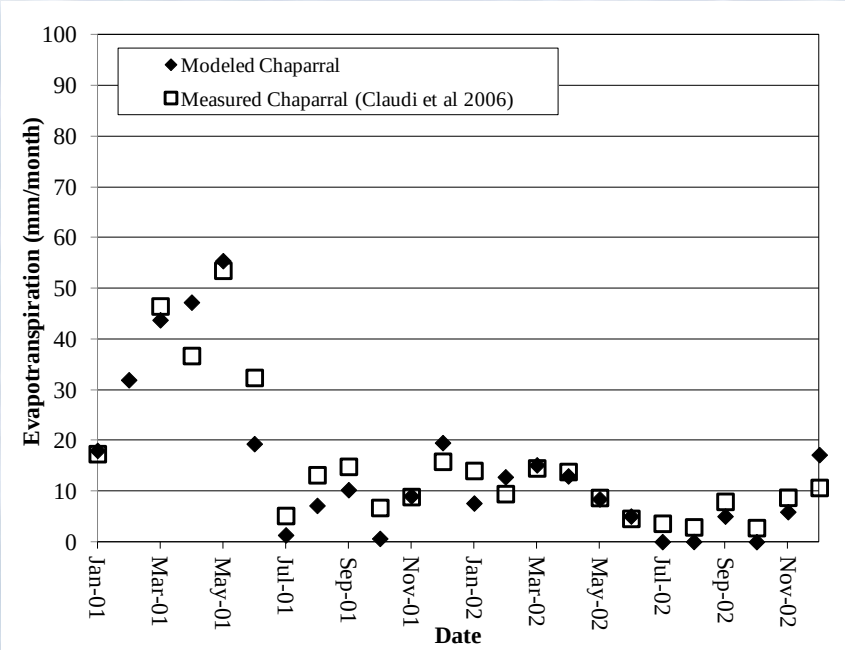
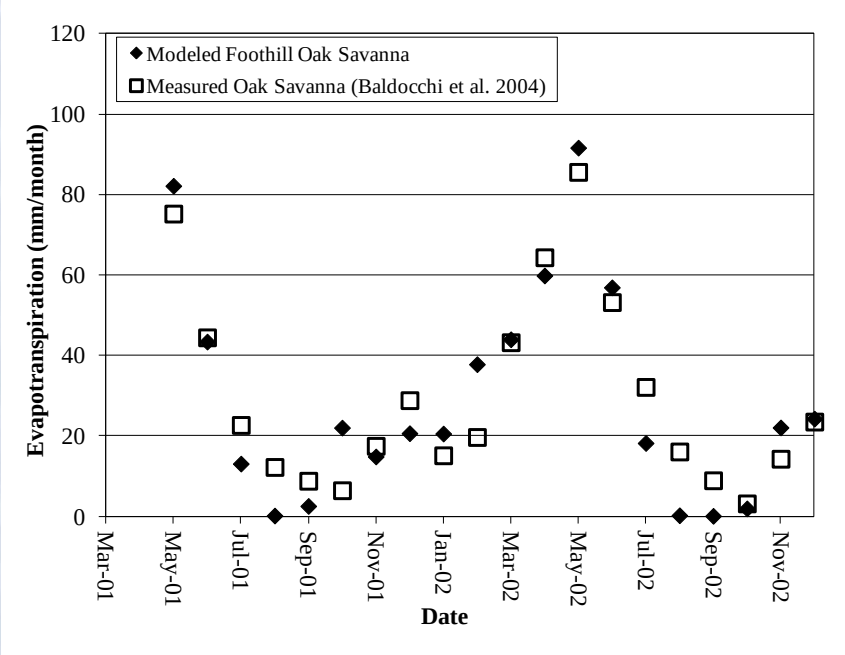
SWB Calibration

- Adjusting
  - Basal Kv (canopy)
  - Development period
  - SMD at onset of stress







Results – Kv values

- Comprehensive tables in future paper
  - Large stand wetlands (5 studies)
  - Seasonal wetlands (2 studies)
  - Small stand wetlands (5 studies)
  - Large stand riparian forest (4 studies)
  - Smaller stand riparian forest (1 study)
  - Perennial grasses (5 studies)
  - Saltbush (4 studies)
  - Shallow open water (3 studies)

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Category	ID	Vegetation	Long-Term Winter Freeze	Water Table Depth	Location	Measurement Method	ET_o Method	Source
Large Stand Wetland	1	Cattails	No	Standing	Fort Drum, FL	tank within vegetation	1	(Mao et al. 2002)
	2	Cattails	No	"	Southern FL	"	1	(Abtew and Obeysekera 1995)*
	3	Tules and Cattails	No	"	Twitchell Island, CA	surface renewal	1	(Drexler et al. 2008)
	4	Tules/Bulrush	No	"	Bonsall, Ca	tank within vegetation	5	(Muckel and Blaney 1945)
	5	Cattails	Yes	"	Logan, UT	Bowen ratio	1	(Allen 1998)
Seasonal Large Stand Wetland	6	Tules, Cattails, Wocus Lilly	Yes	Standing to 0.8 m	Upper Klamath NWR, OR	eddy covariance	1	(Stannard 2013)
	7	Tules/Bulrush	Yes	Standing to 0.8 m	"	eddy covariance	1	"
Small Stand Wetland	8	Cattails	No	Standing	King Island, CA	tank within vegetation	5	(Young and Blaney 1942)
	9	Tules/Bulrush	No	"	"	tank within vegetation	5	"
	10	Tules/Bulrush	No	"	Victorville, CA	tank within vegetation	5	"
	11	Cattails	Yes	"	Logan, UT	Bowen Ratio	1	(Allen 1998)
	12	Tules/Bulrush	Yes	"	"	Bowen Ratio	1	"
Large Stand Riparian Forest	13	Willow	No	High	Santa Ana, CA	tank within vegetation	4	(Young and Blaney 1942)
	14	Cottonwood	Yes	Variable	Middle Rio Grande, NM	SEB/METRIC	1	(Allen et al. 2005)
	15	R.Olive	Yes	Variable	"	SEB/METRIC	1	"
	16	Willow	Yes	Variable	"	SEB/METRIC	1	"
Smaller Stand Riparian Forest (508m by 120m)	17	Reed, Willow, Cottonwood	Yes	0.9 m	Central City, NE	Bowen ratio	1	(Irmak et al. 2013)
Large Stand Pasture with High Water Table	18	Native Pasture	Yes	High	Alturas, CA	tank within vegetation	5	(MacGillivray 1975)
	19	Native Pasture	Yes	High	Shasta County, CA	"	5	"
	20	Irrigated Pasture	Yes	0-0.6m	Carson Valley, NV	eddy covariance	5	(Maurer et al. 2006)
	21	Irrigated Pasture	Yes	0.6-1.5m	"	Bowen ratio	5	"
	22	Meadow Pasture	Yes	0.3-1.2m	Upper Green River, WY	tank within vegetation	1	(Pochop and Burman 1987)
Large Stand Saltbush	23	Saltbush	Minor	.2-.8 m	Owens Valley, CA	stomatal conductance	1	(Steinwand et al. 2001)
	24	Saltbush	Minor	0.4-0.7m	Owens Valley, CA	eddy covariance	2	(Duell 1990)
	25	Saltbush	No	1.6m	Yuma, AZ	tank within vegetation	4	(McDonald and Hughes 1968)
	26	Saltbush	No	1.1m	Yuma, AZ	tank within vegetation	4	"
Open Water	27	Shallow Open Water	No		Fort Drum, FL	tank	1	(Mao et al. 2002)
	28	Shallow Open Water	No		Delta Region, CA	tank	5	(Matthew 1931)
	29	Shallow Open Water	No		Lake Elsinore, CA	water balance	5	(Young 1947)
Rainfed Vegetation	30	Oak-Grass Savanna	No	No	Near Iona, CA	eddy covariance	2	(Baldocchi et al. 2004)
	31	Chaparral - Old Stand	No	N/A	near Warner Springs, CA	eddy covariance	2	(Claudio et al. 2006)
	32	Chaparral - Young Stand	No	N/A	near Warner Springs, CA	eddy covariance	2	(Ichii et al. 2009)
	33	Chaparral	Yes	N/A	Sierra Ancha Forest, AZ	tank within vegetation	5	(Rich 1951)

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Monthly Kv Values

Month	Shallow Open Water Aquatic	High Water Table Perennial Grass	Riparian	Large Stand Wetland	Small Stand Wetland	Seasonal Wetland	Saltbush	Vernal Pool
January	0.65	0.55	0.80	0.70	1.00	0.70	0.30	0.65
February	0.70	0.55	0.80	0.70	1.10	0.70	0.30	0.70
March	0.75	0.60	0.80	0.80	1.50	0.80	0.30	0.80
April	0.80	0.95	0.80	1.00	1.50	1.00	0.35	1.00
May	1.05	1.00	0.90	1.05	1.60	1.05	0.45	1.05
June	1.05	1.05	1.00	1.20	1.70	1.10	0.50	0.85
July	1.05	1.10	1.10	1.20	1.90	1.10	0.60	0.50
August	1.05	1.15	1.20	1.20	1.60	1.15	0.55	0.15
September	1.05	1.10	1.20	1.05	1.50	0.75	0.45	0.10
October	1.00	1.00	1.15	1.10	1.20	0.80	0.35	0.10
November	0.80	0.85	1.00	1.00	1.15	0.80	0.40	0.25
December	0.60	0.85	0.85	0.75	1.00	0.75	0.35	0.60

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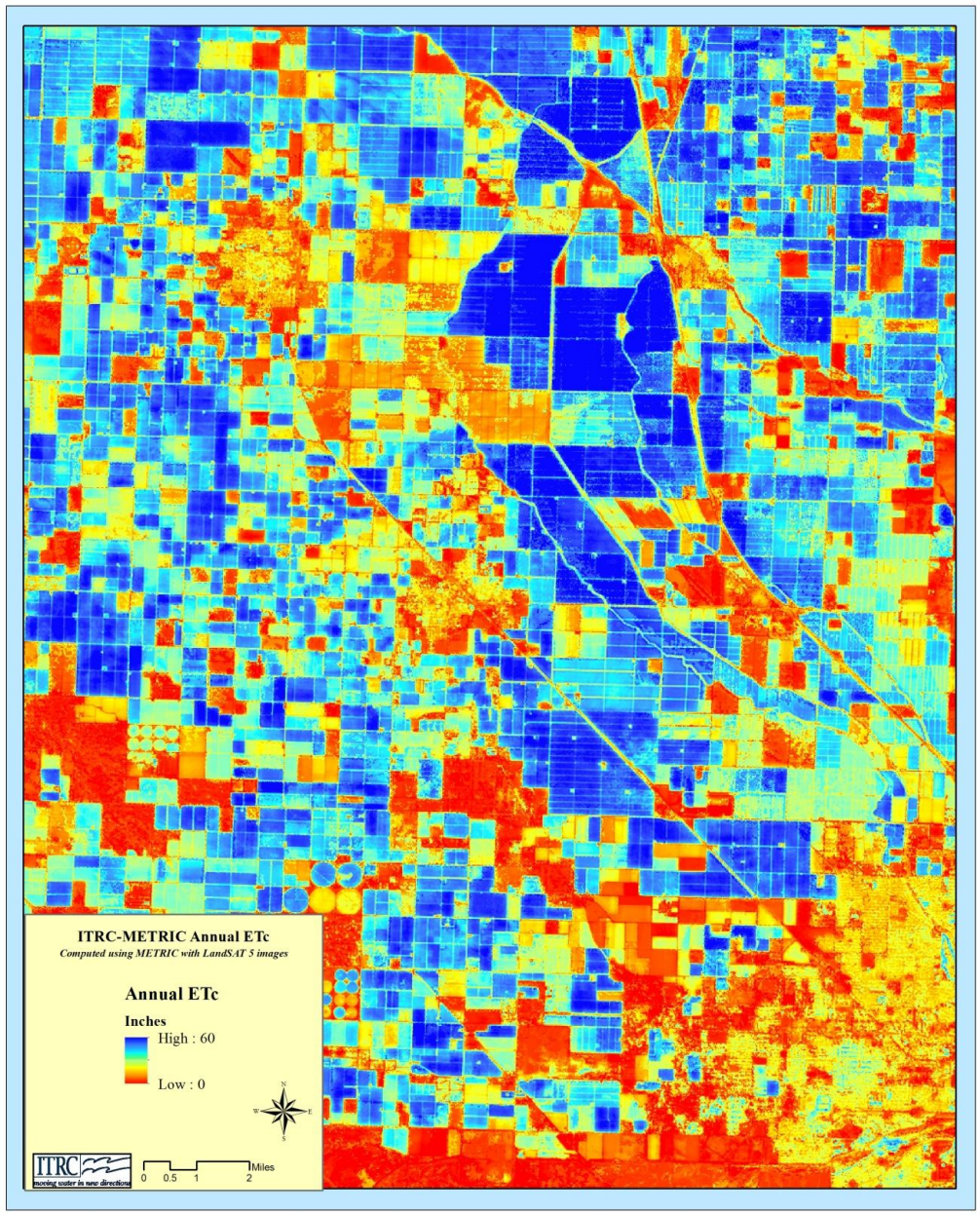
Kv Check – Remote Sensing of ET



ITRC – METRIC Procedure

- Large riparian forest east of Lake Isabella
- Wetland in Kern Wildlife Refuge
- Part of separate projects previously evaluated

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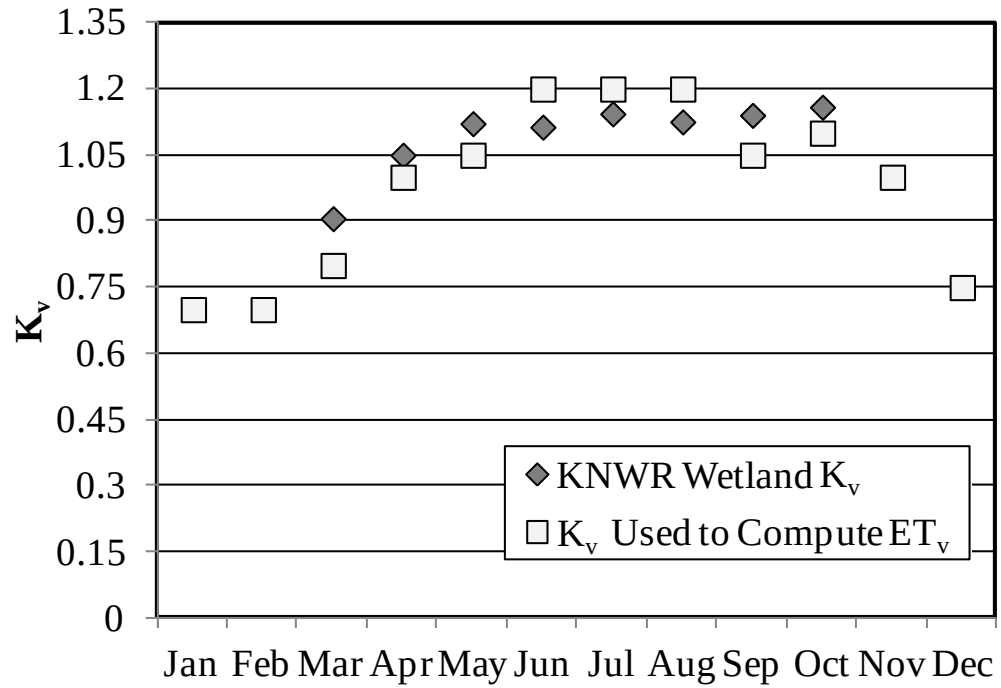
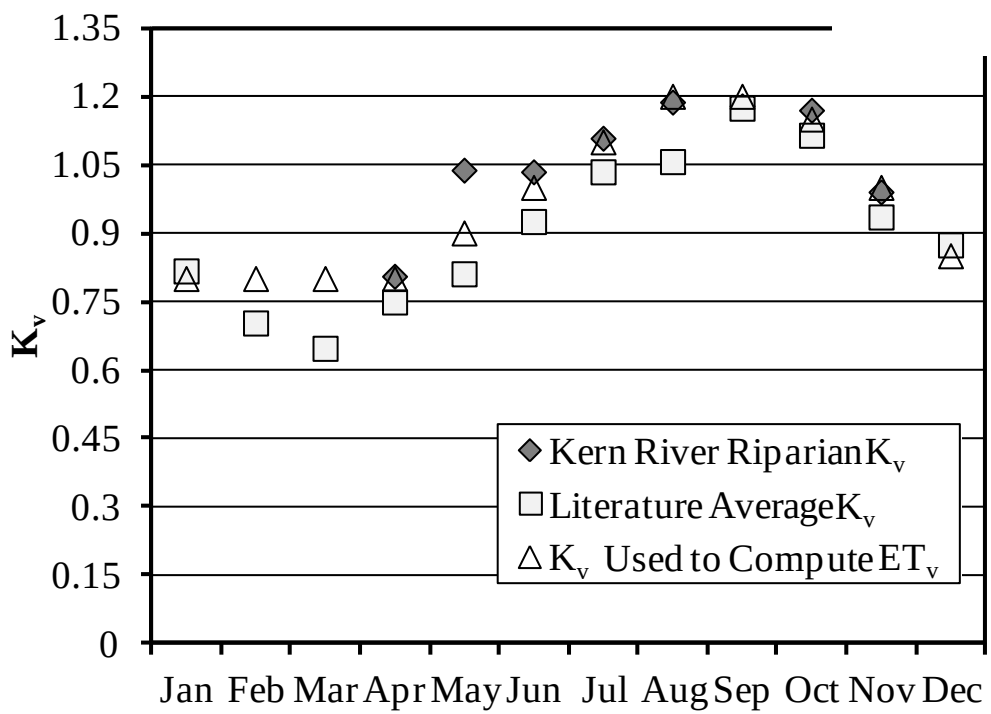
Kv Check

Remote Sensing SEB compared to Kv used in this study





Kv from LandSAT 5 processed for riparian and wetlands in Kern County, CA independent investigation by author

Good Agreement

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Rainfed 88-year average Kv

Month	Rainfed Grassland	Foothill Hardwoods	Valley Oak Savanna	Chaparral
January	0.78	0.80	0.80	0.55
February	0.72	0.77	0.77	0.61
March	0.64	0.69	0.69	0.54
April	0.58	0.61	0.62	0.40
May	0.35	0.52	0.54	0.22
June	0.06	0.20	0.40	0.03
July	0.00	0.01	0.40	0.01
August	0.00	0.01	0.40	0.01
September	0.03	0.03	0.40	0.03
October	0.16	0.15	0.41	0.14
November	0.47	0.46	0.55	0.40
December	0.73	0.71	0.71	0.57

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Long-Term Average ETv by Planning Area

1922-2009 Average Annual Evapotranspiration, mm/year

Planning Area	Large Stand Riparian	Large Stand Wetland	Small Stand Wetland	Seasonal Wetland	Vernal Pools	Perennial Grasses	Salt-bush	Rainfed Grass	Chaparral	Foothill Oak	Valley Oak	Open Water Evap.
503	1,341	1,413	2,043	1,288	755	1,305	602	391	295	451	685	1,274
504	1,325	1,395	2,017	1,271	741	1,289	596	340	288	402	640	1,258
506	1,387	1,461	2,113	1,331	779	1,350	623	324	250	398	672	1,317
507	1,430	1,506	2,179	1,373	803	1,392	643	352	269	427	702	1,358
509	1,396	1,469	2,125	1,339	781	1,359	627	328	247	402	679	1,325
510	1,404	1,478	2,138	1,347	787	1,368	631	312	232	386	673	1,333
511	1,471	1,549	2,241	1,412	820	1,433	662	348	264	426	717	1,397
601	1,166	1,227	1,774	1,118	657	1,135	523	274	190	323	560	1,106
602	1,246	1,312	1,898	1,196	705	1,213	559	272	193	333	590	1,183
603	1,464	1,543	2,233	1,407	821	1,427	659	337	255	415	710	1,391
606	1,392	1,466	2,121	1,337	786	1,356	626	240	174	312	625	1,322
607	1,438	1,516	2,195	1,383	812	1,402	647	293	216	368	673	1,367
608	1,482	1,564	2,264	1,427	841	1,446	667	289	215	366	686	1,410
609	1,558	1,644	2,380	1,499	879	1,521	702	290	220	372	715	1,482
Average	1,393	1,467	2,123	1,338	783	1,357	626	314	236	384	666	1,323

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Conclusions

- For non-water stressed vegetation, Kv values showed good agreement between independent studies
- A list of grass reference based Kv values have been generated from past research for use in estimating vegetation in arid/semi arid climates
- **For vegetation relying on rainfall, a soil water balance model was used to estimate ET**
  - **Calibration of the model based on measured values**

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Work Supported by:

San Luis-Delta Mendota Water Authority and State Water Contractors

Thank You

More Information visit

www.itrc.org

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Ecosystem Changes to the Bay-Delta Estuary: A Technical Assessment of Available Scientific Information

August 17, 2012

Submitted by: State Water Contractors, Inc.
San Luis & Delta-Mendota Water Authority

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Acronyms

AF	acre-foot/feet
BDCP	Bay Delta Conservation Plan
BiOp	biological opinion

C:P	ratio of carbon to phosphorus
cfs	cubic foot/feet per second
chl-*a*	chlorophyll-*a*
CVRWQCB	Central Valley Regional Water Quality Control Board
CVP	Central Valley Project
DEHP	bis(2-ethylhexyl)phthalate
DFG	California Department of Fish and Game
DIN:DIP	ratio of dissolved inorganic nitrogen to dissolved inorganic phosphorus
DIN:TP	ratio of dissolved inorganic nitrogen to total phosphorus
DWR	California Department of Water Resources
EC_{50}	median effect concentration; concentration that effects 50% of population
ETM	estuarine turbidity maximum
K-M	Kimmerer-Monismith (equation)
LC_{50}	lethal concentration 50, concentration that is lethal to 50% of population
MAF	million acre-feet
$\mu g\ g^{-1}$	microgram(s) per gram
$\mu g\ L^{-1}$	microgram(s) per liter
µmol	micromol(s)
$mg\ L^{-1}$	milligram(s) per liter
mm	millimeter(s)
MMHg	monomethylmercury
N:P	ratio of nitrogen to phosphorus
$ng\ L^{-1}$	nanogram(s) per liter
NH_4:NO_3	ratio of ammonium to nitrate
IEP	Interagency Ecological Program
PCB	polychlorinated biphenyls
POD	pelagic organism decline
SSC	suspended-solids concentration
SWB	State Water Board
SWRCB	State Water Resources Control Board
SWP	State Water Project
TAF	thousand acre-feet
USEPA	United States Environmental Protection Agency
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey

Executive Summary

ES1. Introduction

In the upcoming series of workshops, the State Water Resources Control Board (State Water Board) will receive information and conduct discussions regarding the scientific and technical basis for potential changes to the 2006 Water Quality Control Plan for the Bay-Delta. This presentation has been prepared to help inform the first of those workshops on *Ecosystem Changes and the Low Salinity Zone*.

The State Water Board should be applauded for recognizing the need to dedicate significant resources to ensure it can consider the available scientific information on key ecosystem attributes of the Bay-Delta, and other rivers and estuaries elsewhere. The State Water Contractors (SWC) and San Luis & Delta-Mendota Water Authority (SLDMWA) have attempted to compile and critically assess that scientific information below.

The State Water Board can draw on a two-decade history of attempts to enhance numbers of and reverse declining trends in native fish with flows through the Delta. A dominant operating conservation surmise has been that management of flow in the highly dynamic Bay-Delta estuary is the best direct route to enhancing the status of imperiled fishes. But, while a number of directed studies have found correlations between flows through the Delta and population changes in several fishes, no data are available that explain how flows affect the survival and persistence of the Delta's native species, and no studies support the assertion that additional flows will produce greater numbers of at-risk fishes, enhance the resources that support them, or compensate for the highly altered physical landscape that now accommodates both.

The review and analysis presented here indicates that unilaterally managing flows without addressing the actual environmental stressors that are directly and indirectly compromising at-risk fishes and their essential resources will not serve to reduce threats to those fishes' survival and recovery, and actually could contribute to further population declines. The best available science demonstrates that four changes in salient environmental attributes of the Delta have contributed to the current degraded state of the Bay-Delta ecosystem and appear to be proximate causes of declines in desired fishes:

1. changes in the composition of the food web that supports those fishes,
2. increases in water temperatures in portions of the estuary,
3. overall and localized reductions in turbidity, and
4. changes to the physical landscape.

The discussion of environmental changes that have disrupted the food web that supports the Delta's desired fishes presented here includes a review of available scientific information that supports or refutes six possible explanations for observed population declines – changes in 1) flows or flow patterns, 2) water appropriations, 3) contaminants, 4) invasive species, 5) nutrients, and 6) changes to the physical landscape. Some evidence exists that suggests that two or more of those sources of ecosystem change could operate in concert by positively and negatively reinforcing biological and biogeochemical feedbacks.These many changes to the Delta's ecosystems are considered immediately below, and explored in detail in the presentation that follows.

ES2. Changes to the Food Web

ES2.1 Observed Changes

The food web that supports native fishes in the Bay-Delta is different than that of decades ago. Primary productivity and phytoplankton biomass, as measured by chlorophyll-*a* (chl-*a*) concentrations, decreased significantly between 1975 and 1995 and still remain low. A paper that studies freshwater, marine and estuary systems around the world (Nixon, 1988) reports a strong relationship between production at the base of the food web (primary production) and production of fish (fishery yield). It provides an explanation for the low fishery production in the Bay-Delta estuary. Primary productivity data from the Bay-Delta estuary superimposed on the results of the study show very low and declining primary productivity in the Bay-Delta. Based on the results presented in the Nixon paper, that low primary productivity results in low fishery production.*The State Water Board should commission a study that directly applies the principles of the Nixon paper to the Bay-Delta estuary, one that compares total fishery yield to primary production within the Bay-Delta estuary.*

The link between changes (declines) in primary production and fish production in the Bay-Delta estuary is further supported by the shift in the dominant phytoplankton species from diatoms to less nutritious and sometimes toxic algal species. Secondary productivity has also changed, with larger, more accessible zooplankton species being replaced by smaller species. Because aquatic ecosystems are substantively determined by the structure and composition of their constituent food webs, efforts to increase the abundance of native fish in the Bay-Delta require identification of the most important factors affecting phytoplankton production. There is substantial scientific agreement that many of the observed changes in Delta primary productivity and food web composition are a result of introduction of non-native and invasive species, such as the Amur River clam, and that those changes have had significant impacts on the abundance and distribution of several desired species, such as the northern anchovy, mysid shrimp, and striped bass. Changes to the lower levels of the Delta food web also appear to have had detrimental impacts to other native species, including delta smelt and longfin smelt.

A number of explanations have been suggested to account for the observed changes to the composition of the Bay-Delta food web.

ES2.2 Possible Explanations of Changes to the Bay-Delta Food Web

Possible Explanation 1: Changes in flows and flow patterns that affect primary and secondary productivity

There is general agreement that freshwater flow is an important factor in primary and secondary productivity. In an estuary, freshwater flows deliver nutrients from upstream areas, re-suspend nutrients within the estuary, and enhance dispersion with salinity stratification. Soluble and particulate nutrient enrichment from freshwater inflow makes estuaries some of the most productive aquatic ecosystems.

Ecological processes in estuaries, however, are inherently complex due to their dynamic nature, mixing processes, and intricate ecological linkages. Because the Bay-Delta estuary is not a riverine system, but a highly altered tidal environment, the relationship between flow and productivity is neither simple nor linear. Recent research in the Bay-Delta on the relationship between through Delta flows and productivity have produced contradictory results, with some reporting variable results within different reaches of the same channel, some unable to detect a direct relationship, and some identifying an inverse relationship - such as in the Yolo flood bypass, where longer residence time appears to increase productivity. Several studies have concluded that numerous factors influence the relationship between residence time and phytoplankton biomass including growth and loss rates, nutrient balance, abundance of grazers, turbidity, temperature, and other factors.

The Bay-Delta estuary is a tidal environment dominated by instantaneous flows, which are largely beyond human control and exert a much greater influence than net flows, which are the basis for a number of regulatory requirements in the Bay-Delta. During the summer, tidal flows in a typical 25-hour tidal cycle can be greater than 300,000 cubic feet per second (cfs) compared to a net inflow of between 5,000-10,000 cfs. Because of these very large tidal flows, fish and other aquatic organisms have adapted strategies that allow them to maintain position or move around in the estuary, as evidenced by their continual presence in the face of large instantaneous flows. This is even the case for “weak swimmers,” like delta smelt and their prey items.

The observed association between the abundance of some fish species and flow (as represented by the position of the X2 isohaline in the estuary) has led to the resource management proposition that more flows though the Delta will produce increases in fish abundance. However, a causal link between increased flow and fish abundance has not been established.

In many estuaries, freshwater flow regulates the location of the estuarine turbidity maximum (ETM) or entrapment zone where suspended particles, phytoplankton, and zooplankton accumulate to create a biologically rich aquatic environment. The establishment of the spring X2 outflow was largely based on the assertion that the location of the ETM and peaks in abundance of several desired species in the Bay-Delta occurs at 2 practical salinity units (psu). However, more recent research suggests that multiple ETMs exist in the Bay-Delta; they tend to be associated with channel bathymetry and bottom topography. Thus, unlike some other estuaries, locations of ETMs in the Bay-Delta may be largely decoupled from freshwater inflow.

Possible Explanation 2: Appropriation of water that serves to remove productivity from the system

Appropriation of water affects productivity in the Bay-Delta through three mechanisms. First, in-Delta water appropriations remove plankton biomass, both phytoplankton and zooplankton, from the Bay-Delta ecosystem. An analysis of phytoplankton mass balance found that net transport loss, including losses from outflow to Suisun Bay and with appropriated water, accounted for only 6 tons C day^{-1} compared to net production of 44-53 tons C day^{-1} and within Bay-Delta consumption of 38 to 47 tons C day^{-1}. While appropriations remove some of the carbon biomass, they appear to have little effect on the concentration of the remaining phytoplankton. Analysis of average March to June chl-*a* concentrations at plankton sampling stations in the central Delta show no apparent relationship between phytoplankton concentrations and rate of appropriations during this same time period.

