Public Workshop (10/1-2/12)
Bay-Delta Workshop 2
Deadline: 9/14/12 by 12 noon

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The Delta Ecosystem as a Dynamic System, Water Supply Assumptions in Water Rights Decisions 990 and 1275, Summer and Early Fall Delta Flows, and Climate Change Impacts on the Delta

Comments for Second State Water Resources Control Board Workshop
Bay-Delta Fisheries Resources

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Friday/9/14/12

The Delta Ecosystem as a Dynamic System

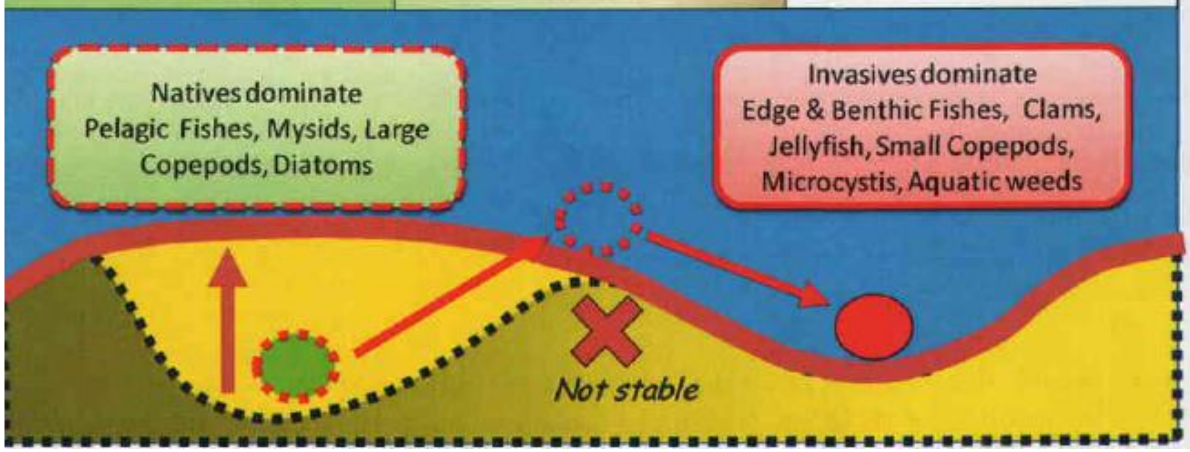
The State Water Resources Control Board is faced with the task of revising the Bay Delta Plan after the Pelagic Organism Decline and the collapse of populations of many native fish species which were formerly abundant in the estuary. It is clear that these populations are on the edge of extinction. The current proposal by federal and state agencies is to use adaptive management to set flow critiera to protect the public trust, including decision trees and further ecosystem studies.

However, it must be understood that this approach to use adaptive management to set flow criteria is not new. In essence, prior decisions by the State Water Resources Control Board (originally the State Water Rights Board) resolved conflicts about water supply for diversions by the state and federal water projects by approving the requested maximum diversions and setting limits related to salinity and fisheries resources, requiring monitoring, suggesting further studies, and retaining continuing jurisdiction. This has effectively been a five decade long adaptive management program.

Unfortunately, the criteria used for adaptive management of ecosystem flows have not been sufficiently protective of the Delta estuary or of San Francisco Bay. The result has been a decades long decline and collapse of native species of fish in the Delta, and a substantial decline in fish populations in the Bay. In the 1980s, the concerns were that populations of pelagic species of fish in the Delta had been reduced by 70%. By the 1990s, the concern was that some formerly abundant species had been pushed to the brink of extinction. In the 2000s, the concern was that populations of many species of fish in the Delta, that had formerly occupied a huge range of ecological niches, all collapsed simultaneously.

It is clear that the Delta ecosystem is far into a new regime. (See diagram below by Randy Baxter.)