Second, appropriation of water impacts residence time in the Bay-Delta by increasing flow rates through the Bay-Delta. Transport time can affect phytoplankton biomass; however, longer residence time does not necessarily translate to greater phytoplankton biomass. The spatial and temporal variations in growth and loss rates within the Bay-Delta are too great to predict with any accuracy the overall impact of changes in residence time.

Third, water appropriations might prevent plankton in the south Delta from reaching Suisun Bay. But, modeling results indicate that over 90% of the time, the San Joaquin River and other eastern tributaries combined contribute less than 10% of the total flow reaching Suisun Bay even with in-Delta appropriations by CVP and SWP completely shut off.

Possible Explanation 3: Increases in contaminants that have direct and indirect effects on the survival and health of aquatic organisms

The presence of a wide diversity of contaminants from both point and nonpoint sources has been documented over the last 25 years, primarily by the Central Valley Regional Water Quality Control Board and the Interagency Ecological Program (IEP). Several recent reviews conclude that contaminants have

the potential to impact the ecosystem but must be considered in view of the complex interactions and uncertainties associated with potential exposures.

Contaminants enter the Bay-Delta estuary and its tributaries by runoff from urban and agricultural land uses, atmospheric deposition, municipal and industrial water treatment effluent, recreational and commercial boating activities, and from historic mining operations. Contaminant levels vary both spatially and temporally and many are highest following rain events (Kuivila and Hladik 2008). Several contaminants, including pesticides, metals, pharmaceuticals, personal care products and nutrients, have been detected in Bay-Delta estuary water and sediment and continue to be the focus of concern by regulatory agencies.

Possible Explanation 4: Increases in invasive species that have caused a significant decline in phytoplankton biomass with resultant impacts on higher trophic levels

There is universal agreement that the invasion by the Amur River clam has had a significant effect on chl-*a* levels in Suisun Bay, with its influence extending into the lower Sacramento and San Joaquin Rivers. The clams have been blamed for the density declines in diatoms, several zooplankton species, and various native fish species. Evidence exists that non-native species have contributed to changes to the Bay-Delta food web, a reduction in those species could increase productivity and populations of remaining, native species.

However, it appears that the arrival of invasive clam species does not fully explain the decrease in the Bay-Delta's productivity. Primary productivity, as measured by chlorophyll-*a* (chl-*a*) concentrations, began to decline prior to the arrival of the Amur River clam, has declined in seasons when clam biomass is low, and has continued to decline even where clam abundance has not. Phytoplankton levels have also declined in upstream parts of the estuary, in areas not affected by invasive clams, such as in the south Delta. The invasive aquatic plants, *Egeria densa*, may be one of the other factors suppressing productivity in the Delta. Egeria has been present in the Delta for about 50 years, but its coverage in channels and embayments began to expand significantly in the mid-1990s. The dense upper "canopy" formed by egeria blocks light that would normally be available to phytoplankton, thus contributing to reduced native fisheries production.

Efforts to control invasive species will need to be coordinated with efforts to address other factors suppressing productivity. While increasing flow has been proposed as a management tool to reduce the adverse impact of clams, the proposal is not supported by available science. Ecological responses in other ecosystems support the hypothesis that nutrient load reductions may reduce invasive clam abundance and improve ecosystem productivity.

Possible Explanation 5: Changes in nutrient concentrations, forms, and ratios cause changes in species composition and abundance at all trophic levels

Changes in nutrient loads are clearly impacting Bay-Delta ecosystem dynamics in complex ways that extend beyond eutrophication. In addition to increases in nutrients, changes in the form of available nutrients (chemical state, oxidized vs. reduced, organic vs. inorganic, dissolved vs. particulate) and the proportion of different nutrients produce adverse effects at both the scale of the primary producers and the entire ecosystem.

Total nutrient loads, including ammonium (mostly from a single source) have increased, and the relative proportion of ammonium (NH_4) to nitrate (NO_3) has changed. For decades, researchers have explored the relative use of – or relative preference for – different forms of nitrogen (N) by phytoplankton. Ammonium (NH_4) is generally considered to be the form of nitrogen preferred by phytoplankton because it requires

less energy to assimilate than NO_3. However, it is also well documented that NH_4 can inhibit the uptake of NO_3, and thus can exhibit a strong negative control on phytoplankton productivity.

The effects of changes in the proportion of NH_4/NO_3 have been shown for the Bay-Delta in both field observations and lab experiments. One recent study identified a 60% decline in primary production in the Sacramento River below the Sacramento Regional Wastewater Treatment Plant, where NH_4 is discharged, compared to production levels above the Treatment Plant's outfall, and found evidence that high rates of carbon uptake are linked to phytoplankton NO_3 use. The increased proportion of NH_4 may help explain reduced primary production in Bay-Delta since the 1970s. The form of available nitrogen also affects phytoplankton species composition, as diatoms generally have a preference for NO_3, while dinoflagellates and cyanobacteria generally prefer more chemically reduced forms of nitrogen (NH_4, urea, organic nitrogen). Furthermore, the ratio of nitrogen to phosphorus (N:P) has doubled in the Bay-Delta over the last 35 years due to increased total nitrogen loads (from increased effluent discharge from wastewater treatment plants and other sources) and declining phosphorus loads (due to the regulation of detergents). A retrospective analysis of 30 years of data from the Bay-Delta found that variation in nutrient concentrations and ratios is highly correlated to variation in phytoplankton species composition and biomass at the base of the food web. Similar observations have been made in ecosystems elsewhere. The balance of N:P can affect other metabolic aspects of phytoplankton besides growth, including toxin production, cell membrane thickness, and other chemical constituents. Several ecosystems elsewhere have seen a resurgence of some native species and a decline of some invasive species, including invasive clams, following reductions in nutrient loads and a restoration of the N:P balance.

Possible Explanation 6: Changes in the land-water interface, including loss of floodplains and loss of tidal wetlands

The predevelopment Bay-Delta was an extensive, complex, and diverse environment, with narrow, meandering, and sinusoidal channels. The massive dredging of the Sacramento River for flood control in the 1920s deepened, widened and straightened the river, resulting in profound changes in the bathymetry and regional hydrodynamics. From 1860 to 1930, approximately 400,000 acres of tidal marsh were converted to Delta farm land, thereby cutting off the tidal prism. Miles of dendritic channels were eliminated and replaced with deep channels with lesser bathymetric diversity. These profound changes to the physical environment resulted in the hardening of the land-water interface, thereby isolating large geographic areas from natural tidal action and flood events.

In the last 150 years, approximately 95% of the tidal wetlands in the Delta have been lost. Shallow-water areas contiguous and adjacent to tidal wetlands and freshwater marshes support high phytoplankton growth rates and produce high quantity and quality productivity and can serve as relatively food-rich areas for desired fishes. Floodplains in the Bay-Delta estuary and in the watersheds of the Sacramento and San Joaquin rivers can produce high levels of phytoplankton and other algae, even after the short-duration flooding that occurs in the spring. Shallow water depth and long water residence time on floodplains facilitate settling of suspended solids, resulting in reduced turbidity and increased total solar radiation available for phytoplankton growth. Periodic small floods boost aquatic productivity of phytoplankton by delivering new pulses of nutrients, mixing waters, and exchanging organic materials with the river.

Reduction in primary productivity resulting from losses of wetlands across much of the Bay-Delta estuary is recognized by agency biologists as a key determinant of declines in zooplankton and the native fish that prey on them. While changes in the land-water interface from decades ago may not explain the most recent fish declines, they contribute to the overall low productivity of the Bay-Delta.

ES3. Changes to the Delta's Physical Landscape

Before European settlement, the Sacramento and San Joaquin Rivers flowed through approximately 400,000 acres of wetlands and other aquatic habitats in the Bay-Delta. The primary landscapes included flood basins in the north, tidal islands in the central Bay-Delta, and a complex network of channels formed by riverine processes in the south.

In the past 160 years, approximately 1,335 miles of levees were constructed and in-Delta channels were widened, straightened, deepened, connected, and in some instances gated, which have collectively altered the pattern and extent of diurnal tidal flows. Most upstream rivers and many of the contributing streams have been modified with dams, diversions, or other "improvements" that have separated channels from their floodplains, changing inflow patterns, and reducing sediment and nutrient inputs to the ecosystem.

The historical changes in the Bay-Delta landscape have affected more than just food web productivity. The complex assemblage of floodplains, freshwater and tidal wetlands, open water and upland habitats historically provided valuable space for rearing, spawning, migration, and refuge from predators for both aquatic and terrestrial species. The extensive changes to the Delta landscape have reduced, fragmented, and isolated these habitats. While land and water were once intricately connected, in the current Bay-Delta landscape, levees maintain complete separation.

ES4. Changes in Temperature

Although annual trends in water temperature have not been observed in recent decades, significant changes in average monthly temperatures have been observed between 1983 and 2007. Climate change is expected to result in further increases in water temperature in the estuary. Cold-water reservoir releases have been used for decades to provide temperature refugia for salmonids; however, climate change could result in a decrease in cold-water pools in upstream reservoirs as the contribution of snowmelt to mountain runoff declines. Additionally, the number of areas experiencing temperatures above lethal ranges for native species is expected to increase. Increased temperature could adversely affect aquatic invertebrates and alter wetland plant communities by causing changes in available carbon.

Water temperatures provide an important constraint on ecological function, including effects on aquatic invertebrates and effects on fish spawning, swimming performance, metabolism, and mortality. The biological implications of climate change effects on water temperatures may be profound, including increasing risk of extinction of native species and increasing dominance of nonnative species.

Water temperatures in the Bay-Delta are primarily driven by atmospheric influences, although thermal dispersion also influences water temperatures, and bathymetric features can influence site-specific water temperatures. Reservoir releases will be unable to affect water temperatures in the Bay-Delta during the warmer summer and fall seasons when cooler water temperatures are most needed.

ES5. Changes in Turbidity

Monitoring by the California Department of Fish and Game (DFG) and the IEP in the Bay-Delta estuary over the past 35 years has documented trends in increased water clarity, reduced turbidity, and declines in chl-*a*. The decline in turbidity has undergone what has been characterized as a significant step decrease, with turbidity in the San Francisco Bay (expressed by suspended sediment concentration) decreasing 36% between water years 1991-1998 and 1999-2007. That decline is thought to have resulted from a shift from depositional to erosion-generating processes in Suisun, San Pablo, and central San Francisco bays. These changes have significant implications for several fish species, including delta

smelt, as turbidity appears to be a critical factor for delta smelt larval feeding. With decreasing turbidity, more light penetration could increase primary productivity.

Reservoirs on the major tributaries have reduced sediment input to the Bay-Delta and the sediment transport capacity of channels below these reservoirs decreases over time as the channels become incised and armored. However, while suspended solids concentrations in the Bay-Delta rise following significant rainfall, releases from upstream reservoirs are not an effective means of delivering suspended sediment to the Delta.

ES6. Changes in Through-Delta Flows

The 2010 State Water Board Flow Criteria Report (2010 Flow Criteria Report) recommends flow standards based on a percentage of unimpaired flows. That approach does not recognize that "unimpaired flow" is a calculation of a hypothetical condition that never existed in the Bay-Delta system. Previous analyses of natural flow indicate that outflow in the historic undeveloped environment are lower, likely substantially, than the unimpaired flows previously considered by the State Water Board as representative of "natural" conditions. Further, the mechanisms through which freshwater flow contributes to desired characteristics in a largely unaltered system are different from than those that would be provided by flows in the highly altered Bay-Delta estuary. In addition, most of the literature and examples of application of a natural flow regime approach are from riverine systems, not systems like the Bay-Delta estuary. Complex ecological and biological processes occur within estuaries, primarily due to their dynamic nature, complex freshwater-seawater mixing processes, random influences, antecedent conditions, and complex ecological linkages.

ES7. Conclusions

There is widespread agreement that adverse changes in the Bay-Delta food web are driven by nutrients, invasive species, changes in landscape attributes at the land-water interface, and potentially contaminants. Several environmental stressors can be feasibly addressed by water quality objectives in the Bay-Delta plan and with implemented actions by the State Water Board and other agencies. Such actions could directly address underlying causes and reduce or reverse adverse changes that have impacted the lower levels of the Delta's food web.

Conversely, the science does not support increasing inflow or outflow as a way to improve the health of the ecosystem. The causal links between flow and fish abundance are largely unknown, and there is insufficient evidence to rely on increased flow as a tool to increase fish abundance.

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1 Introduction

This paper provides the State Water Board with a technical assessment of available scientific information regarding five aspects of ecosystem change that biologists contend have contributed to the current health and integrity of the Bay-Delta estuary:

- Changes to the composition of the food web,
- Anthropogenic changes to the physical landscape,
- Warming of water temperature,
- Reduced turbidity, and
- Changes to flows and the location of the low-salinity zone in the estuary.

Within the discussion of changes to the composition of the food web, this paper describes six factors that may explain all or a portion of the changes: flow, water diversions, contaminants, invasive species, nutrients, and physical landscape.

The scientific community agrees that the San Francisco Bay-Sacramento/San Joaquin River Delta (Bay-Delta) "is one of the most highly modified and controlled estuaries in the world" (Moyle et al. 2010). The same is true for many of the streams and watersheds that feed the estuary. Over the last 150 years, more than 95 percent of the original wetlands, floodplains, and riparian habitats have been destroyed. Channels have been widened, straightened, deepened, connected, and regulated with levees and gates. Rivers tributary to the Bay-Delta have been dammed and flows manipulated. Hydraulic mining has had lasting effects on sediment dynamics. Non-native species have been introduced and have become well established. The human population has grown considerably with resultant land use changes, increases in the demand for water, and increases in pollutant loads in waterways. The climate has changed and is changing, sea level is rising, and ocean conditions have fluctuated, and many of these elements will continue to change into the future. There have been winners and losers among the Delta's native plants and animals as a result of these changes. Unfortunately, many of the estuary's native fish, including delta smelt and longfin smelt, salmonids, and sturgeon have been the losers, while clams, invasive zooplankton, and predatory warm-water fish have been the winners.

Because of the complexity of changes that have occurred in the Bay-Delta estuary, protection of water quality for beneficial uses cannot be realized through water quality objectives that address a single parameter or through authority held by a single regulatory agency. The solution, like the problem, will be need to be comprehensive. So many aspects of the Bay-Delta and its watershed have changed that solutions such as mandating a percent of the "natural flows" will neither restore "natural conditions" nor address many of the key stressors; a more comprehensive approach is necessary. Regulation of water appropriation has been an important tool to provide protection for beneficial uses within the Bay-Delta estuary. This paper does not dispute that. Instead, this paper considers the role of flow (including regulation of water appropriation) in rivers and estuaries. It ultimately reflects the existing science that shows the important function natural flow provides to rivers and estuaries, but that significant changes in the regulation of appropriations should not occur until other physical, chemical, and biological ecosystem changes are addressed.

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2 Major Changes to the Delta Food Web

Summary: The best available scientific evidence indicates that changes to the composition of the food web in the Bay-Delta are the primary factors that have driven historic and recent changes to the Bay-Delta ecosystem. Published literature and data from the Bay-Delta estuary indicate that addressing food web changes should benefit stressed species. There are a number of possible explanations for the changes.

1. **Flow:** There is general agreement that in an unaltered estuarine ecosystem, freshwater inflow can be an important factor in primary and secondary productivity (plankton production). However, in the highly altered Bay-Delta ecosystem, there is no indication that a linear or simple relationship between flow and plankton productivity exists. And, because the Bay-Delta estuary has been so extensively altered, regulation of flow must be carefully considered in spatial and temporal contexts. Regulation of flow must be based on specific flow functions and considered in context with co-occurring changes to localized functions and processes.
2. **Appropriation of Water:** While water appropriations remove plankton from the ecosystem, there are no studies that demonstrate appropriations of water impact on overall productivity. Water appropriations alter patterns of plankton transport, and models indicate that completely ceasing in Delta appropriation by CVP and SWP will not alter the transport of plankton to food limited areas.
3. **Contaminants:** Many contaminants have been detected in Bay-Delta water and sediment, including pesticides, metals, pharmaceuticals, personal care products, and nutrients. Published literature suggests that contaminants have the potential to impact the ecosystem but must be considered in view of the complex interactions and uncertainties associated with potential exposures. While it is clear from studies to date that potential contaminant effects are important to the health of the Bay-Delta ecosystem, it is equally clear that it is important to recognize the uncertainties and complexity of these relationships.
4. **Invasive Species:** The invasive Amur River clam (*Potamocorbula amurensis*[10]) has reduced plankton biomass levels in Suisun Bay and the lower Sacramento River. However, the Amur River clam cannot explain the entire decline in phytoplankton biomass, which began before the clam became established in these bodies of water. In addition, bivalve abundance in upstream regions and in the spring insufficiently explains phytoplankton biomass declines that have been observed in those areas and times.

   While increasing flow has been proposed as a management tool to reduce the adverse impact of clams, the proposal is not supported by available science. Ecological responses in other ecosystems support the hypothesis that nutrient load reductions may reduce invasive clam abundance and improve ecosystem productivity.
5. **Nutrients**: The scientific literature shows that nutrient loads affect ecosystem dynamics in complex ways that extend beyond our historic understanding of eutrophication. In the Bay-Delta, total loads and the forms and relative proportions of nutrients have changed over time. Ammonium loads have doubled, ammonium-to-nitrate ratios have increased, and nitrogen-to-phosphorus ratios have doubled. A review of the science in this and other estuaries indicates that these changes may have had profound effects on the Bay-Delta ecosystem by altering and suppressing the food web that

[10] Also referred to as *Corbula amurensis*, *Corbula,* overbite clam, and Amur River clam.

supports native fish species. Other ecosystems also provide examples of increasing native species and declining invasive species following restoration of balanced nutrient conditions.

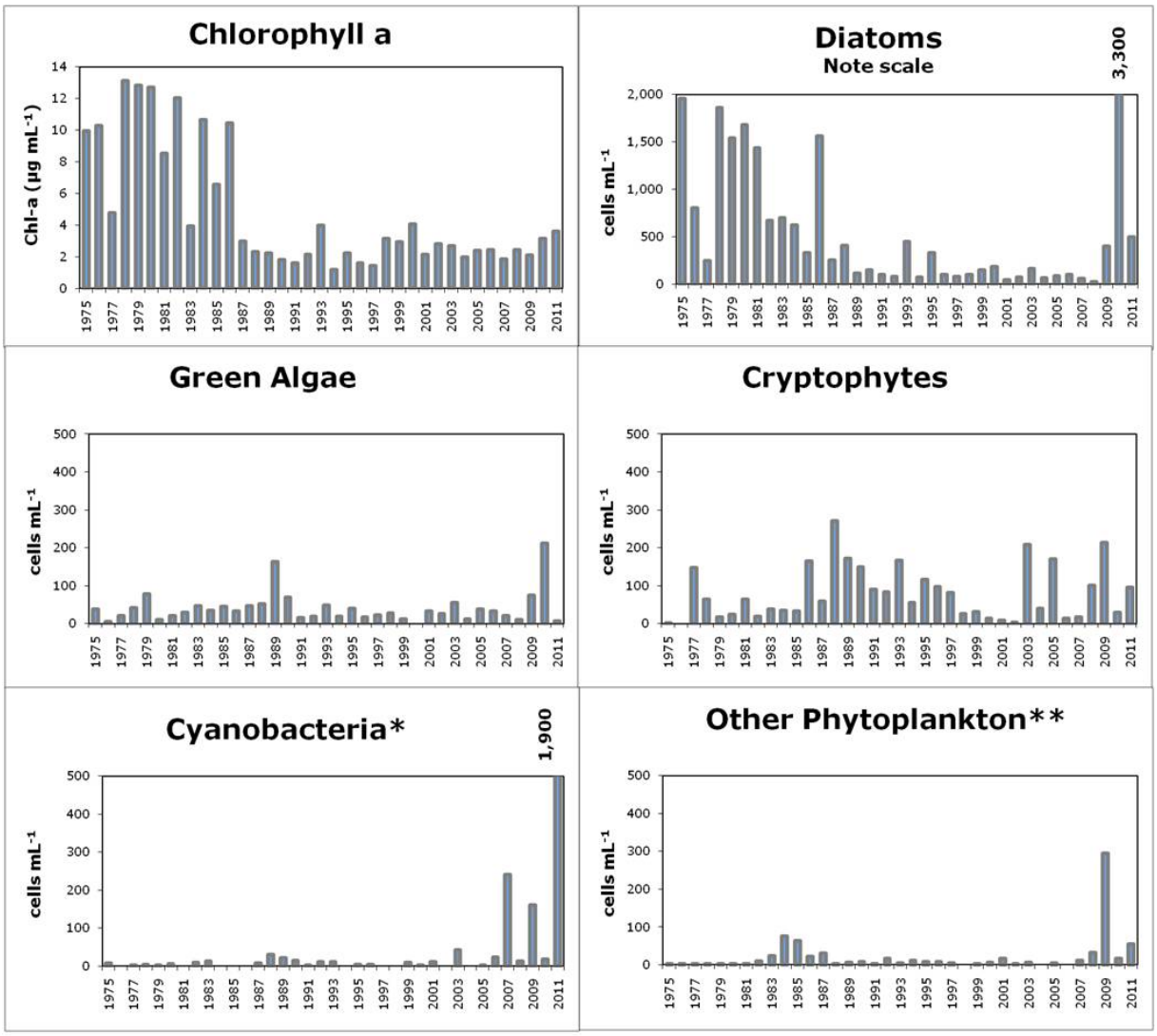
6. **Physical landscape:** The rich diversity and abundance of the aquatic and terrestrial life in the predevelopment Bay-Delta estuary and its tributaries supported dense fish populations. Now the historic connections between land and water have been severed by development, construction of dams, and the draining and diking of wetlands behind a vast network of levees. While changes in the land-water interface from decades ago cannot explain recent fish declines, they do play a role in the overall low productivity.

   The restoration of large floodplain areas could allow for inundation periods that would maximize food web productivity and provide ecosystem benefits at the population level, especially if coupled with measures to restore the nutrient balance.

2.1 Changes to the Food Web

There is agreement in the scientific community that the composition of the food web in the Bay-Delta now differs from that of the past. The dominant phytoplankton species have shifted from diatoms to less nutritious – and sometimes toxic – algal species. The larger calanoid copepods that have been identified as important prey for delta smelt and longfin smelt are now outnumbered by smaller cyclopoid copepods. There is scientific agreement that changes in primary and secondary production (phytoplankton and zooplankton) have had significant effects on the abundance and distribution of several species, such as the northern anchovy (*Engraulis mordax*), mysid shrimp (*Neomysis mercedis*) and striped bass (*Morone saxatilis*). There is also scientific agreement regarding some of the causes of these changes to the food web, such as the invasion by the Amur River clam (*P. amurensis*) in the past, and changes to the Delta landscape in the long term. This report presents the compelling science that reflects that changes at the base of the food web have had detrimental effects on delta smelt and longfin smelt abundance.

There have been changes at all levels of the Delta food web. Primary productivity and phytoplankton biomass in the Delta, as measured by chlorophyll-*a* (chl-*a*) concentrations, are among the lowest of all estuaries studied (Jassby et al. 2002). In fact, chl-*a* decreased significantly in each season except spring (April through June) from 1975 to 1995 (Jassby et al. 2002, 2003), and remains low (Kimmerer 2004). Laboratory experiments suggest that Delta-wide chl-*a* levels are now so low that they are limiting zooplankton abundance (Müller-Solger et al. 2002). Not only has total biomass changed (as measured by chl-*a*), the Delta's algal composition has shifted over time from diatoms to smaller, less nutritious taxa such as dinoflagellates and cyanobacteria (Lehman 2000; Lehman et al. 2005; Lehman et al. 2010; Jassby et al. 2002; Sommer et al. 2007; Glibert et al. 2011; Winder and Jassby 2010). In a retrospective analysis of data collected from 1975-2005 from the Suisun Bay and Sacramento River regions, Glibert et al. (2011) found, "the declines in chlorophyll-*a* and diatoms over the entire time course were significant (R2 = 0.57 and 0.68, p <0.01), as was the increase in dinoflagellates (R2 = 0.30, p 0.05)." Time trends in phytoplankton biomass and species density are shown on Figure 1.



*Cyanobacteria does not include *Microcystis aeruginosa* and other picocyanobacteria that are not sampled accurately by the standard phytoplankton surveys. *M. aeruginosa* blooms were first observed in the Delta in 1999, and have since been occurring with increasing frequency and magnitude (Lehman *et al.,* 2005).

**Other phytoplankton is the sum of Chrysophyta, Euglenophyceae, Haptophytes, and Dynophyceae.

Figure 1. Change in the average March-October concentration of chl-*a* (µg L−1) and abundances of the major classes of phytoplankton and cyanobacteria (cells mL−1) over time. The Delta's algal taxonomic composition has shifted over time from diatoms to smaller, less nutritious species such as dinoflagellates (shown in the other phytoplankton graph) and cyanobacteria (Source: Environmental Monitoring Program, stations D4, D6, D7, D8 in Suisun Bay, lower Sacramento River and lower San Joaquin River).

As reported by Cloern (2001), "changes in phytoplankton species composition can directly impact the population dynamics of metazoan consumers that utilize the phytoplankton as their primary nutritional source." Evidence suggests that this is the case in the Bay-Delta. As shown on Figure 2, the abundance of many zooplankton species has also changed over time, with declines observed in *Eurytemora, Neomysis,* and rotifers, increases in *Acartiella*, and *Limnoithona,* and fluctuating abundances of *Pseudodiaptomus*, *Sinocalanus,* and Harpaticoids. In fact, there are very few zooplankton species that

have not experienced a significant change in abundance since monitoring began (Winder and Jassby 2010).

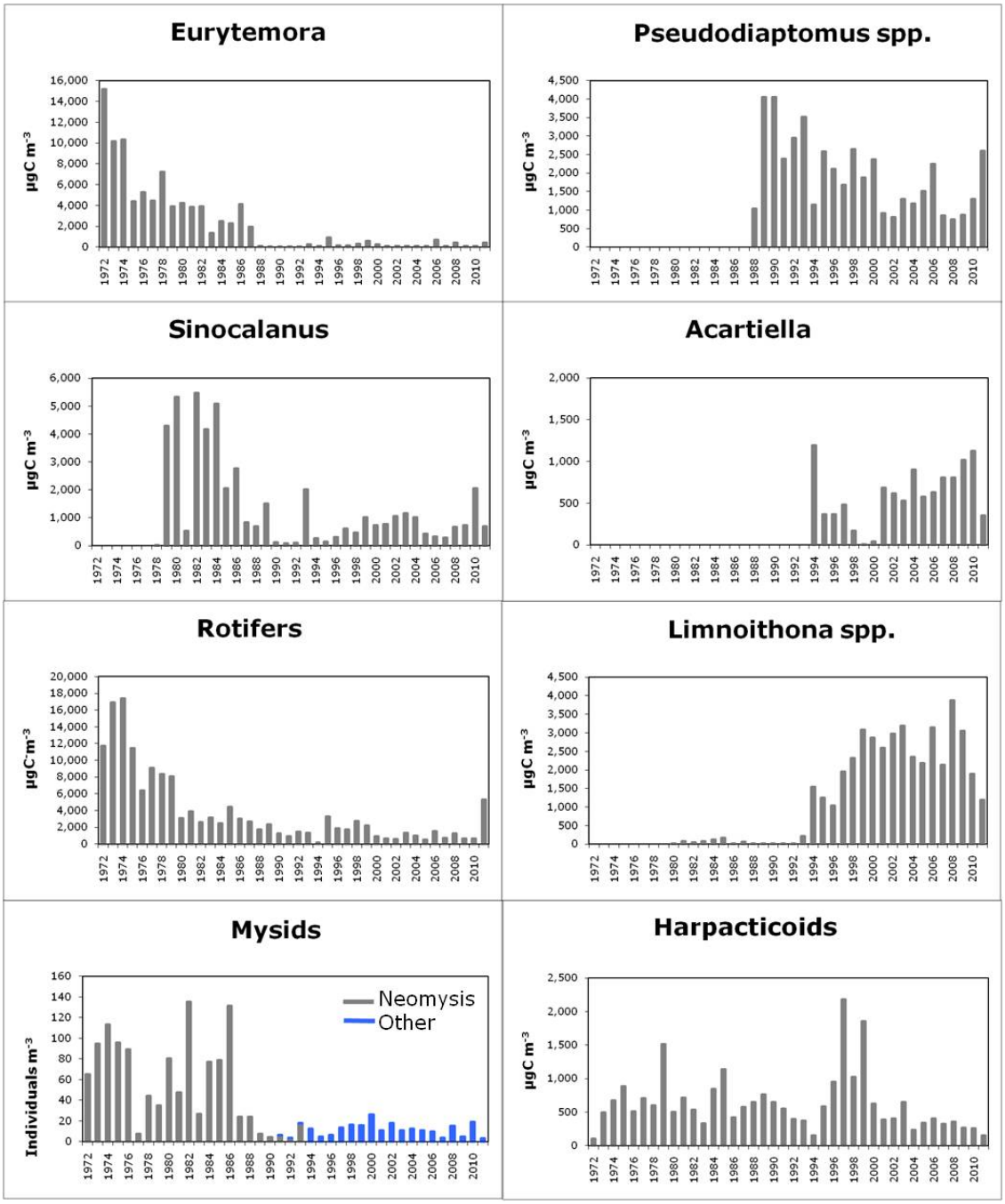


Figure 2. **Average March-October density of zooplankton over time showing significant changes in community composition. (Source: IEP zooplankton survey data from all Delta and Suisun Bay stations with a long continuous record of sampling. Survey counts were converted to biomass using NCEAS C per individual. Biomass was multiplied by volume of region and averaged across regions to obtain average annual volume weighted densities). Note y-axis scale differences.**

When considering trends in Delta fish abundance as a whole, it is apparent that the Delta fish community has not crashed – it has shifted composition. Just as in the lower trophic levels, there have been clear winners and losers in the fish community (Figure 3). Based on California Department of Fish and Game's (DFG's) fall mid-water trawl and summer townet surveys, some native fish species have declined and have been listed as threatened or endangered under the Endangered Species Act. However, the abundances of some fish species have increased over time, including non-native species that are popular for sport fishing, such as largemouth bass and sunfish.

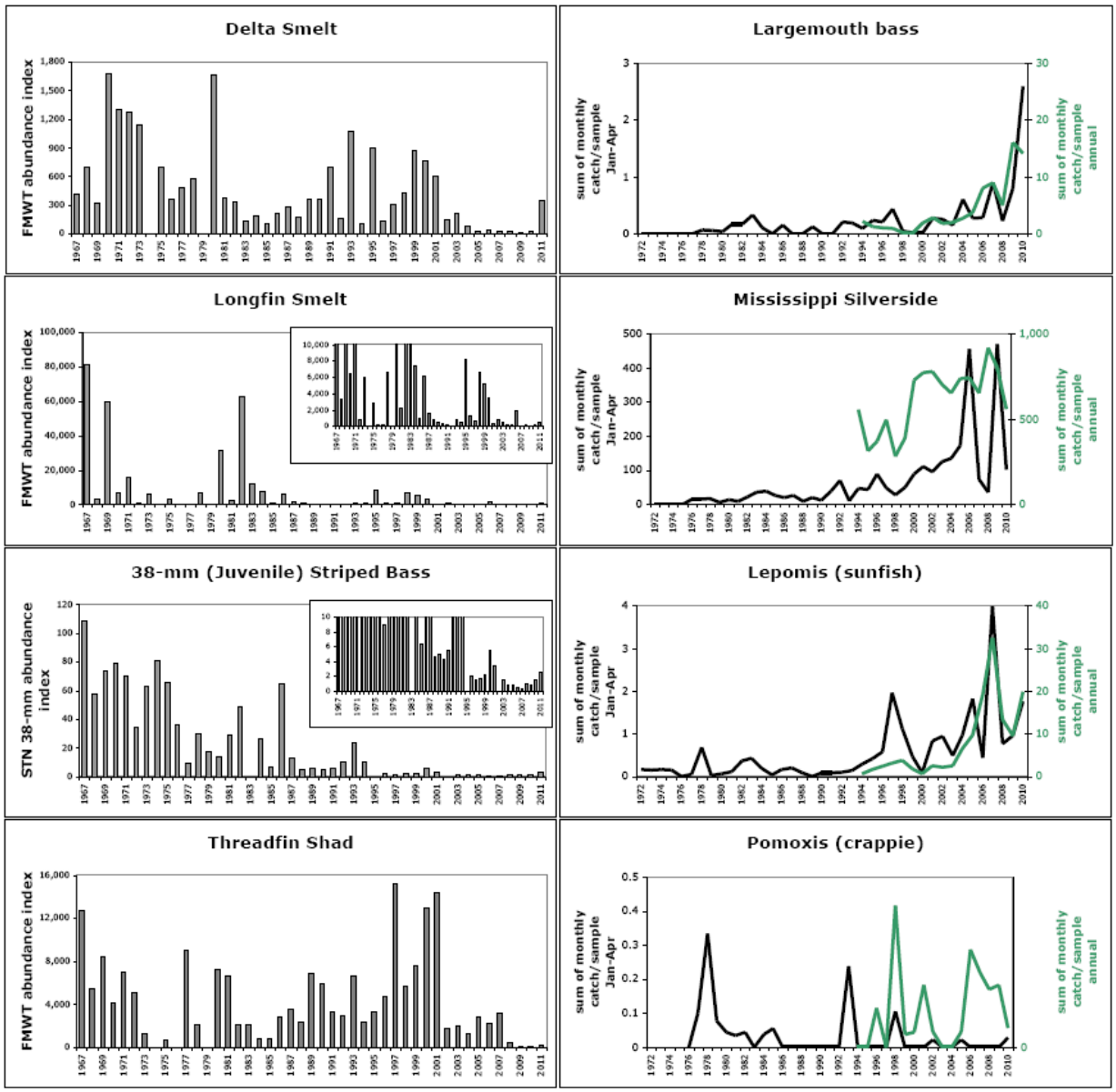


Figure 3. **Trends in fish abundance over time. Just as in the lower trophic levels, clear winners and losers have emerged in the fish community. (Source: Data for delta smelt, longfin smelt and threadfin shad come from DFG's Fall MidWater Trawl Index. Data for juvenile striped bass are from DFG's Summer Tow Net Survey. Data for the panels in the column on the right are from Beach Seine surveys at stations located in the Delta.**

Unfortunately, the winners have predominantly been non-native and littoral fish (fish that occupy near-shore areas), while the native and pelagic fish (fish that occupy open waters) have been the losers. There is evidence that this divergence is due to separate food pathways for the pelagic versus littoral fish (Grimaldo et al. 2009). Results of fish surveys in the Delta have shown a trend of increasing abundance of non-native fish inhabiting the Delta, particularly largemouth bass and sunfish (Figure 4). The Delta is now considered to be a world class largemouth bass fishery, with thousands of anglers and nationally televised tournaments (e.g., Bass Masters), as well as local and regional tournaments occurring throughout the year.

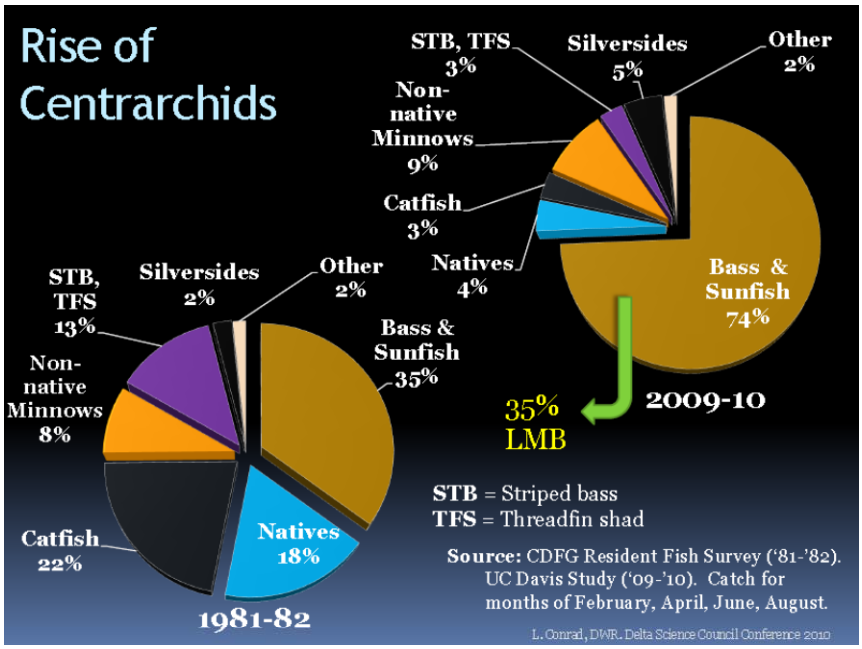


Figure 4. Change in fish species composition in surveys conducted in 1981-1982 and 2009-2010, showing a trend of increasing abundance of non-native fish inhabiting the Delta (Source: Conrad et al. 2010b).

In addition to demonstrating the increasing trend in bass abundance, fish surveys have also shown that the size of largemouth bass inhabiting the Delta has increased in the past decade, with an increase in the occurrence of bass in the size classes from 300 to greater than 500 millimeter (mm) in the population (Figure 5). Increases in both bass abundance and size in recent years reflect the favorable habitat conditions and prey that are available in the Delta for these fish. Increases in submerged aquatic vegetation in the Delta in recent years have been identified as a factor contributing to increased habitat and foraging opportunities for largemouth bass and sunfish (Conrad et al. 2010a, b; Conrad et al. 2011). Using stomach content and stable isotope analyses, Grimaldo et al. (2009) found evidence of two separate food-web pathways, one for pelagic fish and one for littoral fish such as bass and sunfish. They state, "[t]his apparent shift to grazer amphipods may partially explain why centrarchids in the Delta have increased in abundance over the last 2 decades (Brown and Michniuk 2007), whereas declines in pelagic production have apparently had adverse consequences for pelagic fish populations in the estuary (Sommer et al. 2007)."

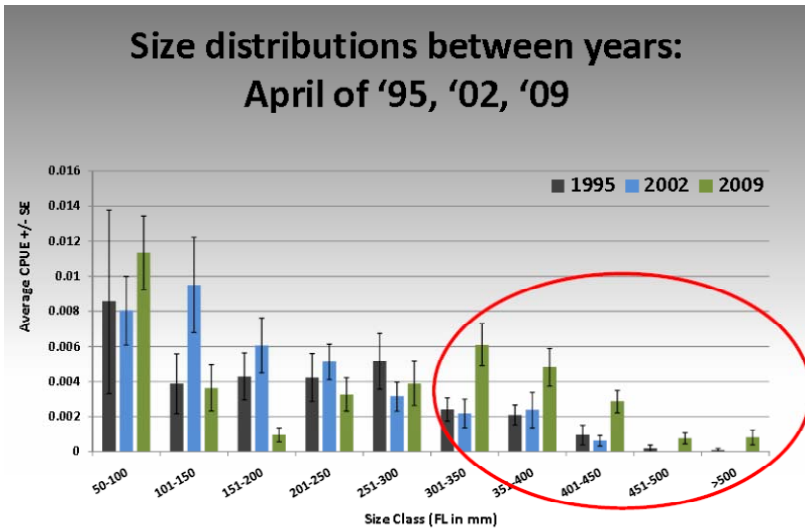


Figure 5. Length frequency trends in largemouth bass collected in the Delta showing the size of largemouth bass inhabiting the Delta has increased in the past decade with an increase in the occurrence of bass in the size classes from 300 to greater than 500 mm in the population. (Source: Conrad et al. 2010a).

2.2 Biological Implications of Changes in the Food Web

Research has established that a strong link exists between food availability and the growth and survival of fish species. In recent studies focused on the Bay-Delta, researchers now hypothesize that food quantity and quality are limiting the growth and survival of several fish species in the Bay-Delta. Winder and Jassby (2010) state, "Low food supply combined with changing food quality likely translated into reduced growth and survival of pelagic fish and affected their long-term and more recent recruitment success." Rosenfield and Baxter (2007) state that, "Food limitation is consistent with our finding of reduced age-class 1 productivity and the disproportionate reduction in age-class 2 recruitment" for longfin smelt. Slaughter and Kimmerer (2010) state, "The combination of low primary production and a long and inefficient food web have likely contributed to declines of pelagic fish." Jassby et al. (2002) conclude, "Overall, the Delta lost 43% in annual primary production during the period [1975-1995]. Given the evidence for food limitation of primary consumers, these findings provide a partial explanation for widespread Delta species declines over the past few decades." Kimmerer et al. (2012) explain, "it seems likely that the persistently low productivity at the base of the food web, particularly for larger cells, has affected higher trophic levels." And, using a multistage life-cycle model, Maunder and Deriso (2011) found that food abundance was one of the most important factors controlling the population dynamics of delta smelt – a result confirmed by Miller et al. (2012).

The link between food availability and fish abundance has been extensively studied. Nixon (1988) reviewed studies from freshwater, marine, and estuary systems around the world and reported a strong relationship between production at the base of the food web (primary production) and production of fish (fishery yield). In fact, Nixon (1988) states, "Although it has long been assumed that there was a strong link between primary production and the yield of fish from the sea, Fig. 6 is the first empirical demonstration that **such a link is strong enough to be seen (at least on a broad scale) against all the other variables that influence fish production**…" [emphasis added]. Figure 6, shows that as primary production increases so does fishery production. The figure shows that most estuaries (solid circles) are high in both primary and fishery production. Suisun Bay, where the Low Salinity Zone is often located, is a striking exception. Figure 6 shows primary productivity data from the Bay-Delta estuary superimposed on Nixon's (1988) figure, showing low and declining primary productivity in the Bay-Delta.

With reference to the Nixon (1988) relationship, Kimmerer et al. (2012) conclude, "…the lack of a substantial commercial fishery in the San Francisco Estuary probably reflects the overall low productivity in this system."

A similar analysis to Nixon's that compares total fishery yield to primary production has not been conducted in the Bay-Delta estuary, but would likely add further support to the role of food in the decline of native fish. The State Water Board should commission such a study.

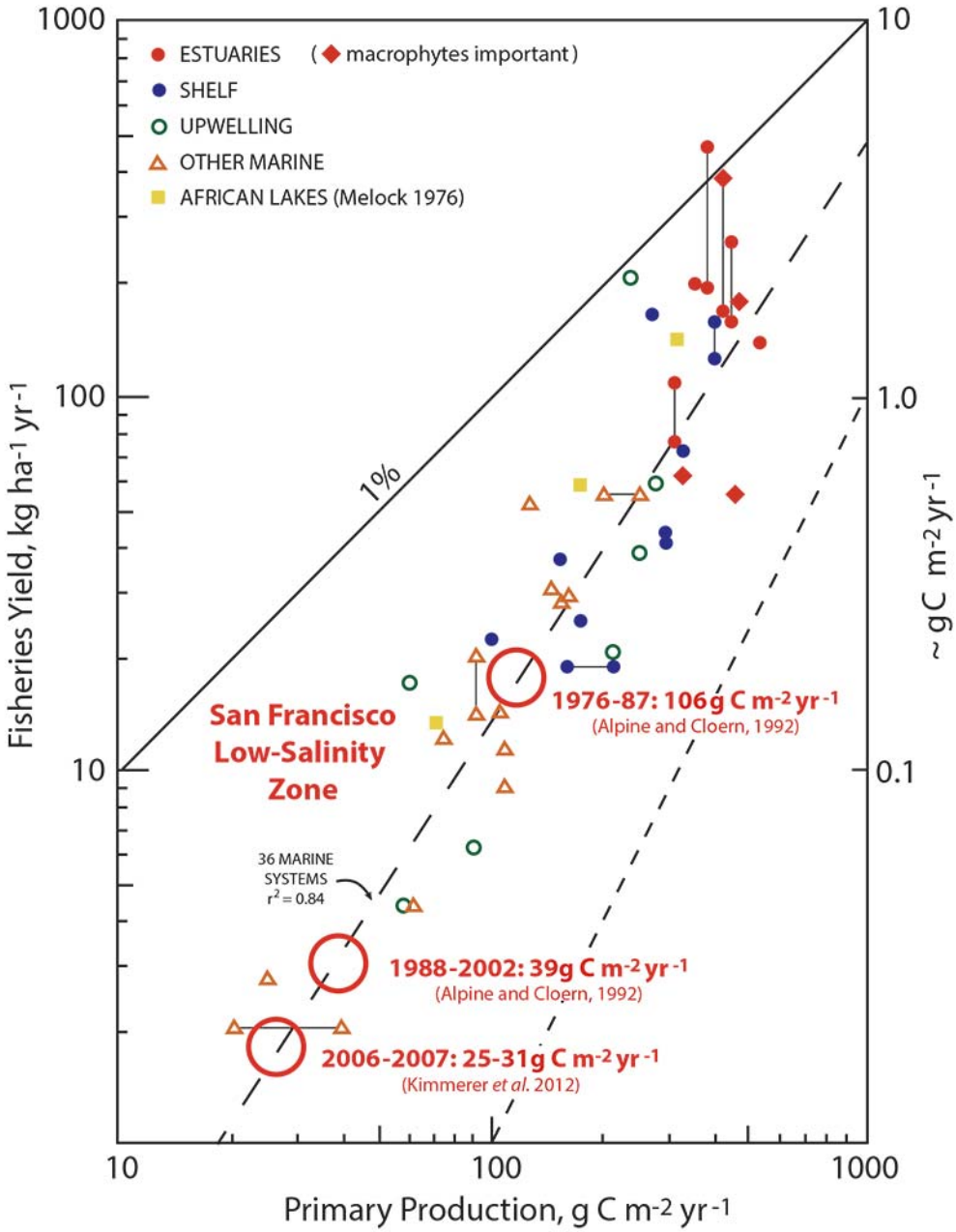


Figure 6. Relationship between primary production and fisheries yield. Fishery yield increases with increasing productivity. (Source: Figure 6 from Nixon 1988, modified with data from Alpine and Cloern 1992 and Kimmerer et al. 2012).

There are numerous examples in the Bay-Delta estuary and elsewhere demonstrating how species abundance and distribution changes in response to changing food resources, including species moving to new locations, declines in total abundances, or changes in feeding habits.

Higher trophic-level species, such as the northern anchovy, have been observed moving to a new location. In response to a significant and abrupt drop in phytoplankton biomass in the Suisun Bay area following the invasion by the Amur River clam, a redistribution of northern anchovy farther downstream occurred, reducing its summer abundance in the Suisun Bay and Delta by as much as 94% (Kimmerer 2006). Kimmerer explored several possible explanations for the dramatic and rapid redistribution of northern anchovy in 1987 and thereafter, including climate variability and biomass, catch, and abundance on the California coast. He concluded that the most parsimonious explanation for the change in anchovy distribution was a direct or indirect response to the decline in chl-*a*.

The shift in distribution of a fish population away from a region that had become inhospitable is not surprising. In the lower Hudson River, several open-water fish species shifted seaward following a reduction in chl-*a* concentration due to the introduced zebra mussel, *Dreissena polymorpha* (Strayer et al. 2004, cited in Kimmerer 2006). Similar behavioral shifts of northern anchovy in apparent response to chl-*a* concentration (or its covariates) have been noted off Baja California (Robinson 2004, cited in Kimmerer 2006).

The shift in distribution can also be vertical or lateral within the same areas. Work by Sommer et al. (2011) examines the distribution shift in striped bass in the Bay-Delta, stating:,

> "The survey data suggest a substantial long-term distribution shift away from channels and toward shoal areas. The hypothesis that young striped bass are under sampled by mid-water trawls is supported by modeling of demographic patterns, which showed that the decline in numbers of age-0 fish was not consistent with increasing trends in age-1 fish. We hypothesize that reduced food availability in pelagic habitat is a major cause of apparent behavioral shifts by age-0 striped bass and some native fishes."

Declines in species population abundance in response to food limitation have also been observed. Orsi et al. (1996) concluded that food limitation is the primary mechanism of decline in the native mysid, *Neomysis mercedis*. Feyrer et al. (2003) observed that 8 of 13 fish species declined in abundance during the study period (1979-1983 vs. 1998-1999) had mysids as important components of their diets in the earlier time period, but not in the latter. Kimmerer et al. (2000) found evidence that carrying capacity for striped bass declined in relation to mysid abundance declines.

Some species change feeding habits. Feyrer et al. (2003) found that striped bass switched to piscivory at a smaller size when mysid abundance declined. Before chlorophyll-*a* declined, striped bass shifted to piscivory at 140 mm FL; after chlorophyll-*a* declined, striped bass shifted to piscivory at about 80mm.

In summation, a change in food availability can and does affect the production and distribution of organisms at all levels of the food web. This linkage between food availability and species abundance and distribution has been demonstrated in the Bay-Delta estuary, as well as aquatic systems elsewhere. This view is strongly reflected in a review of the scientific literature.

2.3 Possible Explanations for Observed Changes in the Bay-Delta Food Web

A number of possible explanations have been suggested to account for the observed changes to the composition of the food web at all trophic levels in the Bay-Delta. The most commonly mentioned are changes in flows and flow patterns, invasive species (particularly the Amur River clam), contaminants,

changes in nutrients, and changes in the land-water interface. In this section, the paper explores those explanations and the available scientific information. This section of the paper also provides evidence that two or more of these explanations could operate in concert, thereby reinforcing biological and biogeochemical feedbacks.

2.3.1 Possible Explanation 1: Changes in flows and flow patterns affect primary and secondary productivity

There is general agreement that freshwater river flow is an important factor in primary and secondary productivity within an estuary. Freshwater flow into an estuary serves to: (1) provide bulk transport of river nutrients to the estuary, (2) resuspend nutrients within the estuary through gravitational circulation, and (3) enhance dispersion of nutrients down the estuary due to salinity stratification.

In this context, the distinction between rivers and estuaries is important; estuaries do not function the same way rivers do. Unlike rivers, “the physical, chemical, sediment, water quality and ecological processes within estuaries are exceedingly complex primarily due to their dynamic nature, complex mixing processes, stochastic influences, strong antecedent effects and the vast number of complex ecological linkages.”(Pierson et al. 2002). The complexity of the Bay-Delta estuary is no different.

While a number of regulatory requirements in the Bay-Delta are based on net flows, aquatic species inhabit environments dominated by “instantaneous” flows, which are far greater than net flows and largely beyond human control. Figure 7 shows the typical maximum flows over a 25-hour tidal cycle in summer conditions. Figure 7 also shows that tidal flows overwhelm the relatively small net inflow. The tidal flows can be greater than 300,000 cfs in the western Delta compared to net outflow of 5,000-10,000 cfs. Because of these very large tidal flows, fish and other aquatic organisms have adapted strategies that allow them to maintain position or move around in the estuary, as evidenced by their continual presence in the face of large instantaneous flows. This is even the case for “weak swimmers,” like delta smelt and their prey items.

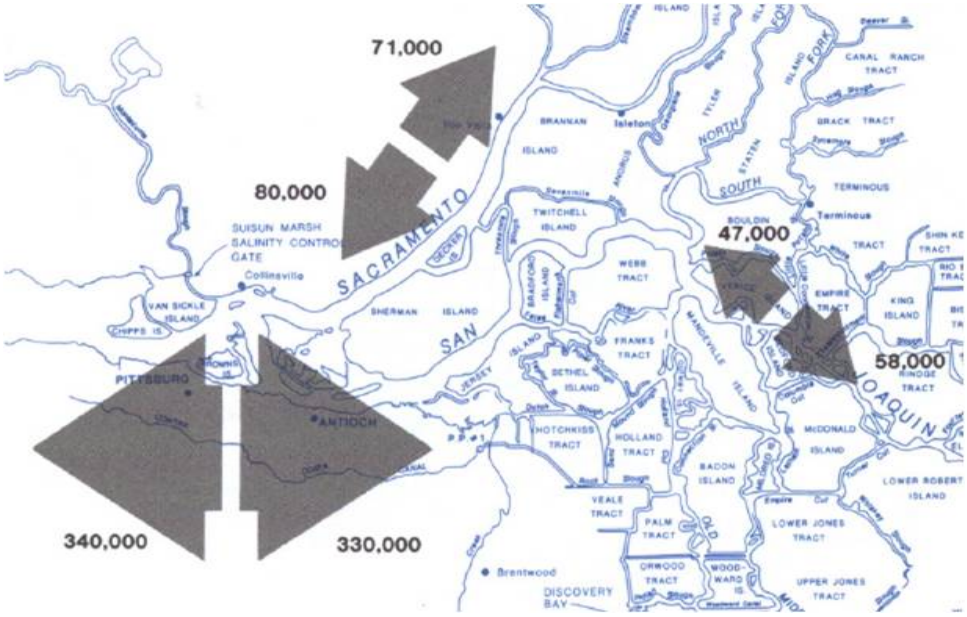


Figure 7. Typical maximum flows over a 25-hour cycle in summer conditions, measured in cubic feet per second (cfs). The flow near Pittsburg during a typical tidal cycle can vary from 330,000 cfs upstream to 340,000 cfs downstream. The “net” summer Delta outflow is a very small amount of the total water movement, generally 5,000

to 10,000 cfs. (Source: DWR 1995, p. 21).

Relationship between Freshwater Inflow on Primary and Secondary Production

In the Bay-Delta estuary, the relationship between freshwater inflow and primary and secondary production has been studied for decades. In the highly altered Bay-Delta estuary, neither a linear nor simple relationship between flow and productivity exists. In one of the early reports on the "Entrapment Zone", Ball and Arthur (1979) reported on the historic understanding of the association between phytoplankton and flow and flow patterns.

> "The quantity of river inflow to the Delta is important to phytoplankton growth in that it regulates nutrient concentrations, affects water transparency, determines water and phytoplankton residence times, and regulates the extent of salinity intrusion and the location of the entrapment zone. These and other factors all interact to determine the quantity and quality of the phytoplankton."

They also reported on associations between residence time and phytoplankton. In many estuaries, the effect of residence time on algal production is described as contributing to eutrophication (Pierson et al. 2002). Ball and Arthur found evidence of reduced residence time associated with increased algal growth in the south Delta in the San Joaquin River. They also found the same association in the north Delta, but at much lower chl-*a* concentrations.

In 1995, Jassby et al. reported a positive correlation between primary production in Suisun Bay and outflow, as measured by X2, from 1975 to 1989. However, they cautioned that the actual mechanisms were understood for only a few species, and they also noted uncertainty:

> "What are the causal mechanisms underlying these relationships? A variety of potential mechanisms deserves a detailed consideration that is beyond the scope of this study…"

They concluded:

> "By ignoring variables other than X2(or Q_{out}) we could therefore be in danger of imposing inappropriate standards, either too stringent or too lenient. The mere fact of a correlation between some ecosystem property and an indicator such as X, is therefore not sufficient grounds for using the indicator as a policy variable. The presence of much unexplained variation is one signal that an existing model can lead to unacceptably biased management policies, and should result in a search for alternative and additional variables."

Kimmerer (2002a) reexamined those relationships in Suisun Bay, expanded the data set to 1999, and incorporated the invasion of the Amur River clam as an additional environmental stressor. Kimmerer found no correlation between freshwater flow and chl-*a*. He found weak correlations between flow and several zooplankton species, and he observed chlorophyll-*a* and zooplankton populations decreases after the invasion of the clam around 1987.

Although both studies used chlorophyll-*a* data from the Suisun Bay location, their results are ambiguous for the time period prior to the invasion of the clam. One reason may be the year intervals used; 1975 to 1995 by Jassby et al. compared to 1975 to 1987 by Kimmerer. Another reason may be the interannual time period used; an annual time period by Jassby et al., compared to spring time and summer time periods by Kimmerer. Similar to Jassby et al., Kimmerer noted uncertainty:

> "Abundance or survival of several estuarine-dependent species also increases with freshwater outflow. These relationships to flow may be due to several potential mechanisms, each with its own locus and period of effectiveness, but no mechanism has been conclusively shown to underlie the flow relationship of any species."

Subsequently, Jassby (2008a), reported on phytoplankton abundance and growth in Suisun Bay and the Delta over the period 1975–2005. The author drew four major conclusions:

1. A long-term decrease in phytoplankton biomass occurred over the period 1975–2005.
2. A shorter-term increase in phytoplankton biomass occurred in the Delta, but not in Suisun Bay, from 1996–2005.
3. A change in the relationship between outflow and Suisun Bay phytoplankton biomass and productivity occurred after 1986 when "…Suisun Bay phytoplankton exhibited relatively low responsiveness to flow variability. This behavior differs from earlier chlorophyll-flow relationships reported in the literature. The reason appears to be the invasion of Suisun Bay by a clam—*Corbula amurensis*—in 1986, which has since maintained the phytoplankton community mostly at low levels by vigorous filter-feeding. In the past, flows into Suisun Bay generally diluted the higher phytoplankton concentrations within the bay; now they bring in higher phytoplankton concentrations from upstream."
4. The increase in phytoplankton biomass and productivity in the Delta was associated with reduced inflow to the Delta from 1996–2005. "The main source of interannual phytoplankton variability in the Delta during 1996–2005, including the upward trend, appears to have been freshwater flow variability and its effect on particle residence time." This is similar to the findings of Ball and Arthur (1979) three decades earlier, but is inconsistent with the majority of estuaries where increased flow is associated with increased phytoplankton production (Pierson et al. 2002; Kimmerer et al. 2012).

In a recent study, Kimmerer et al. (2012) were the first to examine the response of primary productivity within the Bay-Delta estuary across a wide range of freshwater flows during the spring-summer period of 2006–2007. Kimmerer et al. found that temporal and spatial variability in productivity was small. When the study combined data from 2006–2007 with long-term monitoring data, the data did not show any persistent patterns in production rates or biomass accumulation. More importantly, Kimmerer et al. (2012) found that, "**[p]roduction within the low-salinity zone was unresponsive to variation in freshwater flow,** in contrast to findings in other estuaries where nutrient loading drives variability in production and other regions of the [Bay-Delta estuary] where production responds to residence time or to stratification" (emphasis added). With respect to "other regions of the estuary where production responds to residence time", Jassby et al. (2002) and Jassby (2008a) found that greater productivity is related to longer residence time (lower flows).

There are also findings that longer water residence time does not necessarily translate to greater phytoplankton biomass; it depends on the phytoplankton growth and loss rates (Lucas et al. 2009). Loss rates are affected by numerous factors, including nutrient balance, abundance of grazers, turbidity, and temperature, among others. With high loss rates, lower residence time results in greater biomass accumulation. The complicated nature of the relationship between flow and productivity is reinforced by Kimmerer (2002a) who found that, "[i]n contrast with the higher trophic levels, chl-*a* and several species of zooplankton declined markedly after 1987, and had either weak responses to flow or responses that changed after 1987." Elsewhere, Kimmerer (2002b) states, "available evidence does not support flow responses of lower trophic levels." Figure 8 supports this finding; there does not appear to be a clear relationship between different measures of monthly flow and monthly chl-*a* concentrations.