Old Regime	Environmental Drivers	New Regime
Variable, High	Outflow	*Variable, Lower*
To the west, Variable	Salinity gradient	*To the east, Constricted*
Complex, Variable	Landscape	*Simplified, Rigid*
Low, Variable	Temperature	*High, Uniform*
High, Variable	Turbidity	*Low, Less variable*
High P, low N	Nutrients	*Low P, High N (NH_4+)*
Few, Low	Contaminants	*Many, High*
Predation, Fishing	"Harvest"	*Predation and Entrainment*



Regime shift model from Baxter, 2010, as reproduced in "Adaptive Management for Fall Outflow for Delta Smelt Protection and Water Supply Reliability", USBR 2011. Original Caption: "The ecological regime shift in the Delta results from changes in (slow) environmental drivers that lead to profoundly altered biological communities and, as soon as an unstable threshold region is passed a, new relatively stable ecosystem regime."

Over the long term, native species are declining or vanishing and invasive species are increasing at all levels, and the total biomass, both of the Delta and of San Francisco Bay ecosystems, is down significantly. For this reason, any ruling by the State Water Resources Control Board on adaptive management of water exports needs to explicitly consider the issue of ecosystem regimes and long term ecosystem stability. There also needs to be explicit consideration of upper limits on exports of unstored water needed to keep healthy populations of native fish.

In particular, the current permits for the State Water Project and Central Valley Project allow exports of very large amounts of unstored water from the Sacramento River and the Delta. The right to export this water is junior to the needs of the areas of origin. Therefore it needs to be subject to limits which are sufficiently protective of area of origin beneficial uses, including both fishery needs and local water quality needs.

For fishery needs, the public trust requires a management scheme where populations of aquatic species at different trophic levels are maintained within reasonably stable ranges. In addition, the target median population size for all species needs to be sufficiently large for the population to survive forseeable natural events. California has a huge natural variation in precipitation and runoff, that produces large natural variations in populations of aquatic species, and creates huge stresses during dry and critically dry years. Climate change is likely to increase these stresses in a myriad of ways, including reduction in runoff and an increasing frequency of dry and critically dry years, increased water and air temperatures, and changes in ocean conditions.

For this reason, the State Water Resources Control Board must significantly constrain exports of unstored water. Over the long run, it is simply not possible to adaptively manage populations of fish in an extinction spiral. To protect the public trust, the State Water Resources Control Board needs to set a range of exports of unstored water where the center of the range leaves enough water in the estuary to sustain robust, healthy populations of native fish, as well as to maintain water quality in the face of existing streams of contaminants.

Water Supply Assumptions in State Water Rights Board Decisions 990 and 1275

One of the key issues with the original permitting decisions by the State Water Rights Board was the lack of knowledge of hydrology and ecosystem needs. But even within that limited understanding , it became clear in the hearings for Decision 990 in 1959 and 1960 that there were significant conflicts between the assumed water supplies for the U.S. Bureau of Reclamation's applications for diversions from the Sacramento River and Delta, and the application of the California Department of Water Resources for diversions in the Delta.

In particular, at the November, 1959 hearing, became clear that the Bureau of Reclamation water supply study for the Central Valley Project diversions included the "entire flow of the Feather River" (Decision 990, p. 58). The hearing was recessed at the request of the state's attorney. During the following months. The Department of Water Resources and the Bureau of Reclamation worked out the first Coordinated Operating Agreement. In Article 12, the parties agreed to divide unappropriated water in the Delta in the ratio of basis of total diversions under applications permits, which were then 8,300,000 acre feet per year for the Bureau, to 5,260,000 acre feet per year for the Department of Water Resources, and to similarly allocate any shortages.[1] The Board decided that this was sufficient to issue the permits for the Bureau of Reclamation diversions.

The Board did note that "the variances between the Bureau's Central Valley Project and the Department's Feather River Project of 1951 and the plans presented at the hearing, involving no more water than was available in 1951 (except for the Trinity River diversion) poses a problem that cannot be solved by the Board. All it can do is maintain continuing jurisdiction until the Department receives its permits for the

[1] State Water Board, Decision 990, p. 59 Available at http://www.waterboards.ca.gov/waterrights/board_decisions/adopted_orders/decisions/d0950_d0999/wrd990.pdf

State Water Plan and has arrived at an operational agreement with the Bureau as proposed in the testimony of the Director of the Department."[2]

There were also issues in that no explicit reservation was made for the needs of water users in the Delta. The end result was that the permits which were approved for the Bureau of Reclamation relied on water supplies that were double-counted, and allowed export of water needed for the areas of origin.