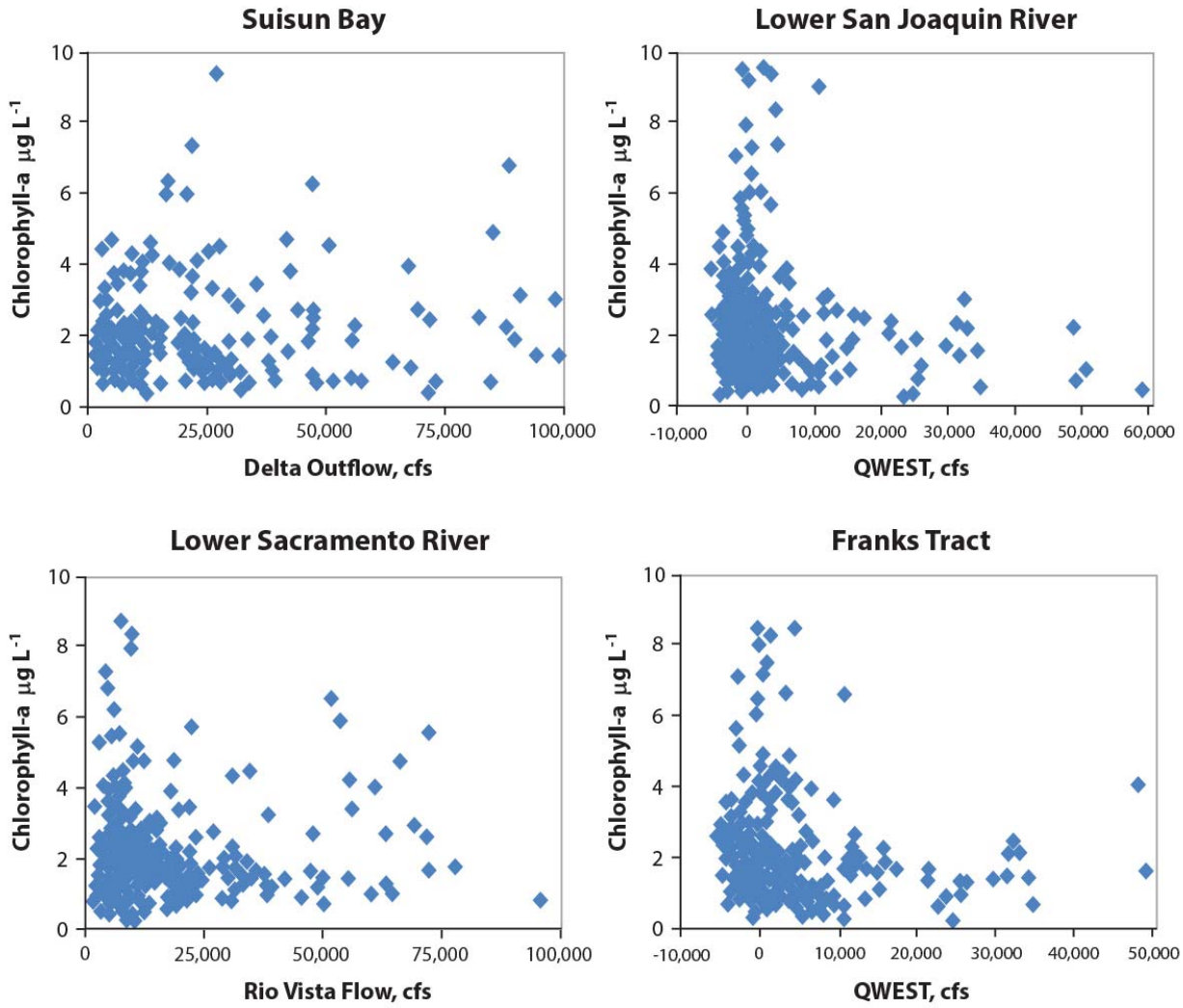


Figure 8. Average monthly chl-*a* concentration plotted with different average monthly flow measures in four regions of the Delta, showing no apparent relationship (Source: Chl-*a* data from EMP monitoring, flow data from DAYFLOW, 1987-2011).

Based on the long history of studies, significant uncertainty exists as to how flow affected primary production within the Bay-Delta estuary, and how flow will affect primary production in the future. What is certain is that a complex relationship exists between flow and productivity. Furthermore, any manipulation of flows must be carefully considered in its spatial and temporal contexts. Manipulation of flows should not occur for the sake of restoring "natural flows" per se; rather, such manipulation should be premised on restoration of localized functions and processes.

Importance of the Estuarine Turbidity Maximum to Primary and Secondary Production

In many estuaries, freshwater flow regulates the location of the estuarine turbidity maximum. The estuarine turbidity maximum, often referred to as the “Entrapment Zone,” is where suspended particles including phytoplankton cells and zooplankton individuals accumulate. It is a biologically rich aquatic environment (Ball and Arthur 1979; Kimmerer 1992). According to Schoellhamer (2001), several factors can contribute to the formation of estuarine turbidity maxima, including (1) gravitational circulation or tidal asymmetry of velocity, (2) cycles of local deposition, bed storage, and resuspension, and (3) suppression

of turbulence by salinity stratification. The location of the Low Salinity Zone is just one of several factors that can influence the location of the estuarine turbidity maximum in an estuary. They can also be located at fixed locations.

The State Water Board established the Spring X2 outflow objective ndard in D-1641 to a large degree because it was believed that the location of the estuarine turbidity maximum and peaks in abundance of several species in the Bay-Delta occurred at 2 practical salinity units (psu) (Jassby et al. 1995). However, work published since that time by Burau (1998) and Schoellhamer (2001) note that locations of the estuarine turbidity maxima in the Bay-Delta are not defined by salinity. Schoellhamer (2001) concludes:

> "Salinity, bottom topography, and tides affect the locations of estuarine turbidity maxima (ETM) in northern San Francisco Bay. **ETMs are not associated with a singular salinity**.
>
> Bottom suspended-solids concentration (SSC) during cruises and tidally averaged **SSC did not show any maxima associated with a particular salinity**.
>
> Bottom topography, especially sills in the channels, is another factor controlling the location of ETMs in northern San Francisco Bay. Locations of ETMs are related to bottom topography because salinity stratification and gravitational circulation are enhanced seaward of sills.
>
> Wind-wave resuspension of bed sediment in shallow water subembayments is another topographically controlled source of suspended solids.
>
> Bottom shear stress and SSC are greatest during spring tides and smallest during neap tides. "[emphasis added]

These researchers found there are multiple areas of maximum turbidity that are primarily associated with the bathymetries of channels (Figure 9). Because bottom topography is important in determining the location of higher concentrations of suspended particles, these locations ("entrapment zones" or "null zones") are more or less stationary, and cannot be greatly moved by flow, provided that the null zone is landward to the location in question (Burau 1998). In other words, unlike some other estuaries, locations of estuarine turbidity maxima in the Bay-Delta estuary are largely decoupled from freshwater inflow.

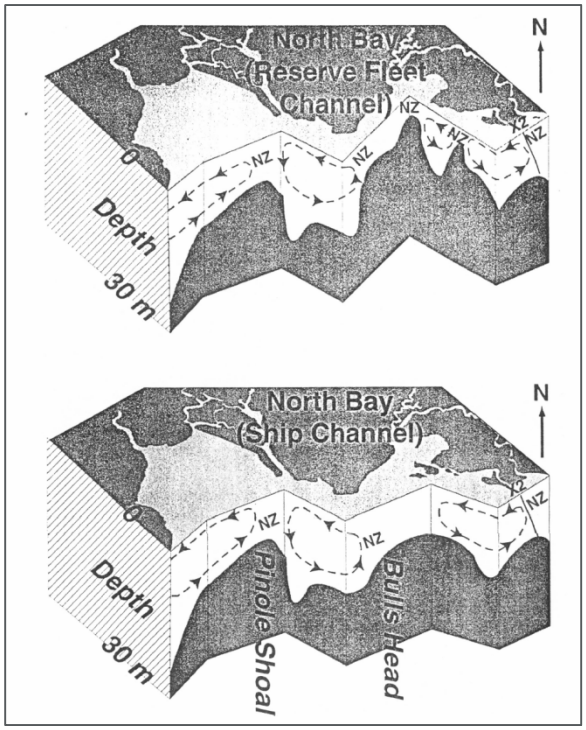


Figure 9. Conceptual model of gravitational circulation in the North Bay, based on the overturning time scale. Longitudinal slices are shown along the axis of (a) Reserve Fleet/Suisun Cutoff channel in the top graph and (b) the ship channel of Suisun Bay and the San Joaquin River in the bottom graph. Salient features of this revised conceptual model of gravitational circulation include the possibility of multiple gravitational circulation cells that terminate near restrictions in depth and a modulation of gravitational circulation cell strength with the spring/neap cycle. (NZ= Null Zone, M= Meters) Source: Burau 1998.

Affect of Freshwater Inflow on Primary and Secondary Production in Floodplains and Wetlands

Flow also affects productivity through inundation of floodplains and wetlands. Numerous, published studies link inundation of floodplains and wetlands to increased productivity, which lead to improvements in growth and survival of some fish species. As described in Section 3, the historic connections between these land areas and water have largely been prevented. In today's Bay-Delta, increased flow sends water through highly altered riverine systems (i.e., rock-lined channels), which, to prevent flooding, prevents water in the rivers from reaching floodplains or wetlands.

In summation, the relationship between flow and productivity is not unidirectional, is often weak, varies over time and space, and is complicated by the many alterations in the Bay-Delta estuary and its tributaries. The lack of response in primary and secondary productivity relative to freshwater inflow, including those observed by Kimmerer et al. (2012), contrasts with results from other systems. The lack of response demands careful consideration of the physical, chemical, and biological attributes of the Bay-Delta, specifically how freshwater inflow may affect food webs and subsequently higher trophic level organisms. Further, there is no science that considers the relative influence that changes in water appropriations may have on primary or secondary productivity in the Bay-Delta estuary, the location or extent of Estuarine Turbidity Maximum, or floodplain and wetland habitats.

2.3.2 Possible Explanation 2: Appropriation of water adversely affects the abundance of plankton (phytoplankton and zooplankton) in the Bay-Delta estuary

Appropriation of water can affect productivity through three mechanisms: (1) directly through removal of biomass, (2) indirectly by altering residence time, and (3) indirectly by altering transport pathways. Plankton biomass (phytoplankton and zooplankton) is certainly removed from the Bay-Delta via appropriation of water; the screens that reduce entrainment of fish at the State Water Project and Central Valley Project fish facilities are far too coarse to filter out plankton, and most other appropriations from the Delta are not screened at all. Jassby et al. (2002) conducted a phytoplankton mass balance assessment and determined that net transport loss, which included losses from outflow to Suisun Bay and with appropriated water, accounted for only 6 tons C day^{-1} compared to net production of 44-53 tons C day^{-1} and within Delta consumption of 38 to 47 tons C day^{-1}.

First, while appropriation of water may remove some of the Delta's carbon biomass, it appears to have little effect on the concentration of the remaining phytoplankton. Figure 10 presents the relationship between average March to June chl-*a* at plankton sampling stations in central Delta locations and export levels during this same time period. These data show no apparent relationship between phytoplankton densities, measured by chl-*a*, and export rates.

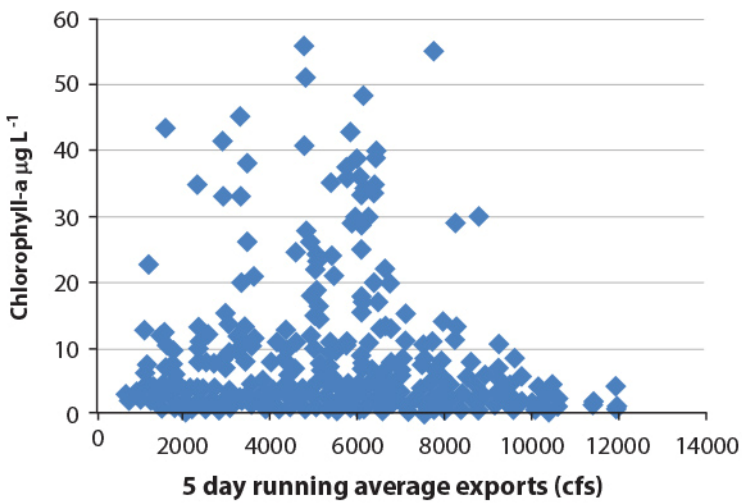


Figure 10. March – June average chl-*a* at zooplankton survey stations NZ080, NZ086, NZD16, NZD19, NZD28 versus 5-day running average export rates. These stations represent central Delta stations north of the export pumps during the period of the year when delta smelt are frequently present. These data show no apparent relationship between phytoplankton levels and export rates.

A second possible effect of appropriations of water is on residence time. Appropriations of water, particularly upstream of the Delta impact water residence time in the Bay-Delta estuary by increasing flow rates through the Bay-Delta. Transport time can affect phytoplankton biomass through the integration of growth and loss rates during the period of transport through the Delta. However, the relationship is not simple. Longer residence time does not necessarily translate to greater phytoplankton biomass; it depends on phytoplankton growth and loss rates (Lucas et al. 2009). The spatial and temporal variation in growth and loss rates within the Bay-Delta are too great to predict with any accuracy the overall effect of changes in residence time.

A third possible effect of water appropriations is on transport of plankton and other small particles from one area to another. For example, appropriations from the south Delta might prevent phytoplankton or zooplankton in the south Delta from reaching Suisun Bay. One hypothesis is that plankton, originating in

the San Joaquin River part of the Delta, are removed by diversions and, therefore, do not subsidize plankton in downstream areas such as Suisun Bay. This hypothesis is based on the assumption that south Delta and San Joaquin River water with its higher plankton biomass is diverted directly to the pumps and therefore does not reach downstream areas.

The DSM2-QUAL model was used to simulate Delta flows under three scenarios: (1) historical hydrology, operations, and SWP and CVP exports ("historical exports"), (2) historical hydrology, operations, and no in delta SWP or CVP appropriations ("no exports"), and (3) historical hydrology, operations, and in-delta SWP and CVP appropriations limited to 50% of the Delta inflow ("reduced exports"). The percent of water originating in the eastern rivers (San Joaquin, Mokelumne, Cosumnes, and Calaveras rivers) that reaches Mallard Island, just upstream of Suisun Bay, was estimated for the 2001-2010 period (Figure 11).

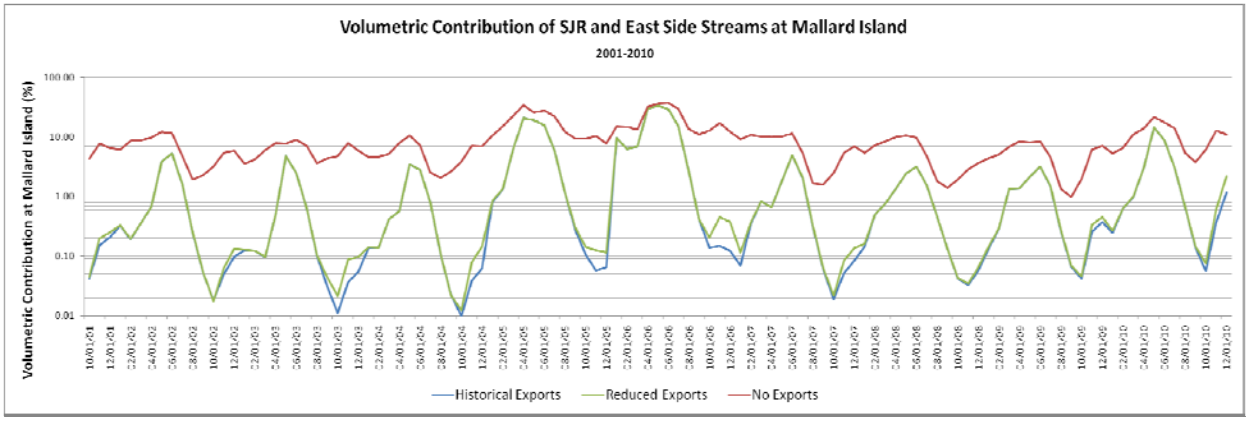


Figure 11. Volumetric contribution of San Joaquin River and east-side streams at Mallard Island between 2001-2010. While the difference between the no exports scenario and the two with export scenarios is significant, even with exports completely shut off, over 90% of the time the San Joaquin River and other eastern tributaries combined contribute less than 10% of the flow at Mallard Island.

Even with in-Delta appropriations by Central Valley Project and State Water Project completely shut off, over 90% of the time the San Joaquin River and other eastern tributaries combined contribute less than 10% of the flow at Mallard Island (percentage data not shown). The "no exports" scenario is included to emphasize the point that in-Delta appropriations have little effect. Reducing them to the minimum of historical exports or 50% of inflow makes very little difference. Assuming no loss of plankton due to predator grazing and senescence during transport, under the "no exports" scenario, plankton densities in the San Joaquin River region would have to be an order of magnitude greater than in the Sacramento River region to make a significant contribution to food availability in the confluence and Suisun Bay regions. Otherwise, increasing the contribution from this area would not have much effect.

The U.S. Fish and Wildlife Service's (USFWS) biological opinion (BiOp) for continued operations of the Central Valley Project and State Water Project (2008) and DFG's Ecosystem Restoration Program Conservation Strategy suggest that water appropriations may remove a disproportionately large share of plankton from the Bay-Delta, but neither source offers scientific support for this suggestion. A subsequent independent peer review of the effects analysis prepared for the BiOp to be unconvincing on this point (PBSJ 2008, p. 9). Court-appointed experts in litigation over the BiOp also addressed the suggestion and found that the BiOp showed no quantitative effects nor showed that entrainment of productivity could have effects at the population level in delta smelt (Quinn and Punt 2010). Based on the findings of the Court-appointed experts, the Court concluded that the assertion by the USFWS was unsupported. (See e.g., Memorandum Decision Regarding Cross Motions for Summary Judgment, Doc. No. 757, p. 167.)

In summation, the findings above refute any suggestion that significant productivity is lost to appropriation of water. While appropriations of water remove plankton from the Bay-Delta, evidence is insufficient to support a conclusion that regulation of water appropriations will improve plankton productivity. The concentration of plankton in the Bay-Delta is unaffected by water appropriations. Water appropriations alter the transport of productivity in the system. However, modeling indicates that completely ceasing in-Delta appropriations will make little difference.

2.3.3 Possible Explanation 3: Increases in contaminants have direct and indirect effects on the survival and health of aquatic organisms

A wide array of contaminants including pesticides, metals, pharmaceuticals, personal care products and nutrients have been detected in Bay-Delta estuary water and sediment. (Nutrient contamination will be discussed in Section 1.3.4). These have been documented through a number of studies conducted over the last 25 years, primarily by the Central Valley Regional Water Quality Control Board and the Interagency Ecological Program. The U.S. Environmental Protection Agency's (USEPA's) 2010 CWA 303(d) List of Water Quality Limited Segments provides a succinct summary of the known impacts of contaminants on aquatic life in the Bay-Delta estuary (USEPA 2010).

Published literature suggests that contaminants have the potential to impact the ecosystem but must be considered in view of the complex interactions and uncertainties associated with potential exposures (Baxter et al. 2010; NRC 2010; 2011, 2012). While it is clear from studies to date that potential contaminant effects are important to the health of the Bay-Delta ecosystem, it is equally clear that it is important to recognize the uncertainties and complexity of these relationships.

2.3.3.1 Potential Sources of Contaminants in the Bay-Delta

Contaminants enter the Bay-Delta estuary and its tributaries by runoff from urban and agricultural land uses, atmospheric deposition, municipal and industrial water treatment effluent, recreational and commercial boating activities, and from historic mining operations. Contaminant levels vary both spatially and temporally and many are highest following rain events (Kuivila and Hladik 2008). Several contaminants, including pesticides, metals, pharmaceuticals, personal care products and nutrients, have been detected in Bay-Delta estuary water and sediment and continue to be the focus of concern by regulatory agencies.

2.3.3.2 Pesticides

Exposures of fish to sublethal concentrations of pyrethroids have resulted in decreased growth (Baldwin et al. 2009), and impaired swimming performance (Connon et al. 2009), increased susceptibility to viral infection (Clifford et al. 2005), and impacts to olfactory response (Sandahl et al. 2004). Acute exposure to some pesticides can have measurable population level effects on larval survival and development rates (Baldwin et al. 2009).

The Bay-Delta Advanced Notice of Proposed Rulemaking identifies the significant data gaps regarding pesticide use, sources, toxicity, and contributions to the Bay-Delta Estuary ecosystem collapse (USEPA 2011, p. 39). However, recent studies indicate that the contribution from urban sources may be significant (Weston et al. 2005; Weston and Lydy 2010, 2012). Several of these studies also indicate that the contribution from agricultural sources may not be as significant as previously indicated (Weston and Lydy 2010) and are improving (Hall 201Oa; Hall 201Ob; Hall 201Oc).

Use of the organophosphates diazinon and chlorpyrifos has been significantly reduced in agriculture and eliminated from urban use; however, pyrethroid pesticides have largely taken their place (Weston and Lydy 2010). In addition, there has been a significant shift to more toxic pyrethroid pesticides in the last decade (Amweg et al. 2005). Weston and Lydy (2010) detected pyrethroids in all but one of 33 urban

runoff samples and observed toxicity over at least a 30 km reach of the American River, and at one site in the San Joaquin River. Similarly, Ensminger and Kelley (2011) sampled 13 urban sites in 2009-2010 and detected pesticides in 95% of the samples; 75% of the samples had 2 or more pesticides. Weston and Lydy (2010) occasionally detected pesticides in agricultural discharges.

Similarly, a USGS study detected 23 different dissolved pesticides in Bay-Delta water samples between 1998 and 2000 (Kuivila and Moon 2004). All water samples contained at least two and up to 14 different pesticides in each sample (with a median of five). Several pesticides overlapped temporally and spatially with the period of peak densities of larval and juvenile smelt.

2.3.3.3 Metals

A diverse array of metals, both naturally occurring and anthropogenic, has been detected in the Sacramento and San Joaquin rivers and the Bay-Delta estuary (SWRCB 1990). Numerous laboratory and field studies have demonstrated that exposure to metals can exert a range of adverse effects Exposure to low levels of copper can affects the olfactory mechanism of many fish species (Sandahl et al. 2007; Tierney et al. 2010; Raloff 2007). The olfactory system conveys critical information to fish, enabling activities such as mating, locating food, discriminating kin, avoiding predators and homing. In a review of studies on contaminant effects to fish olfactory systems, Raloff (2007) cited one researcher that noted, “pesticides and copper at concentrations similar to those in the environment knock out olfactory communications in every species tested to date – whether water fleas, leeches, or fish.” Sandahl, et al. (2007) observed a 40% reduction in olfactory response in juvenile coho salmon exposed to copper concentrations as low as 2 $\mu g\ L^{-1}$ for only 3-hours. This loss in olfactory sensitivity led to a failure to initiate predatory avoidance behaviors in response to chemical alarm cues.

Mercury toxicity in fish is also well documented and includes decreased appetite, ability to catch food, visual activity, and growth; lethargy; loss of equilibrium; gill hyperplasia and reduced respiration; neurotoxicity; nephrotoxicity; and teratogenic and reproductive effects (Reimschuessel 2001, Rodgers and Beamish 1982, Weis and Weis 1991, others). Reproductive effects from mercury exposure are a particularly sensitive endpoint, and can begin with the maternal transfer of mercury to embryos via the yolk (Weis and Weis 1995). Experimental studies have shown that embryo survival can be substantially reduced by very low concentrations of mercury from waterborne exposure or maternal transfer (Birge et al. 1979).

2.3.3.4 Pharmaceuticals and Personal Care Products (PPCPs)

The presence of PPCPs in the Bay-Delta is also a concern for the health of zooplankton and fish. PPCPs enter the watershed by treated wastewater discharges, septic tanks, urban and agricultural runoff. Sublethal adverse effects, such as impaired growth and reproduction, behavioral changes, and even population collapse are well documented in numerous aquatic organisms in response to chronic exposure to low concentrations of one or more PPCPs (Munoz et al, 2009; Cripe et al. 2009; Iwanowicz et al. 2009; Martinovic et al. 2007; Kidd et al. 2007; Dussault et al. 2008). Exposure to multiple compounds can have additive or synergistic adverse effects, which may be compounded by other environmental stressors. There is extensive documentation of these sublethal and synergistic effects on other aquatic organisms (Ward et al. 2007, Oros et al. 2005, Clifford et al. 2005).

The National Water Research Institute (NWRI) recently released a report entitled, "Source, Fate, and Transport of Endocrine Disruptors, Pharmaceuticals, and Personal Care Products in Drinking Water Sources in California" (NWRI, 2010). This study included the collection and analysis of samples from upstream and downstream of the Sacramento Regional Wastewater Treatment Plant. The concentrations of caffeine, carbamazepine, DEET, gemfibrozil, primidone, sulfamethoxazole, dilantin,

and TCEP were higher in the Sacramento River at Hood downstream of the Plant than upstream in the Sacramento River at the West Sacramento Water Treatment Plant Intake and at the Fairbairn Water Treatment Plant intake on the American River.

Schaefer and Johnson (2009) also conducted monitoring up and downstream of the largest POTW in the Delta and detected caffeine, trimethoprim, sulfamethoxazole, gemfibrozil, fluoxetine, ibuprofen, carbamazepine, xylene, nonylphenol, and nonylphenol ethoxylates at one or more of the downstream monitoring sites. None of these compounds were detected in the upstream samples. Schaefer and Johnson (2009) state, "All of the compounds detected in the monitoring effort have been shown to have an adverse effect on one or more aquatic species." In fact, ibuprofen was detected at concentrations far greater than those observed to reduce activity in Gammarus pulex (Aquatic Ecosystems Analysis Laboratory 2009).

Kolpin et al. (2002) sampled 139 streams in 30 states and detected one or more organic wastewater contaminants in 80% of the streams. Half the streams contained seven or more chemicals. Six of the sites are in the Central Valley. Samples from the Sacramento River at Freeport had detectable levels of cholesterol, acetaminophen, and mestranol. Acetaminophen was also found in the San Joaquin River at Vernalis and upstream tributaries. The Turlock Irrigation District Lateral 5 that drains to the San Joaquin River had detectable concentrations of 17 β-estradiol, estriol, 19-norethisterone, 1 cholesterol, coprostanol (measure for the presence of human fecal matter), acetaminophen, caffeine, diltiazem (potent vasodilator of peripheral and coronary vessels), 1,7-Dimethylxanthine (caffeine metabolite), and codeine.

Several studies within the Bay-Delta estuary have observed endocrine disruption. Brander and Cherr (2008) observed choriogenin induction in male silversides from Suisun Marsh. Riordan and Biales (2008) reported endocrine disruption in male fathead minnows following in-situ exposures below the Sacramento Regional Wastewater Treatment Plant. Sommer (2008) reported that the sex ratio of young of the year striped bass in the Bay-Delta is heavily skewed toward male (90:10 male:female). While the cause of this skewed sex ratio is unknown at this time, exposure to endocrine disrupting chemicals cannot be ruled out. And, Connon et al. (2009) reported that “exposure to water from Hood elicited significant transcriptional differences of genes involved predominantly in neuromuscular functions, suggesting that contaminants originating from the SRWTP effluent may impact on swimming performance, growth and development of larval delta smelt. Down-regulation of structural muscle genes may also indicate physiological damage.”

In summation, a wide array of contaminants including pesticides, metals, pharmaceuticals, personal care products and nutrients have been detected in Bay-Delta estuary water and sediment. Several recent reviews conclude that contaminants have the potential to impact the ecosystem but must be considered in view of the complex interactions and uncertainties associated with potential exposures. While it is clear from studies to date that potential contaminant effects are important to the health of the Bay-Delta ecosystem, it is equally important to recognize the uncertainties and complexity of these relationships.

2.3.4 Possible Explanation 4: Increases in invasive species affect productivity

Agreement is universal that the invasion by the Amur River clam has had a significant effect on chl-*a* levels in Suisun Bay (Alpine and Cloern 1992; Kimmerer et al. 1994; Jassby et al. 2002; Kimmerer 2006; Greene et al. 2011) with its influence extending into the lower Sacramento and San Joaquin Rivers (Jassby et al. 2002). As described above, the clams have been blamed for the decline in *N. mercedis* (Orsi et al. 1996; Feyrer et al. 2003), the shift in distribution of anchovies (Kimmerer 2006) and young-of-the-year striped bass (Kimmerer et al. 2000; Feyrer et al. 2003; Sommer et al. 2007), as well as the decline in diatoms (Kimmerer 2005) and several zooplankton species (Kimmerer et al. 1994). The impact of the clams on chl-*a* and the Bay-Delta ecosystem is also reflected by a shift in many of the original correlations between species abundance and X2, that occurred after the establishment of the clams (Kimmerer 2002a; Sommer et al. 2007).

However, invasive clams cannot explain all of the chl-*a* decline. For example, Peterson and Vayssieres (2010) report at the lower Sacramento River station "the downward trend in phytoplankton biomass is coincident with significant reductions in overall benthic organism abundance." Nor can the invasive Amur River clam explain chl-*a* declines in the south Delta. In the south Delta the brackish-adapted *P. amurensis* have never been observed and that area is well beyond the influence of tidal dispersion, yet IEP benthic and phytoplankton data demonstrate that chl-*a* has also declined there (Figure 12). Presence of the invasive freshwater clam, *Corbicula fluminea,* can explain localized declines in chl-*a*, it cannot entirely explain the widespread drop in chl-*a* in the Delta because there is no apparent relationship between clam densities and chl-*a* concentrations after the clam invasion (Figure 12).

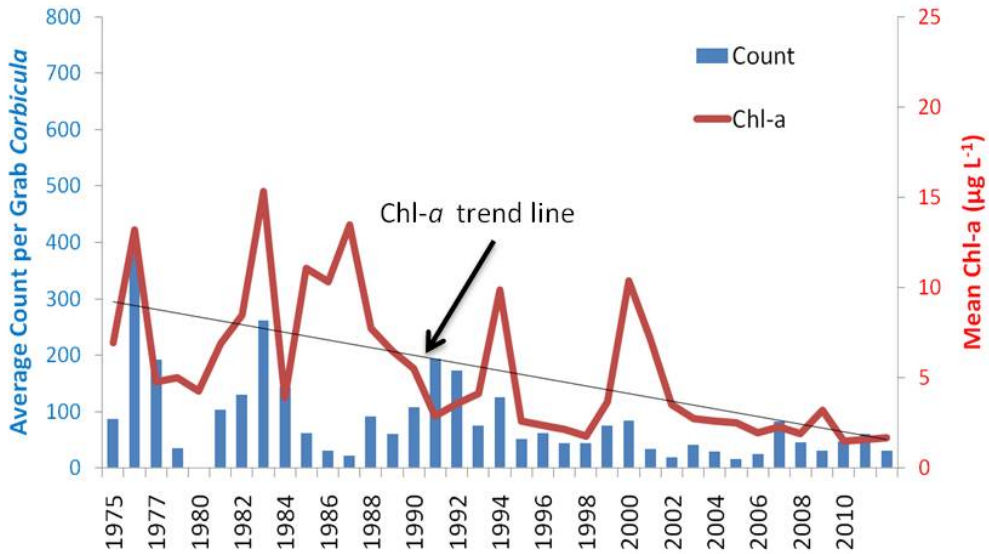


Figure 12. Average annual (March-November) chl-*a* concentration in Old River (station D-28A) and the average annual (March-November) abundance of Corbicula fluminea, showing no apparent relationship between clam abundance and chl-*a* concentration. (Source: IEP benthic and phytoplankton data).

Further evidence that some factor in addition to the clam is responsible for low phytoplankton biomass comes from observations that the decline in chl-*a* and diatoms in the Suisun Bay region began prior to establishment of *P. amurensis*, (Figure 13, Alpine and Cloern 1992; Jassby et al. 2002; Dugdale et al. 2007; Glibert 2010; Glibert et al. 2011). That further evidence also comes from the fact that *P. amurensis* is not abundant in spring (Dugdale et al. 2007), yet IEP benthic and phytoplankton data demonstrate chl-*a* concentrations have declined in spring (Figure 14). As described below, changes in nutrient concentrations and ratios might explain both the increase in clams and the drop in chl-*a* and diatoms.

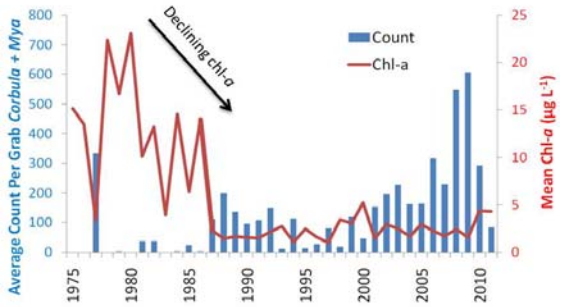


Figure 13. Average annual (March-November) chl-*a* concentration in Grizzly Bay (Station D7) and the average annual (March-November) abundance of *Potamocorbula amurensis* and *Mya arenaria*, showing a drop in chl-*a* concentration in the early 80s, prior to the increase in clam abundance in 1987 (Source: IEP benthic and phytoplankton data).

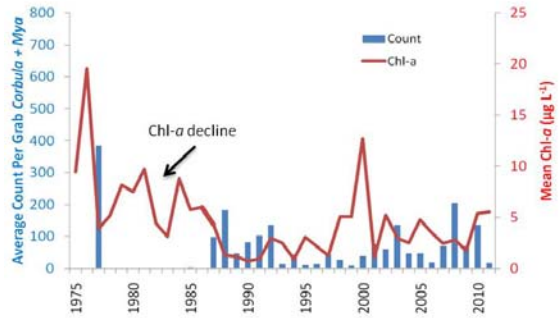


Figure 14. Average spring (March-May) chl-*a* concentration in Grizzly Bay (Station D7) and the average spring (March-May) abundance of *Potamocorbula amurensis* and *Mya arenaria*, showing a drop in chl-*a* concentration prior to the increase in clam abundance and little apparent relationship thereafter. (Source: IEP benthic and phytoplankton data).

Suggestions have been made that increased outflow can be used as a tool to control *P. amurensis* abundance. However, there have been no scientific support for this approach. *P. amurensis* distribution is affected by freshwater flows. But, increasing outflows only offers a temporary and localized solution. Peterson and Vayssieres (2010) report that "[a]ssemblages moved down-estuary in years with high delta outflow, and up-estuary during years with low delta outflow." In other words, high outflow merely moves the problem downstream and unless high outflow is maintained in every year, the clam assemblage may move back when flows decline. In addition, the invasive freshwater clam, *C. fluminea* moves down estuary with high delta outflow as well, occupying the space vacated by *P. amurensis.* Parchaso and Thompson (2002) do not provide any support for this strategy either. They report that "[t]he success of *P. amurensis* in this system is therefore related to its…apparent lack of temperature or salinity control on reproductive activity." In fact, Parchaso and Thompson (2002) found that "[p]opulations of *P. amurensis* at the upstream sites in Suisun Bay and Carquinez Strait were more reproductively active during wet years than dry years." This finding suggests that *P. amurensis* may be able to compensate for the detrimental effects of increased outflow on their abundance and distribution by increasing reproductive activity.

It is also worth noting that large-scale climatic variations may reduce the negative impacts of *P. amurensis* on the Bay-Delta food web. Cloern et al. (2007) observed declines in the abundance of *P. amurensis* in South San Francisco Bay and San Pablo Bay that they attributed to "a state change in the California Current System characterized by increased upwelling intensity, amplified primary production, and strengthened southerly flows."

The invasive aquatic plant, *Egeria densa*, may also affect productivity in the Delta. *Egeria* has been present in the Delta for about 50 years, but the area that it impacts began to expand significantly in the mid-1990s and is now spreading at a rate of 10-20% per year (Department of Boating and Waterways 2006). In addition to blocking channel access for boaters, and clogging diversion pumps, Anderson (1999) describes its effects on the food web as:

> "Other impacts of egeria are less obvious. These include the displacement of native pondweed species (*Potamogeton spp.*), impairment of access for waterfowl, and severe shading of the upper water column. The dense upper "canopy" formed by egeria blocks light that would normally be available to microscopic algae (phytoplankton). The lack of

> primary production by the phytoplankton inhibits fisheries production since these organisms form the base of the food chain."

Egeria may affect more than phytoplankton. Conrad (2010a) reports that submerged aquatic vegetation best explained juvenile largemouth bass abundance. Townsend (2010) developed an ecosystem model for testing the potential causes of POD. In preliminary simulations, chl-*a* and submerged aquatic vegetation biomass best explained both the POD fish declines and the increase in several non-native fish populations.

In summation, there is universal agreement that the invasion by the Amur River clam has had a significant effect on chl-*a* levels in Suisun Bay, with its influence extending into the lower Sacramento and San Joaquin Rivers. However, it appears that the arrival of invasive clam species does not fully explain the decrease in the Bay-Delta's productivity. The invasive aquatic plants, Egeria densa, may be one of the other factors suppressing productivity in the Delta.

2.3.5 Possible Explanation 5: Changes in nutrient concentrations, forms and ratios cause changes in species composition and abundance at all trophic levels

Historically, scientists have described primary productivity in the Bay-Delta as not being limited by nutrients (Cloern 2001; Lopez et al. 2006) and not experiencing signs of classic eutrophication (Cloern 2001). However, the consensus within the scientific community is changes in nutrient loads are affecting ecosystem dynamics in complex ways that extend beyond our historic understanding of the process of eutrophication. Total nutrient load sets the upper limit on total primary production, and ultimately secondary production- and increases in nutrient loading are commonly associated with eutrophication. The most common effects of eutrophication are increased chl-*a* in the water column, development of hypoxia or anoxia (low or no dissolved oxygen, respectively), loss of native submerged aquatic vegetation, increased harmful algal blooms, and changes in biodiversity, including loss of certain fisheries (e.g., Cloern 2001; Anderson et al. 2002).

Nutrient effects on aquatic systems are far more complex and subtle than those normally associated with eutrophication. Changes in nutrient form (chemical state, oxidized vs. reduced, organic vs. inorganic, dissolved vs. particulate) and the proportion of different elements (including carbon (C), nitrogren (N), phosphorous (P), and silicon (Si), among others) also have effects on ecosystems at both the scale of the primary producers (the algae) and throughout the ecosystem. In the Bay-Delta, the total loads, the forms, and the relative proportions of nutrients have been changing over time. These changes have had profound effects on ecosystem structure of this system, as documented below. This paper illustrates the effects of two such changes, the proportion of ammonium to nitrate (NH_4:NO_3) and that of nitrogen to phosphorus (N:P).

2.3.5.1 Ammonium/Nitrate

For decades, researchers have explored the relative use – or relative preference for -- different forms of nitrogen (N) by phytoplankton. Ammonium (NH_4) is generally considered to be the form of nitrogen preferred by phytoplankton due to the more favorable energetics associated with its assimilation compared to that of nitrate (NO_3). It is also well documented that NH_4 can inhibit the uptake of NO_3, but the relative effect of this inhibition is a function of species composition and other environmental factors (Dortch 1990). When NH_4 inhibits the uptake of NO_3 by phytoplankton, it can also exhibit a strong negative control on total productivity (Yoshiyama and Sharp 2006; Dugdale et al. 2007). NH_4 suppression of NO_3 uptake when both nutrients are in ample supply should not be confused with the preferential use of NH_4 by phytoplankton when N is limiting. Under the latter conditions, phytoplankton will use NH_4 preferentially because it requires less energy than NO_3. Under the former conditions, the cells must cope with an excess; and in doing so, their metabolism is less capable of assimilating NO_3.

Within the Bay-Delta's aquatic ecosystems, Wilkerson et al. (2006), Dugdale et al. (2007), and Parker et al. (2012a, b) show that "bloom levels of chlorophyll-*a* are evident only when NO_3 uptake occurs and that NO_3 uptake only takes place at lower ambient NH_4 concentrations." The authors note that sufficient light must also be present to support a bloom. They conclude that NH_4 concentrations greater than 4 micromols per liter [µmol L^{-1}] (0.056 mg L^{-1}) inhibit N uptake by diatoms and thus suppress bloom formation and reduce primary productivity. This level of NH_4 is in line with previous inhibitory level estimates (Lomas and Glibert 1999a; Yoshiyama and Sharp 2006) and is exceeded a majority of the time in the Sacramento River and Suisun Bay (Figure 15). As described in more detail below, the estimate of 4 µmol L^{-1} as an inhibitory threshold will vary as a function of species composition and environmental factors, such as temperature, which affects metabolism. When monthly data of chl-*a* and diatom cell count are plotted against NH_4 levels for the period 1975 to 2012 there is a marked decreasing trend in both as NH_4 levels rise with a increasing effect around 0.056 mg L^{-1} (~4 µmol L^{-1}) NH_4 (Figures 16 and 17).

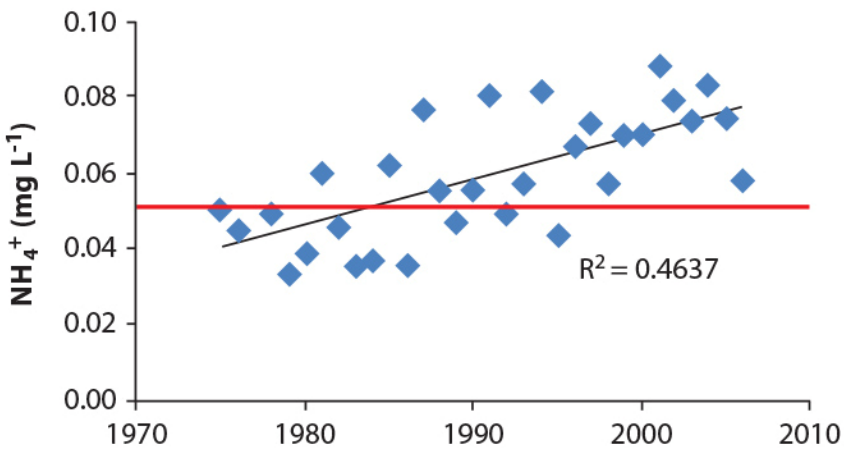


Figure 15. Change in concentration of NH_4^+ over time on an annual basis for stations sampled from the confluence to Suisun Bay. The horizontal red line at 0.056 mg L^{-1} is the concentration at which inhibition of N uptake by diatoms is observed in the Bay-Delta. Coefficient of determination was significant at $p<0.01$.

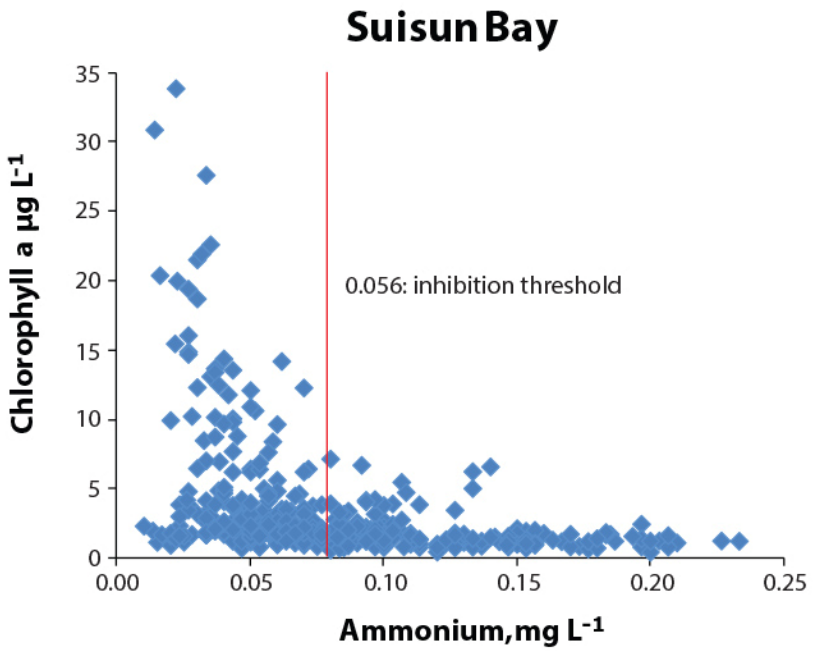


Figure 16. **Chlorophyll-*a* concentration plotted with ammonium concentration in Suisun Bay. As NH_4 concentration increases above the level where inhibition is observed (0.056 mg L^{-1} NH_4), chl-*a* levels decline. (Source: Environmental Monitoring Program data)**

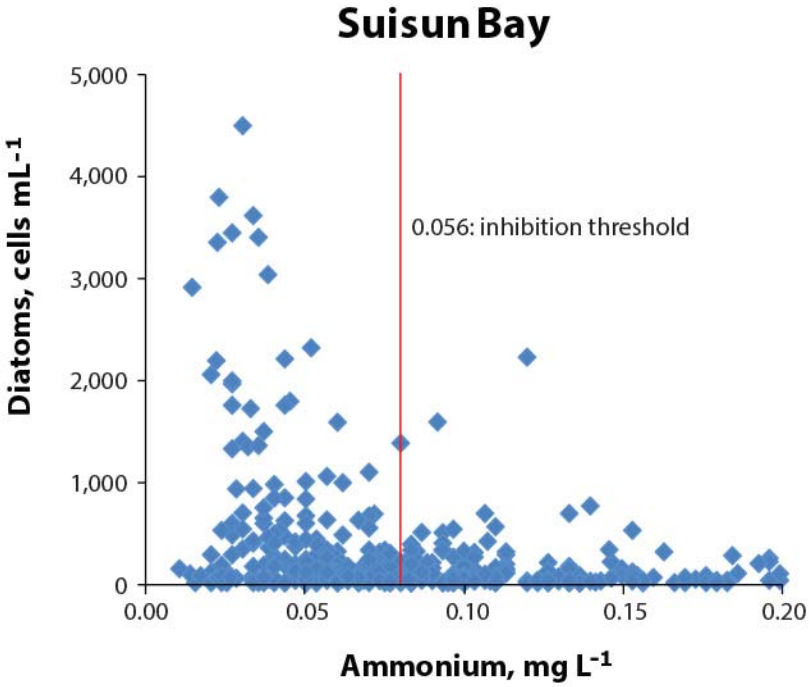


Figure 17. **Diatom cell count plotted with ammonium concentration in Suisun Bay. As NH_4 concentration increases above the level where inhibition is observed, chl-*a* levels decline. (Source: Environmental Monitoring Program data)**

The effects of changes in the proportion of NH_4:NO_3 have been shown for the Bay-Delta in both field observations and laboratory experiments. Parker et al. (2012a) observed a 60% decline in primary production in the Sacramento River below the Sacramento Regional Wastewater Treatment Plant, where NH_4 is discharged, compared to production above the Treatment Plant's outfall. Also supporting this finding, Parker et al. (2012b) found that "[b]y tracing both carbon (C) and N uptake we provide clear evidence that high rates of C uptake are linked to phytoplankton NO_3, and not NH_4, use." They conclude that the increased proportion of NH_4 "may help explain some of the reduced primary production and phytoplankton biomass observed [in the San Francisco Estuary] since the 1970s."

In enclosure experiments with samples from Central Bay, Suisun Bay, and the Sacramento River at Rio Vista, representing a gradient of both nutrient concentrations and proportions of different forms of N, Wilkerson et al. (in preparation) observed "a gradient of decreasing phytoplankton physiological rates in the upstream direction as far as Rio Vista." Phytoplankton productivity rates (both carbon and nitrogen uptake) decreased with increasing concentrations of NH_4.

In a series of recent experiments conducted with natural samples from the Sacramento River the effects of altered proportions of NH_4:NO_3 were also apparent (Glibert et al. 2012). In these experiments, the proportions of these nutrients were manipulated, and both short-term N uptake rates and longer-term N production rates were assessed. Two findings are of note. First, when 20 µmol NH_4 was added to the sample, a concentration commonly observed in the Sacramento River, and the rate of NO_3 uptake was measured across a concentration gradient, the rate of uptake of NO_3 decreased significantly compared to unamended rates measured over a period of < 1 hour (Figure 18). Second, when samples were enriched with NH_4, NO_3, or urea (at the molar equivalent dose) for a period of 24-48 hours, and then rates of uptake of all N forms measured, the summed rate of N uptake in the NH_4-added treatment was significantly lower than that in the NO_3-added or urea-added treatments (Figure 19).

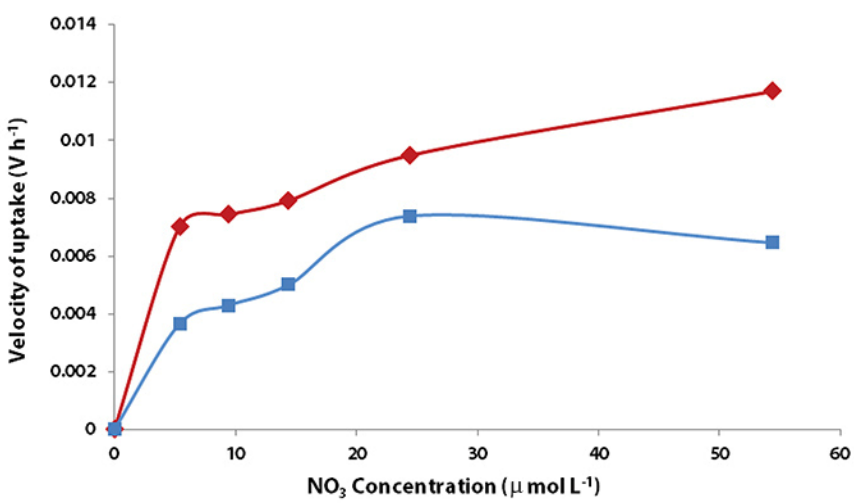


Figure 18. Velocity of uptake of NO_3 as a function of added NO_3 enrichment (red curve), and the same relationship but with a constant addition of 20 µmol L^{-1} NH_4 (blue curve). Nitrate uptake is reduced when NH_4 is added. Experiment was conducted with water collected from the Sacramento River. Data from Glibert et al. (2012).

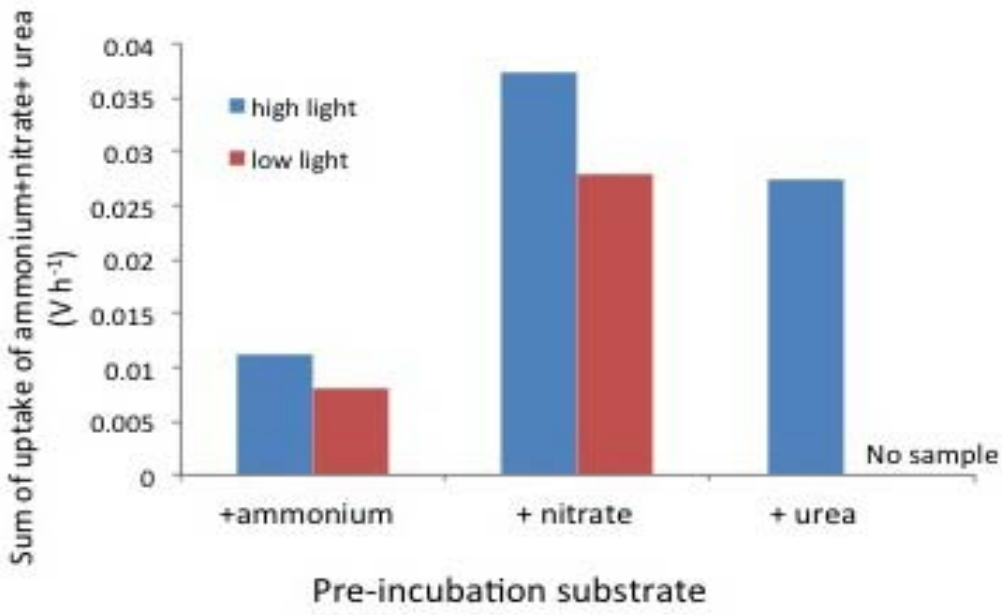


Figure 19. Summed rate of uptake of nitrate+ ammonium+ urea for samples collected from the Sacramento River and pre-incubated with the substrate indicated, after which short-term uptake rates were measured using ^{15}N tracer techniques. The experiment was conducted under both high (blue bars) and low (red bars) irradiance levels. The summed rate of N uptake in the NH_4-added treatment was significantly lower than that in the NO_3-added or urea-added treatments. From Glibert et al. (2012).

These observations of NH_4 suppression are not new in or unique to the Bay-Delta. A large body of scientific research describes NH_4 suppression of algae productivity (*e.g.* Ludwig 1938; Harvey 1953). Some of the early field demonstrations of this phenomenon were carried out by MacIsaac and Dugdale (1969, 1972), followed by research in the Chesapeake Bay by McCarthy et al. (1975). Maestrini et al. (1982) showed that only after NH_4 concentrations were reduced to < 7 µmol L^{-1} (0.098 mg L^{-1}) was NO_3 uptake sufficient to match that of NH_4 uptake. Price et al. (1985) showed that the rate of NO_3 uptake was reduced ~50% in samples that also received an NH_4 spike compared to those receiving a NO_3 spike. Lomas and Glibert (1999a) described the threshold for inhibition of NO_3 uptake at NH_4 levels of approximately 1 µmol L^{-1} (0.014 mg L^{-1}). Yoshiyama and Sharp (2006) saw a "striking decline in production at NH_4 levels above a low threshold (around 10 µmol L^{-1})" (0.14 mg L^{-1}). The importance of NH_4 inhibition of NO_3 uptake was considered to be a necessary interaction to include in a recent model of the emergent phytoplankton community in the California Current System (Goebel et al. 2010). In recent experiments conducted in the tidal freshwater estuarine zone of the Guadiana Estuary (Spain and Portugal), it was also found that NO_3 consumption decreased with increasing NH_4 uptake, and these findings were most pronounced during the most productive period. Total primary productivity was suppressed as a result (Domingues et al. 2011). The now well-supported notion that NH_4 may be inhibitory not only to NO_3 uptake but to total productivity is particularly problematic for the Bay-Delta as it is already a comparatively low producing estuary (Jassby et al. 2002).

The form of N available to a phytoplankton community affects more than just rates of uptake and productivity. Their proportions also affect phytoplankton species composition. The physiological literature strongly supports the concept that different algal communities use different forms of N. Diatoms, once the dominant algal group in the Bay-Delta, generally have a preference for NO_3; dinoflagellates and cyanobacteria generally prefer more chemically reduced forms of N (NH_4, urea, organic nitrogen) (e.g., Berg et al. 2001; Glibert et al. 2004, 2006; Brown 2009). Under some circumstances, diatoms have a physiological requirement for NO_3 (Lomas and Glibert 1999a,b). Moreover, diatoms usually show no evidence of NO_3 uptake saturation under very high NO_3 conditions (Collos et al. 1992, 1997; Lomas and Glibert 1999a), in contrast to the generally accepted saturating uptake kinetic relationships that are used to describe the relationship between nutrients and uptake rate. Cyanobacteria have been shown to preferentially use chemically reduced forms of N, like NH_4, over NO_3. Evidence comes from measurements of enzyme activities in the cells (Solomon et al. 2010), directly determined rates of N uptake using isotope tracer techniques (Glibert et al. 2004; Kendall et al. 2011), direct growth studies (Berman and Chava 1999; citations within Meyer et al. 2009), and observations of changes in community composition with enrichment with different forms of N (Domingues et al. 2011).

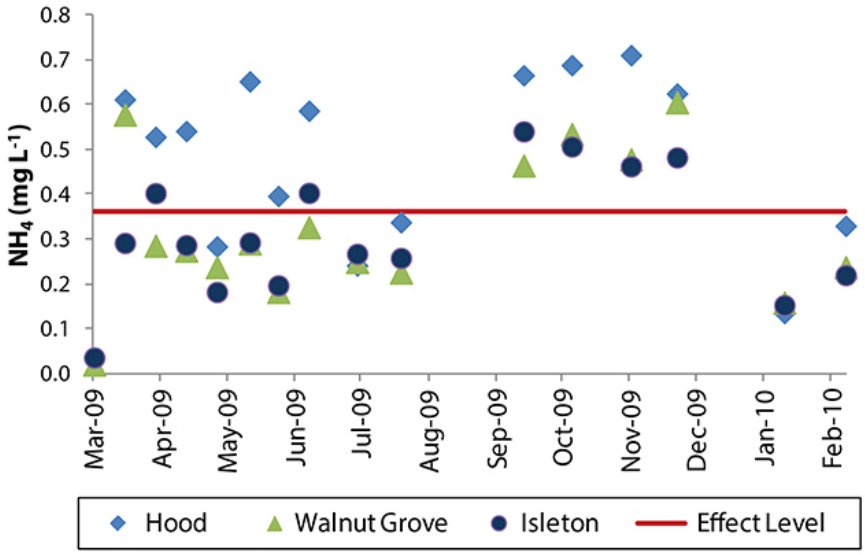
There is also evidence that the increase in aerial coverage by the invasive aquatic plant *Egeria densa* may be attributed to the ratio of nutrient inputs to the system. Feijoo, et al. (2002) experimentally found that *E. densa* absorbed more nitrogen from water when it was present in the form of NH_4 than when it occurred as NO_3.

Thus, although there are many factors that regulate the relative contribution of a nutrient source to different phytoplankton groups, and even species-specific differences within groups, it has generally been established that NO_3 disproportionately contributes to diatoms' uptake and production, while reduced forms of N (both NH_4 and urea) disproportionately contribute to the uptake and growth of cyanobacteria. As stated by Domingues et al. (2011), "…increased inputs of N as NH_4 due to urban waste effluents may result in a shift in phytoplankton community composition, towards a dominance of cyanobacteria and green algae." And, as stated by Lehman et al. (2010), "Recent increases in NH_4 concentration in the western delta may give a competitive advantage to Microcystis which rapidly assimilates NH_4 over NO_3." The phytoplankton community composition in the Bay-Delta estuary has shifted in just this manner. (refer to Figure 1).

Moreover, there is recent evidence that diatom blooms may be restored in the Bay-Delta estuary if NH_4 loading is reduced. In Suisun Bay, an unusual diatom bloom in Spring 2000 reached chl-*a* concentrations of 30 µg L^{-1} when NH_4 concentrations declined to 1.9 µmol L^{-1} (0.027 mg L^{-1}) (Wilkerson et al. 2006). Similarly, chl-*a* concentrations in Suisun Bay reached 35 µg L^{-1} during spring 2010 when NH_4 concentrations declined to 0.5 µmol L^{-1} (0.007 mg L^{-1})(Dugdale et al. 2011; Dugdale et al., in press). These blooms are comparable to spring chl-*a* levels from 1969 to 1977 (Ball and Arthur 1979) when NH_4 concentrations were 1.8 µmol L^{-1} (0.025 mg L^{-1}) during summer and 4.0 µmol L^{-1} (0.056 mg L^{-1}) during winter (Cloern and Cheng 1981).

In addition to altering phytoplankton community structure, growth rates and abundance, NH_4 is also toxic to some higher trophic level organisms. Scientists at UC Davis have investigated the effects of NH_4 to the calanoid copepod *Pseudodiaptomus forbesi* using a full life-cycle bioassay approach (Teh et al. 2011). *P. forbesi* is an important prey item for the young of many fish species in the Bay-Delta including delta smelt and longfin smelt (Nobriga 2002; Hobbs et al. 2006; Feyrer et al. 2003). Teh et al. (2011) found that total NH_4 at 0.36 mg L^{-1} (25.7 µmol L^{-1}) significantly affects the recruitment of new adult copepods and total NH_4 at 0.38 mg L^{-1} (27. 1 µmol L^{-1}) significantly affects the number of newborn nauplii surviving to 3 days (Teh et al. 2011). For comparison, monthly water samples collected between 2009-2010 from the Sacramento River between Hood and Isleton, approximately 30 miles downstream from the point of discharge, exceeded this level of NH_4 44% of the time (Figure 20).

Figure 20. Ammonium concentrations in th



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Sacramento River measured at Hood, Walnut Grove, and Isleton between 2009 and 2010. Hood and Isleton are approximately 8 and 30 miles downstream of the discharge, respectively. The horizontal line at 0.36 mg L^{-1} is the level at which significant toxicity to copepods is observed. Data from Foe et al. (2010).

2.3.5.2 Nitrogen:Phosphorus

Extensive research has found that the N:P ratio also has profound effects on community structure. The N:P ratio of nutrients has doubled in the Bay-Delta estuary over the last 35 years as is apparent from the data on Figure 21. These increases are a result not only of the increasing total N load (due to increasing effluent as well as other sources), but also as a function of declining P loads (Van Niewenhuyse 2007; Glibert 2010, Glibert et al. 2011).

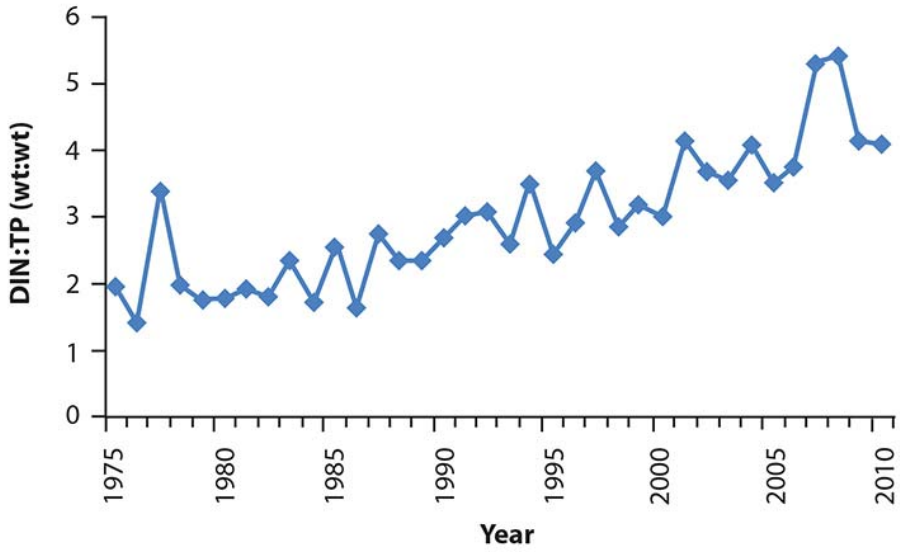

Figure 21. Average annual (March-November) ratio of dissolved inorganic nitrogen to total phosphorus has doubled in the Bay-Delta. (Source: IEP monitoring data from stations in Suisun Bay and the confluence (D4, D6, D7, D8)).

There are a number of strategies available to different types of phytoplankton for coping with an environment where nutrient ratios are not in proportion to their internal requirements (Glibert and Burkholder 2011). For example, cell size is an important determinant of elemental composition (Harris 1986; Finkel et al. 2010). Small cells have a lower requirement for P due to the smaller need for structural components in the cell (Finkel et al. 2010). In comparison to diatoms, very small cyanobacteria such as *Synechococcus* have a much larger cellular ratio of carbon to phosphorus (C:P), on average (Finkel et al. 2010). This explains why small cells, such as *Synechococcus*, have been found to thrive in waters that are comparatively P poor, as is the case in Florida Bay (Glibert et al. 2004).

There is strong support in the scientific literature for the proposition that the N:P ratio influences phytoplankton community composition. For example, in the Seto Inland Sea of Japan, removal of phosphorus also led to a shift in phytoplankton community structure from “nonharmful diatoms to harmful raphidophytes…and then finally to harmful/toxic dinoflagellates” (Yamamoto 2002). In this case the reduction in phosphorus which increased N:P, led to a change in phytoplankton community composition and was suggested to be “the major cause of the reduction in fishery production” (Yamamoto 2002).

In a retrospective analysis of 30 years of data from the Bay-Delta estuary, Glibert et al. (2011) found that the variation in these nutrient concentrations and ratios is highly correlated to variations in the total amount and composition of phytoplankton. This analysis revealed relationships between biological parameters and nutrients and/or nutrient ratios using both the original data and data that were adjusted for autocorrelation. At the phytoplankton level, as described earlier, there has been a decline in total chl-*a* and a decline in total diatoms over the past several decades in proportion to the increase in total inorganic N to total P (Figure 22). The change in chl-*a* with N:P is apparent in different regions of the Bay Delta; as N:P increases, chl-*a* declines (Figure 23).

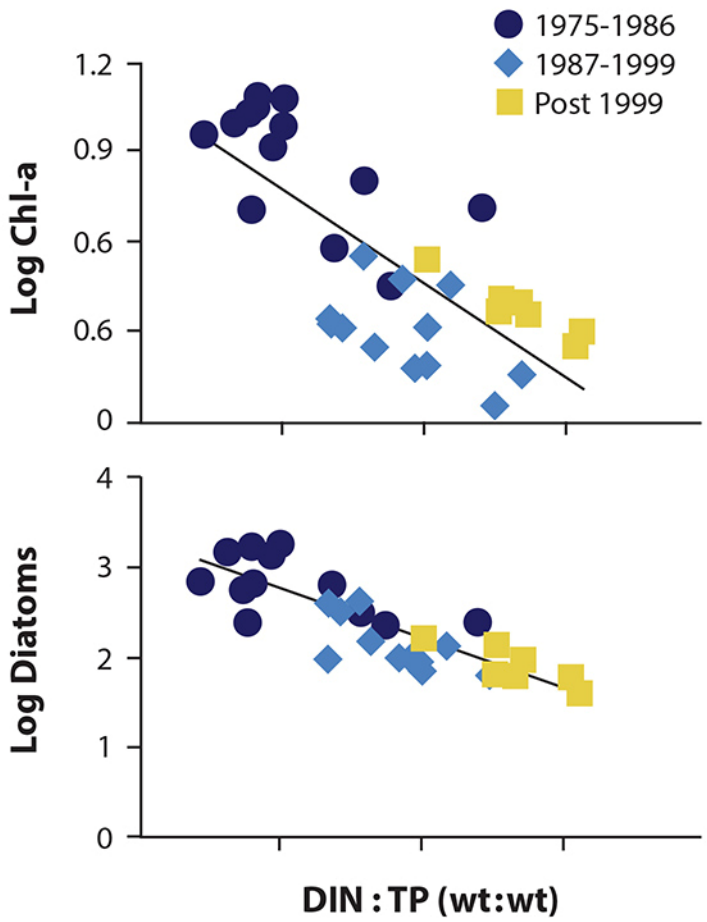

Figure 22. **Change in the concentration of chl-*a* (µg L^{-1}) and abundance of diatoms (Bacillariophyceae, cells mL^{-1}) as a function of dissolved inorganic N to total phosphorus. A loss of total chl-*a* and a loss of total diatoms in the phytoplankton community have occurred over the past several decades in proportion to the change in total inorganic N to total P. The relationship is significant at $p<0.05$. Different periods of time are represented by different symbols: 1975-1986, filled circles; 1987-1999, diamonds; post-1999- filled squares. Data shown are for the years 1975-2005 and cover the region from the confluence to Suisun Bay. All data log-transformed. Data from Glibert et al. (2011).**

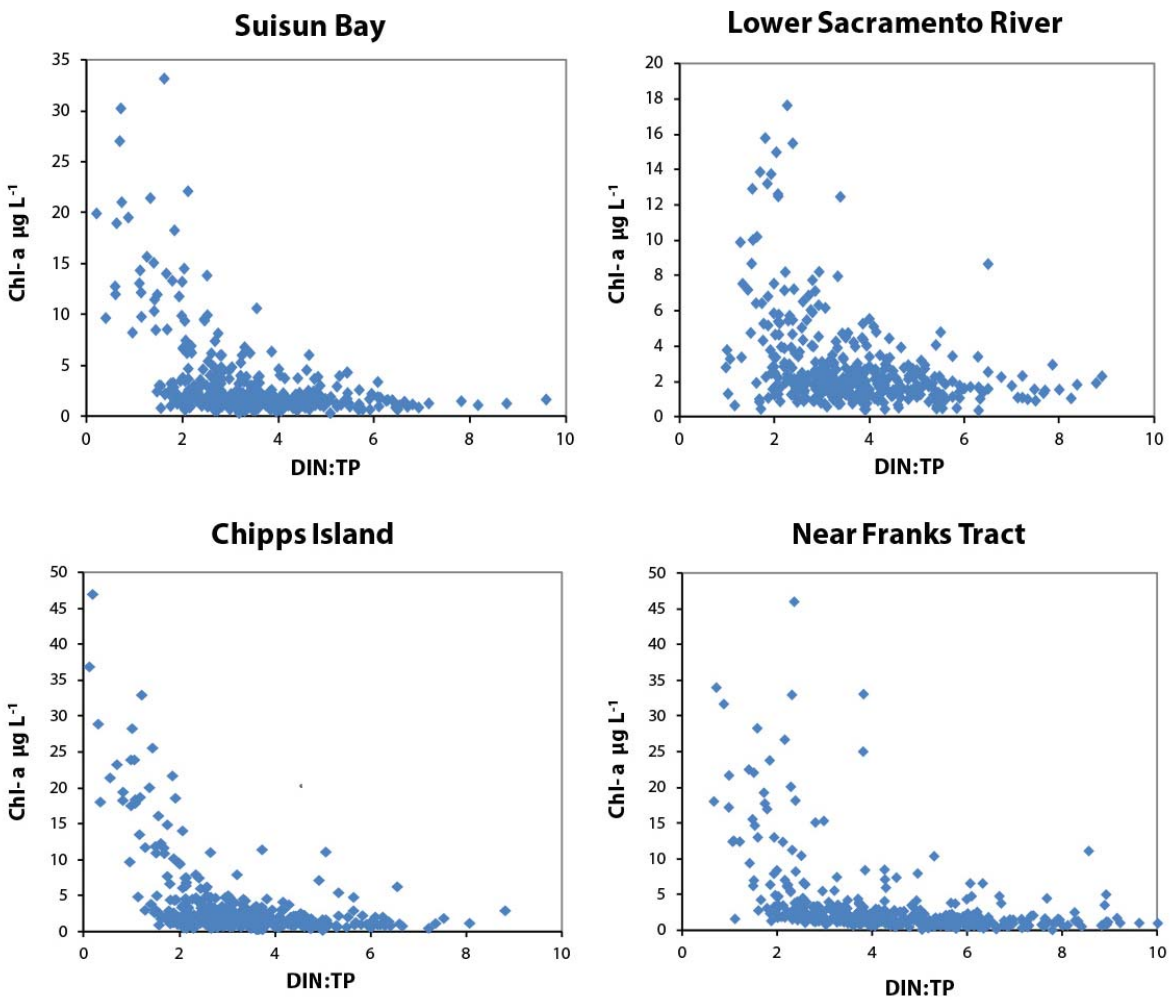

Figure 23. Chl-*a* concentration plotted against DIN:TP for subregions of the Delta, 1975-2011. As DIN: TP increases, there is a loss of chl-*a*. (Source: Environmental Monitoring Program data).

Fast-growing phytoplankton require proportionately more P to satisfy metabolic demands. Diatoms are typically fast-growing, and thus require proportionately more P to meet this metabolic demand. In ecological terms, they are considered a *r*-selected group, would be expected to have a low N:P biomass ratio (due to the high P cellular demand), and thus **would be expected to be outcompeted if N:P in the environment increases**. So-called *r*-selected species are out-competed when the environment changes (e.g., Heckey and Kilham 1988). In contrast, many cyanobacteria are considered to be *k*-selected, implying a slower growth rate and a higher metabolic N:P. In fact, "Reynolds (1984) singled out *Microcystis* as an example of a *k*-selected phytoplankter because it grows slowly in nature" (Heckey and Kilham 1988).

The balance of N:P can also affect other metabolic aspects of phytoplankton besides growth, including toxin production, cell membrane thickness, and other chemical constituents that have been considered to turn good food "bad" (Mitra and Flynn 2005). For example, toxin production by numerous harmful algae has been shown to increase when the cells are grown under nutrient-imbalanced conditions and when there is a change in N or P availability (Flynn et al. 1994; Johansson and Granéli 1999; Granéli and Flynn 2006). In Daechung Reservoir, Korea, researchers found that toxicity of cyanobacteria was related not

only to an increase in N in the water, but to the cellular N content as well (Oh et al. 2000). A recent report by van de Waal (2009) demonstrated in chemostat experiments that under high carbon dioxide and high N conditions, microcystin (an algal toxin) production was enhanced in *Microcystis*. Similar relationships were reported for a field survey of the Hirosawa-no-ike fish pond in Kyoto, Japan, where the strongest correlations with microcystin were high concentrations of NO_3 and NH_4 and the seasonal peaks in *Microcystis* blooms were associated with extremely high N:P ratios (Ha et al. 2009). Thus, not only is *Microcystis* abundance enhanced under high N:P, but its toxicity appears to be as well (Oh et al. 2000).

It is well accepted that the nutritional value of phytoplankton differs from one species to another. Toxin production can inhibit grazing. Some phytoplankton species are rejected by grazers due to their size. Others vary in their nutritional quality. For example, some diatom species produce certain highly unsaturated fatty acids that are essential for zooplankton reproduction (reviewed by Kilham et al. 1997) while flagellates generally produce different fatty acids than diatoms (Olsen 1999). Many trophic interactions, such as rates of growth or fecundity, are dependent on the acquisition of particular fatty acids, as a measure of the food quality of algae (e.g., Ahlgren et al. 1990; Coutteau and Sorgeloos 1997; Weers and Gulati 1997; Brett and Müller-Navarra 1997). In feeding experiments, Ger et al. (2010) observed reduced survival of the copepods, *Pseudodiaptomus* and *Eurytemora,* even when *Microcystis* was only a small portion of their available diet. Brett and Müller-Navarra (1997) developed a food quality rank for 10 species from 5 major phytoplankton groups based on the average of the observed change in the abundance of individual zooplankters that preyed upon these phytoplankton in growth bioassays. They and others (see Park et al. 2003) have applied a 0-1 scale of phytoplankton food quality in which cyanobacteria ranks at 0.2; green algae, 0.525; diatoms, 0.7; and cryptomonads, 0.95. Thus, a trend of decreasing diatoms and increasing cyanobacteria in the Bay-Delta would suggest, based on these rankings, a decrease in food quality for higher trophic levels. Jassby (2008a) states:

> A decrease in percentage of diatom biovolume occurred during 1975–1989, caused by both a decrease in diatoms and an increase in green algae, cyanobacteria, and flagellate species biovolume (Kimmerer 2005; Lehman 1996), i.e., probably in the direction of declining nutritional value per unit biomass. In principle, the total nutritional value of a community could decrease even as its biomass increases. Moreover, changes in size, shape, and motility of species comprising the phytoplankton community could also affect their availability as food particles for crustacean zooplankton and other consumers.

Cloern and Dufford (2005) state, “[t]he efficiency of energy transfer from phytoplankton to consumers and ultimate production at upper trophic levels vary with algal species composition: diatom-dominated marine upwelling systems sustain 50 times more fish biomass per unit of phytoplankton biomass than cyanobacteria-dominated lakes.”

For species that prey on phytoplankton (e.g., zooplankton), stoichiometry affects all aspects of behavior, such as growth rate, fecundity, and ultimately the success of different populations (Jeyasingh and Weider 2005, 2007), but may affect various life stages differently (Moe et al. 2005, p.31): “[a]n organism’s requirements for different elements may vary throughout its life cycle, and thus certain life stages may be more sensitive than others to variation in the stoichiometry of its resource.” For example, copepod juveniles have a relatively high demand for C, N, and P, but at a later stage, while C is still needed for metabolism, more P must be allocated to eggs. Therefore, P-poor food sources can disproportionately affect egg production while not affecting survival (Faerovig and Hessen 2003; Laspoumaderes et al. 2010). In a laboratory study where *Acartia tonsa* was fed diatoms grown on different N concentrations, Kiørboe (1989), confirmed that this zooplankter changes its feeding rate in response to phytoplankton of different chemical composition – thus, in response to food quality. Moreover, egg production followed the variation in algal N content and increased with increasing algal N.

In a review of field and laboratory-based research on stoichiometry in food webs, Hessen (1997) showed that a shift from copepods to *Daphnia* tracked N:P; copepods retain proportionately more N, while *Daphnia* are proportionately more P rich. Often, those organisms that are most able to retain the nutrient in limited supply, in this case P, have the competitive advantage in an unbalanced system. Glibert et al. (2011) illustrated a finding similar to Hessen's, that the decline in calanoid copepods in the Bay-Delta, and the invasion of cyclopoids tracked N:P over time. Variation in proportional densities of the calanoid copepod *Eurytemora* with the cyclopoid copepod *Limnoithona* over time has followed changes in the DIN:TP (dissolved inorganic nitrogen to total phosphorus) ratio (Figure 24), a pattern consistent with these grazers being responsive to changes in elemental stoichiometry and maintenance of altered dynamic equilibria on a long-term scale. In fact, Glibert et al. (2011) found relationships between many of the shifts in zooplankton community composition seen on Figure 2 and shifts in nutrient composition. Results from whole-lake experimentation suggest that the N:P ratio is linked to alterations in zooplankton size, composition, and growth rate, as those animals with increased RNA allocation (more P available for growth) will grow at higher rates due to increased protein synthesis rates (Sterner and Elser 2002). Similar findings were reported from annual studies in the Baltic Sea (Walve and Larsson 1999).

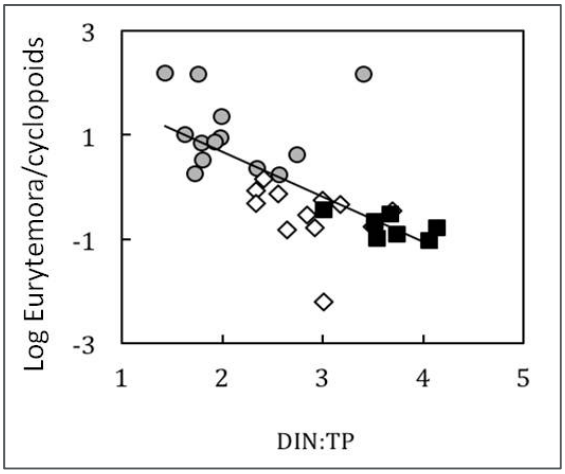

Figure 24. Change in the ratio of Eurytemora to cyclopoid copepods (all data log transformed) as a function of DIN:TP for annually averaged data from 1975-2005 for samples collected between the confluence and Suisun Bay. As DIN:TP increases, the proportion of Eurytemora to Cyclopoids decreases. Different periods of time are represented by different symbols: 1975-1986, filled circles; 1987-1999, diamonds; post-1999 filled squares. The correlation for these and for data that were detrended (not shown) are significant (p<0.05). From Glibert et al. 2011.

Superimposed on these empirical observations is consideration of whether substrate quality or food quality is altered on an episodic basis, or whether changes are long-term and sustained. As conceptualized by Hood and Sterner (2010), a change in predator growth rate depends on the extent to which a diet is sustained or switches between low-quality food and high-quality food as defined by the relative P content.

2.3.5.3 Higher Trophic Level Effects

Disproportionate N and P loads are now recognized to have effects at all scales, from genomic to ecosystems that need further empirical resolution (Peñuelas et al. 2012). When N:P availability changes, food webs change, biogeochemical cycling can change, and these changes can be positively reinforcing. Sterner and Elser (2002) state: "[s]toichiometry can either constrain trophic cascades by diminishing the chances of success of key species, or **be a critical aspect of spectacular trophic cascades with large shifts in primary producer species and major shifts in ecosystem nutrient cycling**" [emphasis

added]. Just as different elemental ratios may affect the composition of the primary producers, different nutrient requirements of organisms occupying higher trophic levels will have an impact on their ability to thrive as community composition changes at the base of the food web. At the ecosystem scale, the total load and balance of nutrient elements have effects that propagate through the food web, with the potential of transforming ecosystems to new stable states. Although the shift in algal community composition in terms of diatoms and cyanobacteria has been emphasized above, this shift in the Bay-Delta estuary has been far more complicated. With the decline in water column chl-*a* and an increase in light availability, other primary producers have increased in abundance, including invasive macrophytes such as *Egeria densa* (Sommer et al. 2007; Nobriga et al. 2005; Glibert et al. 2011). *E. densa* may be particularly well suited to the low DIP:DIN environment of the Bay-Delta since it is able to access sediment bound phosphorus through its roots. In fact, similar increases in macrophytes were observed in many other systems in which N:P increased following N enrichment and P reduction, including the Potomac River, Chesapeake Bay, Ebro River in Spain, and the Rhine River in Germany (Glibert et al. 2011; Glibert 2012). Such macrophyte invasions can have profound impacts on ecosystems, not only because they alter the flow of C and the overall productivity of the system, but they also serve as "ecological engineers," decreasing nutrients through uptake, reducing turbidity by trapping sediments, and providing refuge for zooplankton and habitat for other species, including fish (Yarrow et al. 2009; Glibert 2012).

The interplay between nutrient stoichiometry and biogeochemistry is well illustrated when a system is driven to higher macrophyte productivity. Macrophytes can be highly productive, which can result in elevation of pH due to carbon drawdown in the process of photosynthesis. As noted by Glibert (2012), once pH is elevated, the fundamental physical–chemical relationships related to P adsorption–desorption in sediments change, as does N biogeochemistry (Jordan et al. 2008; Gao et al. 2012). Moreover, under increased pH conditions, the biogeochemistry of calcification is altered, increasing the potential for calcification and the growth of calcifying organisms. Thus, the change in the abundance of the clam *Potamocorbula amurensis* from the time of its introduction in the mid-1980s to 2005 has been shown to be highly and positively correlated to the increase in total N:total P ($r^2 = 0.46$; $n = 20$; $p < 0.01$; all data log transformed), and the average annual abundance of this species has also been found to be highly and positively correlated with mean annual average pH in the estuary ($r^2 = 0.64$; $n = 19$; $p < 0.01$; species abundance data log transformed) (Glibert et al. 2011). Interestingly, the Potomac River, Rhine River and the Ebro River have had similar invasions of macrophytes and *Corbicula* clams that relate to increases in N:P loading (Ibanez et al. 2008; Glibert et al. 2011; Glibert 2012).

In the Bay-Delta estuary, data show top-down grazing of phytoplankton by the clam *P. amurensis* exerts a strong control on phytoplankton biomass, as is also the case for other systems when invaded by bivalve mollusks. Prior interpretations, emphasizing stochastic invasions largely via ballast water exchange imply that the invasive event was the ultimate cause of the change in top-down control of phytoplankton. The ecological stoichiometric interpretation does not preclude strong top-down control of selected component organisms, nor ballast water exchange as the mechanism of introduction. The distinction is that, at the overall ecosystem level, the structuring of species is affected by alterations in nutrients and ecosystem biogeochemistry.

The arguments presented here make the case that bottom-up control contributed to the conditions that allowed *P. amurensis* to become a dominant regulator of phytoplankton production. In other words, invasive species effects and nutrient effects are interrelated. This interpretation is consistent with Ware and Thompson's (2005) insights from a broad survey of the relative contributions of "bottom-up" vs. "top-down" factors that potentially control fish catch in the coastal waters of the western U.S.; they, too, reported that bottom-up factors were more important.

Several recent reviews have investigated the stoichiometry of fish (Sterner and George 2000; Hendrixson et al. 2007; McIntyre and Flecker 2010). Not only does a strong shift in body N:P occur with growth stage (Pilati and Vanni 2007), but strong differences between taxonomic families also do. In fact, Hendrixson et al. (2007) demonstrated, for 20 families of fish, that a phylogenic tree could be developed based on the body nutrient composition.

In the Bay-Delta estuary, numerous changes in fish community composition occurred in relation to phytoplankton and zooplankton changes, and to N:P (Glibert 2010; Glibert et al. 2011) (Figure 25). Glibert et al. (2011) also found that total P "explained at least as much of the variability in delta smelt as did the [Feyrer et al. 2011] habitat index, and dinoflagellate abundance explained even more." Unlike the X2 correlations where the underlying mechanisms driving the correlations are largely unknown, the nutrient relationships have a strong mechanistic explanation in ecological stoichiometry and stable state principles. For this reason, there is relatively low uncertainty that changes in nutrient stoichiometry in the Bay-Delta estuary, achieved through both external forces (altered land-based nutrient loads) and internal, organism- driven, assimilative and dissimilative processes, are related to community compositional changes (Glibert et al. 2011; Glibert 2012).

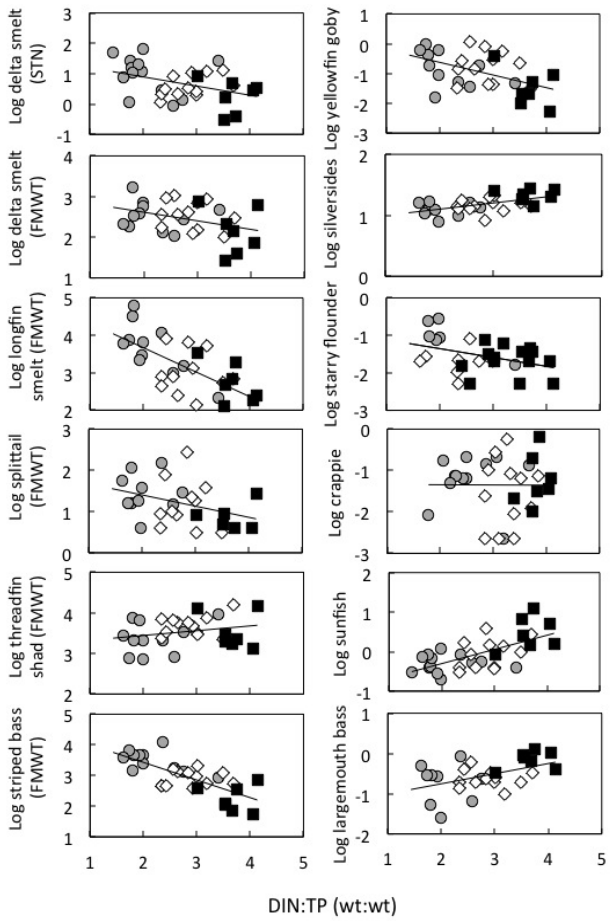

Figure 25. Changes in the abundance of major fishes in relation to ratio of dissolved inorganic nitrogen to total phosphorus from 1975-2005. Different periods of time are represented by different symbols: 1975-1986, filled circles; 1987-1999, diamonds; post-1999 filled squares. All data were log-transformed. The correlations for all fish except crappie were significant ($p<0.05$) in these data as well as in data that were detrended. Source: Glibert et al. (2011).

Eutrophication, ecological stoichiometry and alternate stable state theories combine to serve as a unifying framework for understanding the complexity of responses not only in the Bay-Delta estuary but also, more generally, in many comparative systems. This interpretation does not negate the importance of ecological invasions, habitat changes, multiple stressors and food-web complexities, but adds an explanatory mechanism to those interpretations through biogeochemistry and organismal stoichiometry. Ecological stoichiometry affects systems by setting elemental constraints on the growth of organisms. This, in turn, affects food quality and the relationships between predators and prey.

A growing body of literature documents improvements in ecosystem functions where nutrient loading is reduced and stoichiometric balance is restored. Reducing nutrient loading in the Chesapeake Bay, Tampa Bay, and coastal areas of Denmark has proven to be effective at reversing the harmful effects of previously undertreated discharges and restoring the native food webs. For example, within several years of increasing nutrient removal at the Blue Plains treatment plant in Washington DC, N:P ratios in the Potomac River declined, the abundance of the invasive *Hydrilla verticillata* and *Corbicula fluminea* began to decline (Figure 26 showing *C. Fluminea Halic*), and the abundance of native grasses increased (Ruhl and Rybicki 2010).

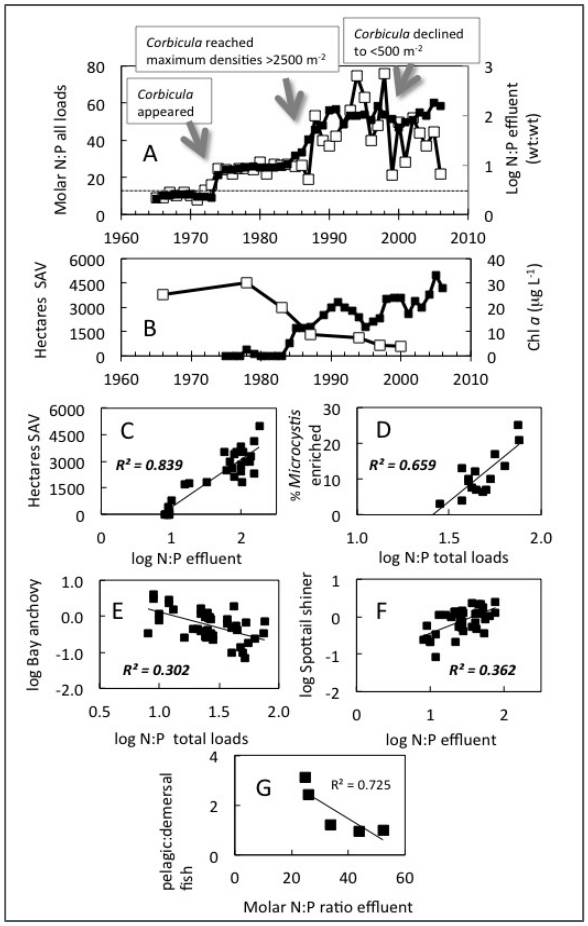

Figure 26. Comparative relationships for the Potomac River. Panel A shows the change in effluent N loading and the relative abundance of the invasive clam, *Corbicula fluminea*. C. fluminea appeared coincident with a sharp increase in N:P and increased in abundance as N:P increased. When N:P decreased sharply around 1999, *C. fluminea* abundance also declined sharply from >2500 m^{-2} to <500 m^{-2} Data derived from Dresler and Cory (1980), Jaworski et al. (2007), and Cummins et al. (2010). Figure reproduced from Glibert et al. (2011).

Tampa Bay provides another important example. Eutrophication problems in Tampa Bay were severe in the 1970s, with N loads approximating 24 tons per day, about half of which was due to point source effluent (Greening and Janicki 2006). Several years after nitrogen and phosphorus reductions were achieved, native seagrass began to increase. Lower nutrient discharges also had positive effects on the coastal waters around the island of Funen, Denmark (Rask et al. 1999). Since the mid 1980s, there has been a roughly 50% reduction in the loading of N and P in the region due to point source reductions. Again, native grasses returned and low oxygen problems were reversed.

Cloern (2001) provides additional examples of recovery following reductions in nutrient and waste inputs (Figure 27). Citing other researchers, Cloern (2001) shows improvements in dissolved oxygen levels in the Forth Estuary in Scotland following improvements in wastewater treatment. Citing a second study, Cloern (2001) shows increases in fish diversity in the Thames Estuary following improvements in wastewater treatment there (Figure 27).

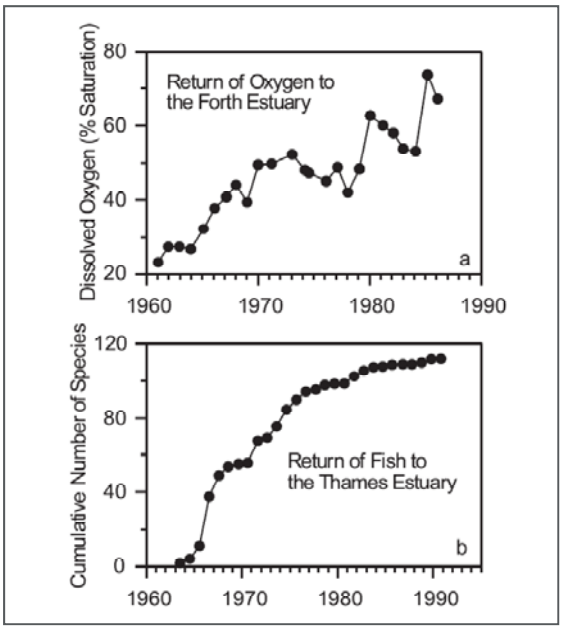

Figure 27. Two examples of recovery following actions to restore water quality in estuaries impacted by nutrient and waste inputs: (a) trend of increasing dissolved oxygen concentration (summer months) in the Forth Estuary, Scotland, following Improvements in wastewater treatment; (b) trend of increasing diversity of fishes in the Thames Estuary following implementation of advanced wastewater treatment and increases in oxygen concentrations (Source: Figure 20 from Cloern 2001).

Release of stored water will not contribute to restoring the N:P balance. As demonstrated by Figure 28, outflow, as measured by the location of the X2 isohaline in the estuary, is correlated with concentrations of individual nutrients (e.g., total phosphorus and phosphate concentration are correlated with the amount of outflow); however, because the sources and geochemical processes governing nitrogen and phosphorus differ, there is no relationship between outflow and the N:P ratio (Glibert et al. 2011).

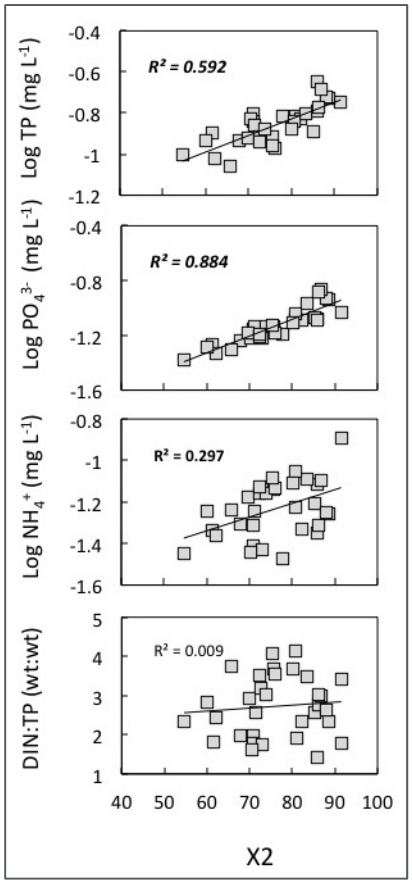

Figure 28. Comparison of the relationship between nutrients and X2 for the time course from 1975–2005. Outflow, as measured by X2, does affect concentrations of individual nutrients (top three graphs), but does not affect N:P ratio (bottom graph) (Source: Figure 36 from Glibert et al. 2011).

In summation, changes in nutrient loads are clearly impacting Bay-Delta ecosystem dynamics in complex ways that extend beyond eutrophication. In addition to increases in nutrients, changes in the form of available nutrients (chemical state, oxidized vs. reduced, organic vs. inorganic, dissolved vs. particulate) and the proportion of different nutrients produce adverse effects at both the scale of the primary producers and the entire ecosystem.

2.3.6 Possible Explanation 6: Changes in the land-water interface have negatively impacted Bay-Delta productivity?

Moyle et al. (2010) believe the rich diversity and abundance of aquatic and terrestrial life in the predevelopment Delta imply,

> "…high productivity, which was likely generated by nutrients from the extensive riparian corridors, marshes and seasonal floodplains. High connectivity among the habitats allowed the dispersion of these nutrients throughout the system and into the estuarine food webs, supporting the dense fish populations."

The predevelopment Bay-Delta was an extensive, complex and diverse environment (The Bay Institute 1998). The pre-settlement Sacramento River was narrow, meandering, and sinusoidal, but the massive dredging of the Sacramento River for flood control in the 1920s deepened, widened, and straightened the

river, resulting in profound changes in the bathymetry and regional hydrodynamics (James and Singer 2008). From 1860 to 1930, approximately 400,000 acres of tidal marsh were leveed from the channels and converted to Delta farm land, thereby cutting off tidal prisms (Lund et al. 2007). Miles of dendritic channels were eliminated and replaced with deep channels with far less bathymetric diversity (James and Singer 2008). These profound changes to the physical environment resulted in the hardening of the land-water interface and isolating it from natural tidal action and flood events. The loss of floodplain and wetlands habitats has reduced primary production (Baxter et al. 2010), and this is an arena where management actions can be taken to improve the food web.

2.3.6.1 Floodplains

Natural floodplains are among of Earth's most productive and biologically diverse ecosystems (Tockner and Stanford 2002). Floodplains benefit species that directly access them, such as fishes that spawn or forage on floodplains when they are inundated (Moyle et al. 2007). In addition, floodplains can potentially provide regional benefits by exporting food resources such as phytoplankton to downstream systems (Sommer et al. 2004; Ahearn et al. 2006; Lehman et al. 2008).

However, most floodplains in the Bay-Delta estuary and in the watersheds of the Sacramento and San Joaquin Rivers have been severed from their rivers by levees, channelization and flow regulation (Mount 1995). This disconnect affects functional attributes of floodplains, including reduced nutrient replenishment and associated food-web development, and decreased variability of flood-dependent habitats (Jeffres et al. 2008; Opperman et al. 2010).

Historically, floodplains produced high levels of phytoplankton and other algae, particularly during long-duration flooding that occurred in the spring (Sommer et al. 2004; Ahearn et al. 2006). The shallow water depth and long residence time in floodplains facilitated settling of suspended solids, resulting in reduced turbidity and increased total irradiance available for phytoplankton growth in the water column (Tockner et al. 2000). At the Cosumnes River Preserve, the inundated floodplain progressed from a physically driven system when connected to the river floods to a biologically driven pond-like system with increasing temperature and productivity once inflow ceased (Grosholz and Gallo 2006). Periodic small floods boosted aquatic productivity of phytoplankton by delivering new pulses of nutrients, mixing waters, and exchanging organic materials with the river (Ahearn et al. 2006). Aquatic productivity was greater in floodplain ponds than in river sites (5-10 times greater chl-*a* values and 10-100 times greater zooplankton biomass) (Ahearn et al. 2006; Grosholz and Gallo 2006). Zooplankton biomass increased rapidly following each flood event to a peak approximately 7–25 days after disconnection from the river, with highest observed values (approximately 1,000–2,000 mg/m^3) at approximately 21 days (Grosholz and Gallo 2006).

In addition, as reviewed by Lehman et al. (2008), phytoplankton produced on the floodplains are often higher in nutritional quality than phytoplankton found in rivers because they have a wider spherical diameter and thus higher carbon content (Hansen et al. 1994; Lewis et al. 2001). Diatoms and green algae, which are the dominant algal species in the Yolo Bypass (Lehman et al. 2008), have the highest cellular carbon content in the San Francisco Estuary phytoplankton community (Lehman 2000; Hansen et al. 1994).

Studies of the Yolo Bypass provide evidence of the incremental value of floodplains to the Bay-Delta estuary (Sommer et al. 2001a, 2001b, 2008). Chl-*a* levels were significantly higher in the floodplain than in the river and were negatively associated with flow. These results were consistent with longer hydraulic residence times, increased surface area of shallow water, and warmer water temperatures. Copepod and cladoceran densities were similar in the river and its floodplain, and were mostly negatively associated with flow. Chironomid fly abundances were positively correlated with flow (discharge and flow velocity);

these organisms were one to two orders of magnitude more abundant in the Yolo Bypass floodplain than the adjacent Sacramento River channel (Sommer et al. 2001a).

Providing river–floodplain connectivity can rapidly enhance production of lower trophic level organisms (Sommer et al. 2004). In the Yolo Bypass, some food-web organisms respond within days and attain very high densities soon after inundation, including smaller fast-growing algae (e.g., picoplankton, small diatoms, nanoflagellates), vagile organisms such as drift insects, and organisms associated with wetted substrate such as chironomid flies. These organisms, particularly chironomids, provide a food source to fish that is available prior to the development of food-web productivity associated with long residence times (e.g., phytoplankton and zooplankton responses to inundation) (Sommer et al. 2004).

Floodplains have been proposed as "productivity pumps" (Junk et al. 1989) that can export food resources, especially algae, to support food webs in downstream aquatic ecosystems (Sommer et al. 2001b; Ahearn et al. 2006; Lehman et al. 2008). By periodically pulsing small "floodplain activation floods," it may be possible to pump high concentrations of algae to downstream waters (Ahearn et al. 2006). Analysis of suspended algal biomass in the Cosumnes River channel and floodplain by Ahearn et al. (2006) documented an increase in chl-*a* concentrations on the floodplain during periods of river-floodplain disconnection, and subsequent increase in chl-*a* in the river when connection was restored. Lehman et al. (2008) suggested that the quantity and quality of riverine phytoplankton biomass available to the aquatic food web could be enhanced by passing river water through a floodplain such as the Yolo Bypass during the flood season.

2.3.6.2 Wetlands

Over the last 150 years, approximately 95% of the tidal wetlands in the Bay-Delta estuary have been lost due to local development (The Bay Institute 1998). In an investigation of the ecological values of shallow-water areas contiguous and adjacent to tidal wetlands and freshwater marshes, Lopez and her colleagues found that such areas in the estuary support high phytoplankton growth rates (Lopez et al. 2006). Mueller-Solger et al. (2002) conclude, "From a restoration perspective, the results of this study emphasize the importance of tidal marsh and floodplain preservation and restoration as relatively food-rich areas for pelagic primary consumers." Table 1 reproduces Table 1 from their report and shows high levels in all measures of food availability for tidal marsh and floodplains. These findings are consistent with the prevailing belief that wetlands in areas such as Suisun Marsh and the Cache Slough complex contribute to primary production. In a summary of a workshop on Suisun Marsh restoration, Brown (2004) reported that tidal marsh restoration would fuel the estuarine food web. At the same time, such production can be variable and is related to connectivity in aquatic ecosystems driven by advection, dispersion, and gravitational circulation (Brown 2004; Lopez et al. 2006).

Cloern (2007) used a nitrogen-phytoplankton-zooplankton model to illustrate how shallow water bodies sustain fast phytoplankton growth and net autotrophy (photosynthesis exceeds community respiration), whereas deep, light-limited areas within the Delta channels sustain low phytoplankton growth (Jassby et al. 2002) and net heterotrophy. Lopez et al. (2006) found that surplus primary production in shallow areas provided potential subsidies that likely supported zooplankton in neighboring areas, except in areas heavily colonized by the invasive clam *Corbicula fluminea*.

Table 1. Median POC and Chl-*a* concentrations in the <243 µm Seston size fraction and related estimates for Delta habitats and seasons. Scenedesmus equivalent carbon (SEC) concentrations associated with observed Daphnia growth rates; phytoplankton carbon concentrations (PHY C) estimated from Chl-*a* concentrations. All concentrations are in mg L^{-1}. High levels in all measures of food availability are apparent for tidal marsh and floodplain habitats.

	Season			
Habitat	Winter	Spring	Summer	Fall
POC				
River	969	805	841	1,373
Flood plain	1,312	1,801	—	—
Flooded island	382	845	749	953
Tidal marsh	2,902	2,555	2,682	2,323
Chl *a*				
River	3.3	4.4	3.2	2.8
Flood plain	5.0	7.6	—	—
Flooded island	2.6	9.1	3.1	3.1
Tidal marsh	14	15	6.3	8.4
SEC				
River	108	181	61	193
Flood plain	178	773		
Flooded island	140	546	113	1,321
Tidal marsh	1,014	1,001	600	558
PHY C				
River	116	154	112	98
Flood plain	175	266	—	—
Flooded island	91	319	109	459
Tidal marsh	473	525	221	294

Source: Table 1 from Mueller-Solger et al. 2002

In summation, major changes to the Bay-Delta landscape over the past 150 years have resulted in the hardening of the land-water interface, thereby isolating large geographic areas from natural tidal action and flood events. Reduction in primary productivity resulting from losses of wetlands across much of the Bay-Delta estuary is recognized by agency biologists as a key determinant of declines in zooplankton and the native fish that prey on them. Reestablishment of emergent wetlands will contribute to food production for desired fish, provide fish spawning and rearing areas, refugia from predators, and aid in migration and within-Delta dispersal.

3 Changes to the Landscape

In an unaltered state, the physical landscape of an estuary provides valuable spaces for rearing, spawning, migration, and refuge from predators. There is no disagreement that the changes to the Delta landscape have been extensive and have reduced or eliminated many of those functions. Where land and water were once intricately connected, now levees maintain substantial if not complete separation.

Historically, the flood basins of the Bay-Delta and its tributaries were the home to vast tracts of permanent tule marsh or swamps. Areas now with levees were populated with riparian forests of cottonwood, willows, sycamores, elders, ash, walnut, and Valley oak and a thick understory of grape, wild rose, blackberry, poison oak, and other vines (Katibah 1984 as cited in Garone 2011; Kooser et al. 1861). Luxuriant native grasses, often 3 to 5 feet high, covered much of the plains area outside of these flood basins (Garone 2011; Holmes et al. 1915 as cited in Katibah 1984).

Before European settlement began in the early 1800s, the rivers flowed through approximately 400,000 acres of wetlands and other aquatic habitats in the Delta (Delta Stewardship Council 2012). The primary landscapes in the historical Delta included flood basins in the north Delta, tidal islands in the central Delta, and a complex network of dendritic channels formed by riverine processes in the south Delta. Over the last 160 years, 1,335 miles of levees have been constructed to drain wetlands and convert them into farmland. Today, over 95 percent of the wetlands once present in the Delta are gone (Moyle et al. 2012).

3.1 Biological Implications of Changes to the Landscape

Several studies support the notion that access to wetlands is important to the success of many of the Delta's desired fish species (Moyle et al. 1992; Lindberg and Marzuola 1993; McIvor et al. 1999). Both the DFG and USFWS have made restoration of wetlands a condition of authorizations issued for the CVP and SWP for longfin smelt and delta smelt, respectively.

Floodplain inundation provides spawning and rearing habitat for fish that take advantage of the high productivity on the floodplain (Poff et al. 1997; Sommer et al. 2001a, b; Feyrer et al. 2004; Schramm and Eggleton 2006; Grosholz and Gallo 2006). During these periods of connection to the river, fish can move on and off the floodplain to forage or spawn (Moyle et al. 2007). The low-velocity, shallow, and vegetated conditions of the floodplain serve as a refuge from the fast, turbid waters of the river during high flows (Sommer et al. 2001a; Jeffres et al. 2008).

Large floodplain areas such as the Yolo Bypass (24,000 ha) have the capacity to influence fish abundance and survivorship at the population scale. The duration of inundation of the Yolo Bypass is a strong predictor of year-class strength for Sacramento splittail (*Pogonichthys macrolepidotus*) for the entire Central Valley and Delta system (Sommer et al. 1997; Feyrer et al. 2005).

The Sacramento splittail is perhaps the most floodplain-dependent species in the Delta (Sommer et al. 1997). Adults migrate onto the inundated floodplain to spawn on vegetation in February-March at both the Cosumnes floodplain (Moyle et al. 2007) and the Yolo Bypass (Sommer et al. 2004). Juveniles rear on the floodplain and depart when it drains in April-May, achieving better condition on the floodplain than in river habitats (Ribeiro et al. 2004).

Juvenile Chinook salmon also benefit from floodplains as foraging and refuge habitat. Juveniles migrate downstream onto floodplains in February to March to forage on the abundant invertebrates in the flooded vegetation, prior to emigrating to the sea (Moyle et al. 2007; Grosholz and Gallo 2006). At the Cosumnes

River, growth rates of juveniles reared in enclosures are faster on ephemeral floodplains than in the river (Jeffres et al. 2008) (Figures 29 and 30).

Figure 29. **Comparison of juvenile Chinook salmon reared 54 days at the Cosumnes River Preserve in (1) intertidal river habitat below the floodplain (left) and (2) floodplain vegetation (right). Growth rates of juveniles reared in enclosures were faster on floodplain habitats than in the river (Source: Jeffres et al. 2008).**

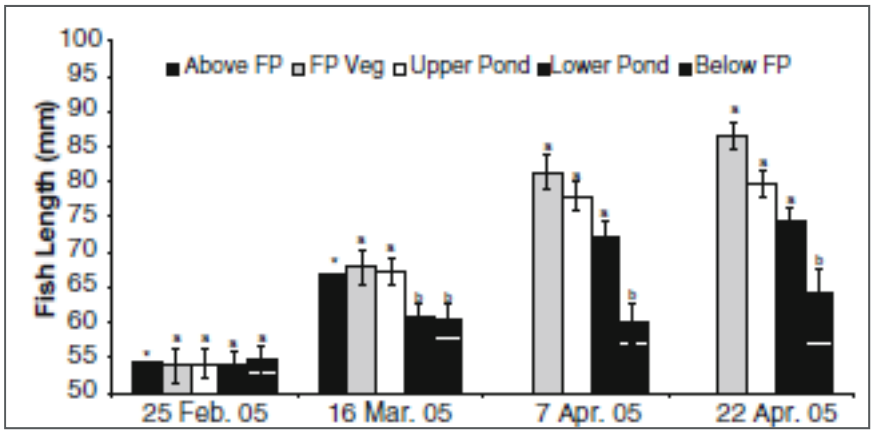

Figure 30. **Size (mean fork length ± standard error) of juvenile Chinook at the Cosumnes River Preserve reared in floodplain habitats (FP Veg,Upper Pond, and Lower Pond) and river channel sites (Above FP and Below FP) over four sampling sessions during the 2005 flood season. Growth rates of juveniles reared in enclosures were faster on ephemeral floodplain habitats than in the river habitats with different letters are statistically different. Asterisks indicate habitats not included in the statistical analysis (Source: Jeffres et al. 2008).**

At the Yolo Bypass, juvenile Chinook salmon grow larger and are in better condition than those in the river (Sommer et al. 2001a). Drifting macroinvertebrates, such as chironomids and terrestrial invertebrates, are an important food resource for fish. Yolo Bypass salmon have significantly more prey in their stomach than salmon collected in the Sacramento River (Sommer et al. 2001a, 2004). Chironomids, the primary food resource for juvenile Chinook, are 1 to 2 orders of magnitude more abundant in the floodplain than the adjacent Sacramento River channel (Sommer et al. 2001a).

Wetlands also provide benefits to delta smelt. Recently, researchers carried out a habitat affinity analysis for delta smelt. While reduced turbidities and unacceptably high water temperatures in summer and early autumn render much of the south and east Delta unacceptable to delta smelt, remaining portions of the Delta where bays, embayments, and larger channels abut shallow waters, marshes, and wetlands provides habitat for the species (Hamilton and Murphy, in review). Hamilton and Murphy conclude that efforts to conserve delta smelt will best be realized, not by altering contemporary flow regimes in the estuary, but by carrying out strategically located marsh and wetland restoration efforts intended to restore functions and processes, where those areas are adjacent to open waters and shallow circumstances that support spawning. The work by Hamilton and Murphy suggests that inattention to the importance of wetlands has contributed to the degraded status of native, pelagic fish in the Delta.

In summation, floodplains, wetlands, and riparian habitat provide valuable landscape features that are used by desired fishes for rearing, spawning, migration, dispersal, and refuge from predators. Physical improvements are needed to restore these features and the functions they provided.

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4 Changes in Temperature

Another ecosystem change that must be considered is temperature. Jassby (2008b) states,

> "Water temperature trends are of particular interest because the success of both desirable and undesirable species can be highly temperature-sensitive. For example, the nuisance cyanobacterium Microcystis aeruginosa, which has been spreading in the estuary since 1999, has a high optimum temperature over 25°C, depending on the strain (Nalewajko and Murphy 2001). In contrast, the endangered native delta smelt Hypomesus transpacificus appears to have a lethal limit near 25°C (Swanson et al. 2000)."

Jassby (2008b) did not find an overall long-term trend in the mean, minimum or maximum daily water temperature from 1983 to 2007. However, he did find significant monthly trends that ranged from -0.09 to 0.09°C y^{-1}, or more than 2°C over the 25-year period from 1983 to 2007, based on Theil-Sen slopes.

Climate change modeling suggests that water temperatures in the estuary will increase (Cloern et al. 2011; Wagner et al. 2011), although effects throughout the system may not be even (Wagner et al. 2011). A potentially serious effect on water temperature from climate change could be a decrease in the cold water pool of upstream reservoirs as the snowmelt contribution to runoff declines (Cloern et al. 2011). Areas experiencing thermal maxima at or above lethal ranges for native species, such as delta smelt, will increase.

Source of Temperature Changes

Water temperatures in the Bay-Delta are primarily driven by atmospheric influences (Kimmerer 2004; Cloern et al. 2011; Wagner et al. 2011; Jassby 2008a, b). On shorter timescales, flow can affect water temperature in the estuary during high flows that result from storm events (Wagner et al. 2011; Cloern et al. 2011); however, these high flow events occur during the cooler, winter-spring months when water temperatures are not reaching critical levels in the Bay-Delta. Thermal dispersion also influences water temperatures. Monismith et al. (2009) found effects of tidally driven thermal dispersion in the San Joaquin River near its confluence with the Sacramento River. Bathymetric features can also influence site-specific water temperatures by causing upwellings of deeper, cooler oceanic water. Schoellhamer (2001) has reported on the effect of several sills in and around Suisun Bay where gravitational circulation creates turbidity maxima.

Jassby (2008a) conducted a trend analysis and found,"[f]or both the Delta and Suisun Bay, the resulting negative Kendall's rank correlation between flow and temperature during 1996–2005 was not statistically significant: *tau* = -0.33 (p = 0.21) and *tau* = -0.022 (p = 0.99), respectively." Jassby (2008b) found similar results using temperature data on a shorter time step, stating, "[t]he significant water temperature trends, as one would expect, appear to be driven primarily by corresponding trends in air temperature." And, a model developed by Cloern et al. (2011) was able to predict water temperatures in the Delta using air temperature, insolation, and the previous day's water temperature with an r^2 of 0.964 for the verification period.

4.1 Biological Implications of Temperature Changes

Water temperatures provide an important constraint on ecological function. Examples include effects on fish spawning (Myrick and Cech 2011), swimming performance (Myrick and Cech 2000), metabolism (Myrick and Cech 2011), and mortality (Parker et al. 2011) as well as effects on aquatic invertebrates

(Vannote and Sweeney 1980). Specific examples of species of concern within the estuary that are sensitive to water temperatures at various points in the life cycles include salmonids (Myrick and Cech 2011), the Sacramento splittail (Moyle et al. 2004), and the delta smelt (Bennett 2005). Aquatic plants in tidal wetlands are also sensitive to water temperature (Parker et al. 2011). Temperature changes can alter wetland plant communities, causing changes in available carbon.

The biological implications of climate change effects on water temperatures may be profound. Winter-run Chinook salmon eggs develop in summer, when river temperatures reach their highest levels. Summer river temperatures are projected by Cloern et al. (2011) to reach lethal levels as a result of climate change. In fact, the study by Cloern et al. (2011) indicates an increasing risk of extinction of native species and increasing dominance of non-native species due to effects of climate change. MacNally et al. (2010) found lesser effects of warmer summer temperatures and duration of water temperatures during spawning. Wagner et al. (2011) verifies that climate change will increase the number of days above delta smelt's thermal maxima (especially along the Sacramento River) and a shift to earlier spawning.

Engineered solutions such as reservoir releases (which have been used for decades to provide temperature refugia for the salmonids in the upper stream reaches) would not be effective at controlling Delta temperatures during the warmer summer and fall seasons when cooler water in the Delta is most needed. There is already a delicate balance between providing sufficient cold water pool releases for each of the salmon runs and maintaining a large enough carryover pool for future dry years. And, as reported by Cloern et al. (2011), this cold water pool may diminish further with climate change. Unfortunately for Delta aquatic organisms, we have no control over atmospheric and oceanic influences, and reservoir releases are unable to affect Delta temperatures during the warmer summer and fall seasons when cooler water in the Delta is most needed. Thus future trends in temperature will need to be considered when considering options to improve conditions for desirable aquatic species.

In summation, water temperatures have warmed and will continue to warm. The number of areas experiencing temperatures above lethal ranges for native species is expected to increase. The biological implications of climate change effects on water temperatures may be profound, including increasing risk of extinction of native species and increasing dominance of nonnative species. Water temperatures in the Bay-Delta are primarily driven by atmospheric influences, although thermal dispersion also influences water temperatures, and bathymetric features can influence site-specific water temperatures. Reservoir releases will be unable to affect water temperatures in the Bay-Delta during the warmer summer and fall seasons when cooler water temperatures are most needed.

5 Changes in Turbidity

Another ecosystem change that must be considered is turbidity. Turbidity is a physical characteristic of water and is an expression of the optical property that causes light to be scattered and absorbed by particles and molecules rather than transmitted in straight lines through a water sample. It is caused by suspended matter or impurities that interfere with the clarity of the water. Constituents of turbidity may include clay, silt, finely divided inorganic and organic matter, soluble colored organic compounds, plankton and other microscopic organisms (USEPA 1999). Turbidity is one among many environmental variables that affect the quality of habitat for aquatic organisms. Monitoring by the DFG and IEP in the Bay-Delta over the past 35 years has documented trends of increased water clarity (Moyle and Bennett 2008), reduced turbidity (Schoellhamer 2011), and declines in chl-*a* (Jassby 2008a; Jassby et al. 2002; Kimmerer et al. 1994).

Water clarity, historically measured as Secchi disc depth (the depth to which a white disc lowered into the water is no longer visible), has been measured by the DFG and IEP several times a month at multiple stations for eight different programs for over 35 years. Moyle and Bennett (2008) documented a trend of increased water clarity between 1976 and 2008, coincident with the decline in delta smelt and striped bass (the POD) and increases in invasive species, including inland silverside and centrarchid species. Increasing water clarity has long been attributed to sediment retention behind dams and the proliferation of submerged aquatic vegetation.

Secchi depth data collected by the DFG and IEP has been compiled into a single data set and averaged by month and then by subregion as shown on Figure 31. As illustrated on these figures, water clarity has been increasing across most of the Delta over the past 35 years.

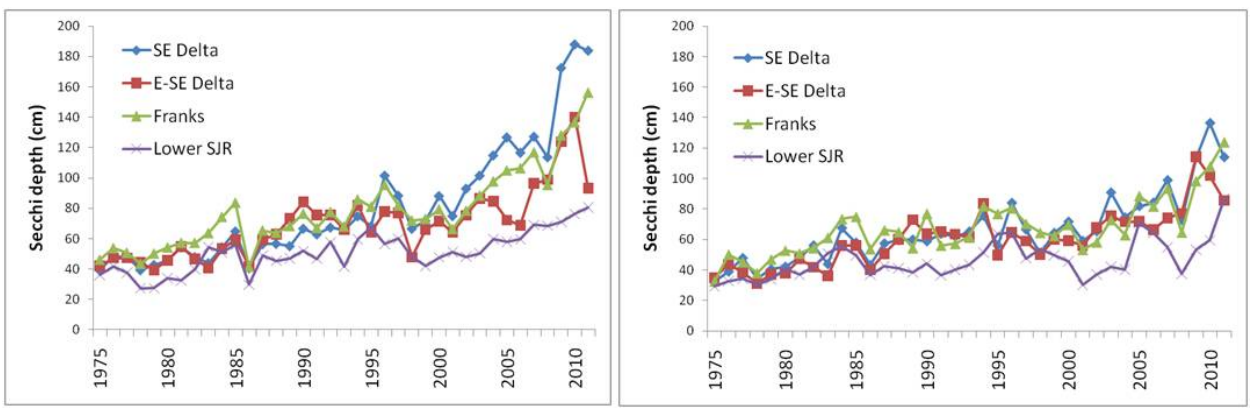

Figure 31. Average July-October (left panel) and March-June (right panel) Secchi depth in the South and Southeast Delta from 1975-2011, showing increasing clarity over the time course. (Data compiled from: Environmental Monitoring Program (conducted by DWR and USBR with assistance from DFG, USGS, and USFWS); Fall Midwater Trawl, Summer Townet Survey, 20-mm Survey, Kodiak Trawl, Monthly Zooplankton Survey, and Bay Study (conducted by DFG); Suisun Marsh Fisheries Monitoring (conducted by UC Davis).

Turbidity in the Bay-Delta has more recently undergone what has been characterized as a “significant step decrease” (Schoellhamer 2011). Turbidity, expressed as suspended sediment concentration (SSC), in the San Francisco Bay decreased by 36% between water years 1991-1998 to 1999-2007 (Schoellhamer 2011). This sudden clearing of the estuarine waters coincided with the decline in

abundance of the Delta's desired fishes. Schoellhamer (2011) postulated that the sudden drop in SSC during this period resulted from the depletion in the erodible pool of sediment that had been in the system until the documented step decrease. While sediment supply from the Sacramento River and other tributaries has declined as a result of bank protection, flood bypasses, the construction of dams and reservoirs and resultant trapping of sediment behind dams, and diminishment of sediment pulses from hydraulic mining (Schoellhamer et al. 2005; Wright and Schoellhamer 2004), the step decrease in SSC does not appear to be due to a sudden decrease in river-supplied sediment. The river supply of sediment to San Francisco Bay varies annually and decreased 1.3% per year during the latter half of the 20th century, which does not account for the sudden 36% decrease in suspended mass in 1999. The decrease in turbidity in the estuary is thought to have resulted from a shift from depositional to erosional processes in Suisun, San Pablo, and the Central Bays.

An increase in submerged aquatic vegetation (SAV), including the rapidly expanding *Egeria densa*, also contributes to increased water clarity (Kimmerer 2004). Anderson (1999) states, "In addition to negative impacts on wildlife, *Egeria* acts like a filter and accelerates deposition of suspended materials. Each year, hundreds of tons of organic and inorganic materials are carried downstream with seasonal snowmelt. In areas where *Egeria* has formed dense stands, the water is slowed and materials that are normally transported and spread throughout the Delta and upper Bay become entrapped and settle." Hestir et al. (2010) investigated the relationship between turbidity and SAV cover and found that SAV cover explains an estimated 21-70% of the trend of decreasing turbidity in the Bay-Delta.

Since plankton and other microscopic organisms are constituents of turbidity, the decline in turbidity may also be related to the decline in primary and secondary productivity described in Section 2.0, Major Changes to the Food Web.

While suspended sediment concentrations in the Bay-delta rise following significant rainfall, releases from upstream reservoirs are not an effective means of delivering suspended sediment to the Delta for the following reasons:

- Releases from reservoirs would not transport the sediment impounded behind dams into the rivers downstream of the dams because those sediments have been deposited to the bed of the reservoirs and the flow velocities in the reservoirs are too low to mobilize them.
- Water released from rim dams is very clear. The clear water released from the dams erodes downstream channels. Over time, the sediment transport capacity of the channel is reduced as the channel becomes incised and armored (Schoellhamer 2005). Vegetation encroachment along the channel may also reduce the sediment transport capacity of the channels downstream from dams.
- The Sacramento River is the major contributor of sediment to the Delta, delivering approximately seven times the sediment yield of the San Joaquin River (Oltmann et al. 1999). Wright and Schoellhamer (2004) estimated that during the period 1999-2002, 85% of the suspended sediment entering the Delta came from the Sacramento River (including the Yolo bypass), 13% came from the San Joaquin River and 2% was from eastside tributaries. The well-armored levees in the Delta prevent them from being significant sources of sediment.
- While the Sacramento River delivers much of the sediment transported into the Delta, most of that sediment is not transported into the Delta's network of channels. In a study of sediment budgets for the years 1999-2002, Wright and Schoellhamer (2004) estimated that at least 82% of the sediment entering the Delta from the Sacramento River watershed either deposited along the Sacramento River or moved past Mallard Island and into San Francisco Bay. They estimated that not more than 18% of the Sacramento River sediment moves towards the San Joaquin River. On

the San Joaquin River, there was a significant loss of sediment between Vernalis and Stockton (64% over the period 1999-2002), due to deposition in this reach or its entry into the south delta channel complex through Middle River (Wright and Schoellhamer 2004).

- Although Wright and Schoellhamer did not model sediment transport dynamics associated with reservoir releases, given the transport processes they describe for the Delta, one can infer from their study results that relatively little sediment transported by the Sacramento River from reservoir releases would move towards the San Joaquin River.
- The delivery of suspended-sediment from the Sacramento River has decreased by about one-half between 1957 and 2001 after the two major reservoirs in the watershed (Shasta and Folsom dams) were constructed (Wright and Schoellhamer 2004). This trend is likely caused by the depletion of erodible sediment from hydraulic mining in the late 1800s, reservoir sedimentation and bank protection. Increased releases from Sacramento River watershed reservoirs would not reverse these factors.

5.1 Biological Implications of Turbidity Changes

The changes in water clarity have significant implications for several Bay-Delta fish species, with particular significance for delta smelt. Clearer water with abundant submerged aquatic vegetation favors centrarchid fishes and is less desirable habitat for delta smelt (Moyle and Bennett 2008). Turbidity appears to be a critical factor for delta smelt larval feeding, providing better contrast between prey and their background, enabling larval predators to better locate their prey (Boehloert and Morgan 1985 in Lindberg et al. 2000). The physical components of “green” or turbid water rather than chemical properties of algal filtrate that contribute to turbidity appear to be important (Lindberg et al. 2000).

In laboratory experiments on feeding behavior of delta smelt larvae, Baskerville-Bridges et al. (2004) observed maximum feeding responses at the highest algal concentrations and light intensity, and relatively high prey density, supporting the conclusion that they are “…better able to forage under turbid conditions, which may also provide refuge from predators.” Baskerville-Bridges et al. (2003) found that larval delta smelt in culture were most effective at feeding in the highest light intensity and algal concentrations of the study. A second experiment showed that feeding responses were very low without algae present, but dramatically increased at high concentrations; and high rotifer (prey) density significantly enhanced feeding behaviors.

In considering ramifications of decreased SSC, Schoellhamer (2011) stated:

> “Reduced SSC may be one of several factors that have contributed to a collapse of several San Francisco Bay estuary fish species that occurred around 2000 (Sommer et al. 2007). Abundance of some fish species increases in more turbid waters (Feyrer et al. 2007). The population collapse has had the most serious consequences for delta smelt which require turbid water for successful feeding and predator avoidance. The relation between decreased SSC and fish decline, however, is not well established, and the concurrence of less SSC, more phytoplankton, and fewer fish merits additional study.”

Moyle (2002) describes the importance of turbidity for delta smelt: "…individual fish apparently hang out in the water column and rely on their small size and transparency to hide them from predators in turbid water. The fact that they are rarely found in the stomachs of such predatory fish as striped bass, white catfish, and black crappie, even when they are abundant is a good indication that this strategy is successful."

However, there are also biological benefits of reduced turbidity. Turbidity can lead to light limitation for primary producers. Several researchers have hypothesized that light penetration controls primary

productivity in the Bay-Delta (e.g., Cole and Cloern 1984; Kimmerer 2004). With decreasing turbidity, there is more light for phytoplankton. More light also potentially reaches the benthos where benthic primary productivity can also increase, providing another food source.

In summation, water clarity in the Bay-Delta estuary has increased over the past 35 years. This change has significant implications for several fish species, including delta smelt, as turbidity appears to be a critical factor for delta smelt larval feeding. With decreasing turbidity, more light penetration could increase primary productivity. Reservoirs on the major tributaries have reduced sediment input to the Bay-Delta and the sediment transport capacity of channels below these reservoirs decreases over time as the channels become incised and armored. While suspended sediment concentrations in the Bay-delta rise following significant rainfall, releases from upstream reservoirs are not an effective means of delivering suspended sediment to the Delta.

6 Changes in Through-Delta Flows

The final determinant of ecosystem change that has been proffered as important in the decline of the Delta's desired fishes is changes to through-Delta flows and the location of the low-salinity-zone. Enright and Culberson (2010) did an extensive review of trends in Delta outflow and salinity. They examined precipitation, outflow, and salinity trends before and after 1968 to discern outflow and salinity response to CVP and SWP operations (they also include analysis of pre- and post-Suisun Marsh salinity control gate operations, which began in 1988). They conclude that the data do not verify variability reduction; rather, annual and by-month salinity variability is generally greater in the post-project period: coefficients of variability for precipitation, outflow, and salinity increased after the projects were initiated. This increase suggests that more powerful mechanisms are at play including land-use changes and climate, which overpower the homogenizing influence of appropriations of water, including those by the CVP and SWP, when considering long-term trends.

A detailed analysis of historical outflow, including outflow as measured by the location of X2 over the period of record 1922–2011 and a description of some of the causes of identified changes in outflow over time will be submitted for the Analytical Tools for Evaluating Water Supply, Hydrodynamic and Hydropower Effects Workshop. Here, the paper describes the difference between "unimpaired flow" and "natural flow" as well as some of the uncertainties regarding application of a natural flow regime to a highly modified estuary such as the Bay-Delta estuary.

6.1 Difference between "Unimpaired" and "Natural" Flow

The 2010 Flow Criteria Report identifies a percentage of unimpaired flows as an approach to improving conditions in the Bay-Delta estuary. That approach fails to account for the fact that unimpaired flow is a calculation of a hypothetical condition that never existed in the Bay-Delta. This section describes "natural" Delta outflow during the predevelopment era. It shows that unimpaired flows are not natural flows. An extensive investigation of acreages of undeveloped native land cover and associated ET in the Bay-Delta estuary is under development and will be submitted during the Analytical Tools Workshop.

Natural flow approximates the flows under which native species evolved. Historic rim inflows flooded out of the original river channels into wetlands and floodplains that reduced the flood peaks and supported vast acreages of natural vegetation. Natural flow patterns did not approximate flows under the currently configured system, where outflow rushes through rock-lined channels surrounded by levees. Native species did not evolve in an environment with long-term, annual-average unimpaired outflow of 25 MAF/year.

The word "natural" connotes the Central Valley landscape in a predevelopment state. Under natural conditions, the Central Valley functioned as a series of natural reservoirs, located along the major river courses, rather than at the headwaters of the streams. These streamside reservoirs filled and drained every year. Dense tule marshes occupied these reservoirs and evapotranspired significant amounts of the water that flooded into them. The main river channels were lined by wide, naturally formed levees that were much larger and more developed along the Sacramento River than along the San Joaquin River (Hall 1880, Part II, p. 51). Lush riparian forests occupied these naturally occurring levees and uplands.

Under natural conditions, groundwater generally moved from recharge areas along the sides of the valley toward topographically lower areas in the central part of the valley, where it discharged primarily as ET from marshes and riparian forests (The Bay Institute 1998 ,Sec. IV.B.2; Bertoldi et al. 1991, pp. A17, A23, Fig. 14A; Williamson et al. 1989 p. D33; Davis 1959, p. 86). Groundwater was near the surface in much of the Valley (Bryan 1915, Plate 11 and p. 19; Kooser et al. 1861, p. 265). The USGS estimates that under

natural conditions, direct evapotranspiration from groundwater would occur in areas where the groundwater table was less than 10 feet below the surface. They estimated that under natural conditions, groundwater levels were less than 10 feet below the surface over about 62 percent or 8,000 square miles of the Central Valley (Williamson et al. 1989, p. D40). The groundwater system was in a state of dynamic equilibrium. Natural recharge was balanced by natural discharge. This balance has been recently confirmed for the San Joaquin Valley (excluding the Tulare Basin) using a physically based, surface-subsurface numerical model (HydroGeoSphere - see Bolger et al. 2011, pp. 322-330).

"Unimpaired" flows, on the other hand, are calculated flows that include various adjustments to remove consumptive use. Unimpaired flow is rim flow, delivered to the Bay-Delta through contemporary river channels, but without any reduction for storage or upstream use. Unimpaired flow is a measure of how much water is available for use, upstream of the reservoirs with current channel configurations.

Unimpaired outflow is greater than natural outflow. The State Water Board proposed essentially the same unimpaired flow approach in its 1987 Bay Delta Plan hearings. Testimony presented in those hearings, which is just as relevant today as it was then, led the DWR to conclude:

> *"Since unimpaired flow estimates assume present channel configurations and levee and flood bypass systems, they are not the same as natural flows (i.e., flows that occurred in a state of nature, before development). Natural flows through the Delta would probably be far smaller than unimpaired flows due to consumptive use by extensive natural marshes and riparian areas that were later leveed and reclaimed. Monthly distribution of flows would also be different"* (California Department of Water Resources (DWR) 1987, p. 10).

In those 1987 hearings, general agreement was reached with the DWR regarding the conclusion that natural outflow was likely lower than current outflow. Dr. Leopold, a member of the National Academy of Sciences, testified that he agreed with DWR's conclusion that natural flow would be lower than the estimates of unimpaired flow (1987 Bay Delta Plan Reporter's Transcripts, LVI, p. 60). Dr. Phyllis Fox (1987) presented extensive analysis on the distinction between natural and unimpaired flows, including in State Water Contractor Exhibits 260, 262, 276, 281, 351, 352, and 353 as well as indirect and rebuttal testimony. Dr. Horne, a Professor of Ecology in the Civil Engineering Department of the University of California at Berkeley, concurred and testified that he had made similar natural flow calculations.

6.2 Biological Functions of Natural Flows

As described above, unimpaired flows are not the same as natural flows. This section describes the scientific uncertainty associated with a restoration effort that is based on release or bypass of a percent of "natural" flow in a system like the Bay-Delta estuary, which as described above is a highly modified system.

The natural flow regime is a concept that evolved for riverine systems as a synthesis from the research and concepts of many earlier authors (Poff et al. 1997). Ecologists, geomorphologists, and other scientists studying rivers and streams recognized that human alteration of flows and physical changes to the environment within watersheds were contributors to ecological degradation, declines and extirpation of species, changes in channels, changes in sediment transport and supply, loss of riparian vegetation, declines in water quality and availability, and more frequent and intense flooding. However, while individual causes were recognized as affecting individual components of the rivers by many researchers, little analytical integration occurred due to the complexity and periodicity of flows.

The concept of the natural flow regime, as indicated by the five flow characteristics described by Richter et al. (1996) and Poff et al. (1997), magnitude, frequency, duration, timing (daily and seasonal), and rate

of change, represents maintenance of flow characteristics that have **implied** relationships to physical and ecological processes, but not **explicit** relationships. In fact, one of the concerns, expressed by Poff and Zimmerman (2010) and others is that the relationships between ecological processes and flow are not well understood and require further study.

Although the intent behind implementing a natural flow regime is to protect unaltered or largely unaltered systems, or to assist in conservation or restoration of altered systems, much of the literature surrounding the application of the natural flow regime paradigm addresses measures to restore ecosystem and physical processes in largely unaltered systems. Poff et al. (1997) asked and answered,

> *"Can reestablishing the natural flow regime serve as a useful management and restoration goal? We believe that it can, although to varying degrees,* ***depending on the present extent of human intervention and flow alteration affecting a particular river****"* [emphasis added].

Poff and Zimmerman (2010) reviewed 165 papers related to the natural flow regime. A narrative summary of the reported results strongly corroborated previous, less comprehensive, reviews by documenting strong and variable ecological responses to all types of flow alteration. Study results revealed some sensitivity of different ecological groups to alterations in flow magnitudes, but robust statistical relationships were not supported. The Poff and Zimmerman results revealed:

> *"Macroinvertebrates showed mixed responses to change in flow magnitude, with abundance and diversity both* ***increasing*** *and* ***decreasing*** *in response to elevated flows and to reduced flows. Fish abundance, diversity and demographic rates consistently declined in response to both* ***elevated*** *and* ***reduced*** *flow magnitude. Riparian vegetation metrics both* ***increased*** *and* ***decreased*** *in response to reduced peak flows, with increases reflecting mostly enhanced non-woody vegetative cover or encroachment into the stream channel."* (emphasis added).

Of the 165 papers, 92 percent concluded adverse response of ecological metrics to flow alterations, whereas 13 percent reported beneficial ecological metric responses. The authors state that their analyses did not support use of the existing literature to develop general, transferable quantitative relationships between flow alteration and ecological response. They did believe that the results support the inference that flow alteration is associated with ecological change and that the risk of ecological change increases with increasing magnitude of flow alteration. However, it is clear from the review that these ecological changes resulting from flow alteration include both adverse and beneficial outcomes to ecological metrics. The authors point out the need for careful monitoring, especially before and after flow alterations.

As Poff and Zimmerman (2010) explained, "Given that alteration of flow regimes is typically confounded with other environmental factors, we would not necessarily expect unambiguous relationships between single measures of flow alteration and ecological response." These confounding relationships have also been observed by other researchers. Bunn and Arthington (2002) describe the uncertainties associated with attempting to restore "natural" flow to promote ecological restoration.

> *"In writing this review, we often encountered reports of river systems affected by multiple stressors and were unable to definitely separate the impacts of altered flow regimes from those of the myriad of other factors and interactions. How much of an observed decline in species diversity can be attributed directly to modified flow compared with diffuse inputs of nutrients and other contaminants? A similar problem occurs in our attempt to unravel the cause and effect of exotic species on aquatic diversity. Is an observed decline in native fish species the result of a modified flow regime or direct impact of an introduced*

> *species (or both)? Alternatively, is the proliferation of exotic species a direct response to the modified flow or the decline in native species (or both)? Ecological science is not yet able to answer these questions, important as they are.*
>
> *Ecologists still have much to learn about the ecological significance of individual flow events and sequences of events, and descriptive science can take us only so far in unraveling these linkages. The advice from aquatic ecologists on environmental flows might be regarded at this point in time* ***as largely untested hypotheses about the flows that aquatic organisms need and how rivers function in relation to flow regime****"*[emphasis added].

In largely unaltered river systems, the importance of flow in sustaining biodiversity and ecological integrity is well established (Poff et al. 1997; Hart and Finelli 1999; Bunn and Arthington 2002; Poff and Zimmerman 2010). However, establishing an appropriate flow regime for an estuary is not as simple (Pierson et al. 2002). Within an estuary, freshwater inflow mixes with seawater through physical mechanisms of density gradients, gravitational circulation, tidal action, and wind energy, creating variable brackish conditions for a variety of species during all or a part of their life cycles. Complex ecological and biological processes occur within estuaries, primarily due to their dynamic nature, complex freshwater-seawater mixing processes, random influences, antecedent conditions, and complex ecological linkages. Key differences between riverine and estuarine systems are summarized in Pierson et al. (2002) and presented in Table 2.

Table 2. Key Relevant Differences between Fluvial and Estuarine Systems (Source: Pierson et al. 2002)

Characteristic	Rivers	Estuaries
1. Flow Direction	Unidirectional	Reversing
2. Depth determined in	Flow	Primarily tides
3. Flow cross section determined by	Sedimentary regime	Sedimentary regime, flocculation, littoral drift
4. Water masses	Fresh only	Fresh and salt
5. Pollutant flushing	Rainfall runoff	Rainfall runoff and tidal flows
6. Water Quality changes	Downstream of source	Both upstream and downstream of source
7. Antecedent effects in relation to physical and chemical character	Moderate	Potentially very important
8. Biota	Limited diversity	More diverse
9. Ecological interactions	Less complicated	Much more complicated
10. Size of literature pertinent to environmental flows	Large	Small
11. Understanding of environmental flow effects	Limited	Very limited

Mechanisms through which freshwater flow contributes to desired characteristics in a largely unaltered system are summarized below by Pierson et al. (2002), followed by a discussion of how these mechanisms would respond in the highly altered Bay-Delta estuary.

- Freshwater inflow influences the volume and distribution of brackish water: the variability in freshwater inflow influences the variability in brackish water both longitudinally and vertically, and within and between years.

In a largely unaltered system, brackish water variability affects the distribution of estuarine organisms (plants, invertebrates, and vertebrates), triggers changes in their behavior such as daily, seasonal, or interannual spatial distribution or movements within the estuary, positioning within the water column, or reproductive behavior (spatial distribution of suitable spawning and/or rearing habitat conditions, mates), and affects their ability to forage by changing the daily, seasonal, and interannual distribution of nutrients and/or food organisms.

In the highly altered Bay-Delta, the efficacy of freshwater inflow to contribute to these characteristics is reduced due to changes in the volume and variability based not only on human water demands, but current regulations for protected species. Human water demands reduce the volume of freshwater inflow on an annual basis, and change the in-season hydrograph for agriculture and urban use. Layered on that are the regulations for protected species.

California native fishes evolved in a complex and dynamic environment, thereby promoting a competitive advantage over non-native species. Richness of the fauna has been shown to increase as habitat complexity increases (Bunn and Arthington 2002). In the highly altered Bay-Delta this function cannot be restored with reservoir releases. Varying flows in leveed, riprapped channels will not increase the complexity of species habitat, nor will it cause the hydrodynamics to be more dynamic at a variety of spatial scales. ***However, the BDCP can restore this flow function through habitat restoration that includes strategic levee breaches and tidal marsh restoration. This flow function will be discussed in greater detail in the submittals for the pelagic and salmonid workshops.***

- Freshwater inflow provides nutrient enrichment[11]: in an estuary, enrichment mechanisms include (1) bulk transport of river nutrients (both soluble and particulate), (2) resuspension of nutrients within the estuary through gravitational circulation, and (3) enhanced dispersion of nutrients down the estuary due to salinity stratification. The nutrient enrichment of estuaries from freshwater inflow makes them some of the most productive aquatic ecosystems (Pierson et al. 2002).

In the highly altered Sacramento-San Joaquin River watersheds, transport of river nutrients is diminished due to diking of floodplain habitat, removal of riparian habitat, and channelizing, deepening, and widening of waterways for flood control, navigation, and agricultural and urban land reclamation.

Similarly, within the highly altered Bay-Delta, nutrient input is diminished due to diking of tidal perennial aquatic habitat, tidal mudflats, tidal marsh, floodplain and seasonal wetlands and riparian habitats, and channelizing, deepening, and widening of estuarine waterways for flood control, navigation, and agricultural and urban land reclamation.

The nutrient enrichment function of river flows has not been corroborated by phytoplankton and zooplankton production in the Bay-Delta as previously described in Section 2. In the waters of the Bay-Delta, analyses that have relied primarily on biomass measurements have shown weak effects of freshwater flow on primary and secondary production (Kimmerer 2002a; Kimmerer et al. 2009). In a recent study, Kimmerer et al. (2012) were the first to examine the response of primary productivity within the San Francisco Estuary across a wide range of freshwater flows during the spring-summer period of 2006–2007. They found that temporal and spatial variability in production was small. When they combined and compared data from 2006–2007 with long-term monitoring data, they did not

[11] It should be noted that nutrient enrichment in this context refers to both soluble and particulate nutrients, including nutrients bound in primary and secondary productivity, nutrients in detrital material and microbial nutrients.

discern patterns in production and biomass, even though time and salinity levels were variable. More importantly, they found that primary production within the low-salinity zone was unresponsive to variation in freshwater flow, in contrast to findings in other estuaries (Kimmerer et al. 2012).

The lack of response in primary productivity relative to freshwater flow observed by Kimmerer et al. (2012) contrasts with results from other systems and emphasizes the need to carefully consider the physical, chemical, and biological attributes of estuaries, and the Bay-Delta in particular, which influence how freshwater flow affects their food webs and subsequently higher-trophic-level organisms.

- Freshwater inflow transports depositional material: depositional material is transported in an estuary through the same three mechanisms described above: bulk transport, resuspension, and longitudinal transport. Depositional material is important to the maintenance of tidal perennial aquatic areas, tidal mudflats, tidal marsh, floodplain and seasonal wetlands, and riparian areas through the seasonal and spatial distribution of sediment deposition and/or erosion (Collier et al. 1997; Poff et al. 1997; Flannery et al. 2002). These landscape cover types are very productive and diverse, providing food and protection to many species of plants and animals.

In the highly altered Bay-Delta, sediment transport from rivers is reduced and/or altered due to dam emplacement and channel hardening. In addition, the function of deposition is reduced by alterations in the estuary that disconnect the rivers from the landscapes dependent on the deposition. This function cannot be restored with reservoir releases. Unlike natural rain events, reservoir releases do not wash sediment down from the upper watersheds and into the Delta and they do not overflow levees into tidal and wetland areas needing the sediment. Compounding altered sediment dynamics, decreased sediment loads may increase erosion in the Bay-Delta and contribute to remobilization of buried contaminants (McKee et al. 2006). Estimates of sediment inputs to the San Francisco Estuary indicate a shifting equilibrium dynamic. Spanning years 1957 through 2001, Wright and Schoellhamer (2004) show that the delivery of suspended sediment from the Sacramento River to San Francisco Bay has decreased by approximately one-half. The Sacramento River is considered the primary source of new sediment input into the estuary, and delivers approximately 7 times the sediment yield of the San Joaquin River (Wright and Schoellhamer 2004). See Section 5 for more discussion on turbidity.

Deposition is reduced by alterations in the estuary including diking of tidal perennial aquatic habitat, tidal mudflats, tidal marsh, floodplain and seasonal wetlands and riparian habitats, and channelizing, deepening, and widening of estuarine waterways for flood control, navigation, and agricultural and urban land reclamation. Tidal marshes have been diked and drained to create farmland, evaporation ponds for salt, and residential and industrial land. Such land reclamations were largely complete by the end of the 1920s. Today, approximately 125 square kilometers of the original 2,200 square kilometers of tidal marsh remains in the estuary (Nichols et al. 1986). Throughout the estuary, overall, an estimated 79 percent of historic tideland marshes have been lost to diking and development (Goals Project 1999). Historical land reclamation is evident today; the Delta is comprised of around 70 island tracts, surrounded by 1,100 miles of levees and 700 miles of interspersed waterways. Over the subsequent decades, decomposition of exposed peat soils resulted in profound subsidence of reclaimed land with most of the Delta now below sea level and a large portion of the western and central Delta at least 15 to 25 feet below sea level (USGS 2008).

- Freshwater inflow inundates seasonal floodplain and wetland and riparian habitats: Floodplain habitats and seasonal wetlands offer a variety of relatively shallow water habitats, some with submerged vegetation. Riparian habitat within an unaltered estuary includes all successional stages of woody riparian vegetation and provides important cover in the form of shaded riverine habitat. Floodplain habitats are particularly important to the growth of important migratory fish species such as juvenile salmon. (Pierson et al. 2002).

In the highly altered Bay-Delta and upper watershed, the combination of dam construction, channel deepening and widening, land reclamation, and levee building reduce the frequency, magnitude, and duration of inundation of floodplains and seasonal wetlands. Those functions cannot be restored with reservoir releases. Physical intervention is needed to alter the landscape to restore this connection. However, the BDCP can restore this flow function through modifications to the landscape and changes to water control structures, like notching the Fremont Weir, to extend periods of flooding in the Yolo-Bypass. See Section 2.3.6.1 for more discussion of floodplains.

- Freshwater inflow promotes native vegetation cover and composition, and leaf litter deposition and decomposition: In an unaltered system, water table depth and periodic natural flooding promotes vegetation growth (Rood et al. 1995; Molles et al. 1995). In the highly altered Bay-Delta this function cannot be restored with reservoir releases. Most of the large rivers are largely bordered by rock-lined levees. The levees would have to be set back and the riprap removed before riparian vegetation could propagate. However, the BDCP can restore this flow function through levee modification and habitat restoration.
- Freshwater inflow contributes to turbidity: In a largely unaltered system, freshwater inflow contributes to turbidity in an estuary through bulk transport, resuspension, and longitudinal transport of sediments and depositional material. A secondary mechanism to increase turbidity is through the effect of freshwater inflow on nutrient enrichment and phytoplankton production. In addition to providing depositional material, turbidity enhances the ability of many prey organisms to avoid predation. As previously described, these functions are diminished in the highly altered Bay-Delta and cannot be restored with reservoir releases. See Section 5 for further discussion on turbidity.
- Freshwater inflow facilitates suspension, dispersion, and transport of eggs and larvae: In an unaltered system, freshwater inflow contributes to suspension, dispersion, and transport of eggs and larvae through recirculation, seasonal variability in freshwater inflow, and longitudinal transport. Suspension prevents eggs and larvae from anoxic conditions, typically found in the sediments. Dispersion and transport of eggs and larvae may be necessary for semidiadromous species (Pierson et al. 2002).

In the highly altered Bay-Delta, the efficacy of freshwater flow to contribute to dispersion and distribution of eggs and larvae is also affected by the significant landscape modifications. This flow function will be discussed in greater detail in the submittals for the pelagic and salmonid workshops.

- Freshwater inflow provides migration cues: Anadromous salmonids use freshwater cues to return to their natal spawning grounds. Other diadromous or semidiadromous species use freshwater cues to disperse or migrate. In the highly altered Bay-Delta, changes in the magnitude and timing of freshwater inflow may affect the ability of salmonids to find their natal spawning grounds. Existing regulations attempt to rectify this situation. However, the efficacy of freshwater inflow to cue salmonid migration to natal streams is diminished due to other mitigating factors including dam blockage, hatchery practices, and contaminants. Dams block most salmonids from reaching all or part of their natal spawning grounds, hatchery practices have accelerated straying rates, and contaminants affect salmon olfactory senses. This flow function will be discussed in greater detail in the submittals for the pelagic and salmonid workshops.

The organisms that occur in California rivers and streams are the evolutionary result of physical, chemical and biological characteristics of the regional environment that have been shaped by the sequential, predictable, seasonal flooding, and extended base flows that occur over each annual cycle. California's hydrological patterns are the result of its Mediterranean climate (Gasith and Resh 1999; Bonada et al. 2008), which differs markedly from other locations discussed in the literature regarding the results of restoring natural flows. The adaptation of the resident organisms to the conditions of wet season high

flows and dry season low flows, whether they were stable or continuing to decrease until the onset of rains in autumn, influences organism response to departures from this Mediterranean hydrologic pattern.

In the 2010 Flow Criteria Report, the State Water Board proposed a percent of unimpaired flow approach only for the months January through June (State Water Board 2010, p. 96.) and, subsequently, contradicts the approach by seeking to artificially maintain high outflow during the reminder of the year, during the dry season, when historically Delta inflows would be lower. By doing so, the 2010 Flow Criteria Report proposes an unimpaired flow approach that increases outflow, year-round, without regard for natural interannual flow patterns.

Implementation of the natural flow regime in California has generally involved partial application of the concepts for the purpose of achieving specific ecological goals (Cain et al. 2003; Brown and Bauer 2009; Kiernan and Moyle 2010). They have included combinations of minimum instream flows for habitat for various life stages, passage flows, flows for channel maintenance, flows for riparian vegetation maintenance, and more rarely channel-forming flows. However, while the steps of assessing the natural flow regime have taken place in those proceedings, the information was primarily used to negotiate flows that would have specific ecological benefits, rather than for a broad implementation of a natural flow regime absent identification of specific desired outcomes as is currently contemplated by the 2010 Flow Criteria Report.

In general, in the literature, the function that is being targeted is clearly articulated and the specific ecological benefit is identified. Rather than targeting a general goal like “fish abundance” as was done in the 2010 Flow Criteria Report, in most cases the mechanism or function of flow is identified and flows are set to target the function. This is particularly important in the Bay-Delta estuary where there are relatively few intact remnants of the natural Bay-Delta environment. There have been some limited scientific investigations that estimate historic or “natural” conditions of the Bay-Delta, prior to land reclamation, dam construction, and river dredging and straightening. As described above in Section 6.2, several prior analyses indicate that flows in the historic undeveloped environment were lower, likely substantially, than the unimpaired flows described in the 2010 Flow Criteria Report..Many of the general functions that have been targeted in other ecosystems, and in the literature, cannot be achieved in the highly altered Bay-Delta with reservoir releases.

There is little scientific support for application of a natural flow regime, as it is currently proposed, to the highly modified Bay-Delta. Alternate actions, with a lower degree of uncertainty are supported by the science and by the literature. Based on (1) the non-explicit nature of the natural flow regime, (2) natural flow regime has only been partially implemented in highly modified systems, and (3) the uncertainty of success where it has been implemented, little scientific support exists for application of a natural flow regime, as it currently exists, to the highly modified Bay-Delta. Therefore, it is necessary for the State Water Board to consider regulations that address nonflow factors, specifically nutrient pollutants, other toxicants, habitat restoration, and invasive species to enhance the efficacy of flow on ecosystem functions prior to modifying current flow regulations.

7 Conclusions

The physical landscape of the Bay-Delta bears little resemblance to the system that existed more than 160 years ago; a system tha cannot feasibly be fully restored.

The ecosystem will continue to change and evolve. However, without intervention, the decline of certain species, such as the native salmonids and smelt will continue, or even accelerate. Local intervention to date has not worked. Science does not support increasing inflow or outflow as a way to improve the health of the ecosystem. No causal link between flow and fish abundance has been identified, and there is insufficient evidence to rely on increased flow as a tool to increase fish abundance.

Contrary to flow, the scientific literature is clear; the ecosystem's food web has changed substantially, including decreases in primary and secondary productivity and abundance of native fish species. The literature is equally clear that those adverse changes have been driven by nutrients, invasive species, changes in the land-water interface, and potentially contaminants. Each of these can be addressed by water quality objectives in the Bay-Delta plan and the associated implementation actions by the State Water Board and other agencies.

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8 References

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