These problems were further exacerbated by Decision 1275 in 1967, when the permits were issued for the California Department of Water Resources diversions in the Delta. A joint water rights investigation by the Bureau of Reclamation and the Department of Water Resources showed that there was likely too little water in the Delta for the State Water Project to divert any more water than the yield of Oroville reservoir. The Department of Water Resources produced studies showing that with an extra 900,000 af/year of water from the proposed Dos Rios Dam on the Eel River to supplement flows in the Sacramento River, that there would be enough water for the proposed diversions. The State Water Resources Board granted the diversion permit in the Delta based on these studies.

As we all know, by 1967, the construction of the proposed dam on the Eel River had become hugely controversial. In 1968, Governor Reagan intervened to mandate the development of alternatives. In 1972, the state legislature designated the Eel River as a Wild and Scenic River, as well as portions of the Klamath, Smith, and Trinity rivers. The Eel and undeveloped portions of the Trinity Rivers were designated federal Wild and Scenic Rivers in 1981.

The end result was that the upstream water supply for the permits issued by the SWRB for diversions in the Sacramento River and Delta was been short by millions of acre feet per year for the last five decades. As a result, there has been increasing reliance on export of unstored flows in the Delta, which has been very detrimental to fish populations.

State Water Rights Boards Decisions about availability of unstored water for export in summer and early fall

Decision 990 also explicitly considered the availability of water for export in the summer and early fall. The Bureau of Reclamation, the Department of Water Resources, and the Sacramento River and Delta Water Association produced studies of the existing diversions along the river. Page 28 of D990 describes the studies:

> In an effort to reach an agreement on existing water rights along the Sacramento River and in the Delta, the Bureau, the Department and the Sacramento River and Delta Water Association (hereinafter referred to as Association) entered into a cooperative study program. For the purposes of the these studies the engineers for each agency agreed upon certain assumptions with respect to hydrologic conditions and water rights. The final report acknowledged these assumptions, particularly with respect to water rights, may differ considerably from the rights as may be determined by a court of law. The results of these studies are presented in "Report on 1956 Cooperative Study Program" (USBR 107)

The study is referenced with respect to diversions:

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[2] Ibid., p. 62

> With respect to the availability of water along the Sacramento River from Shasta Dam to the Delta and in the channels of the Delta, Study C-2BR indicates that no water is available during August and only infrequently available during July. Study C-650D indicates that September is also a month of questionable supply (USBR 139 and SRDWA 39).

This was true even though the studies relied on methods of estimating pre-existing diversions that were fairly incomplete, as well as completely outdated assumptions about needed Delta outflows. The studies assumed minimum Delta outflows of only 3,300 cfs in all months, and some of them assumed minimum Delta outflows of only 2,000 cfs.

D990 states that other evidence was presented by the Bureau of Reclamation and the Department of Water Resources about return flows:

> However, the Bureau presented evidence that because of return flows from applied Project water, there will be unappropriated water available in various reaches of the River below Keswick Dam and in the Delta year-round. This evidence is corroborated by testimony submitted by the Department (RT 10928-30).

This newly presented evidence likely double-counted the return flows, since the original 1956 Cooperative Study Program report included generous estimations of return flows in its calculations of water available for diversions. However, the State Water Rights Board allowed these estimates:

> There is no doubt that Project water applied to lands which drain into channels tributary to the Delta will provide additional return flows, but the quantities cannot be predicted with any degree of accuracy (RT 10972-75). Return flows from applied Project water will enter the Sacramento River at various points below Keswick Dam (USBR 164). It appears proper, therefore, to allow a year-round direct diversion season at points below Shasta Dam as requested by the Bureau.

But the Board continued:

> Any necessary reduction in the season can be made at the time of licensing when the project is fully developed and the extent of return flow can be more accurately determined.

Tables B through E, reproduced at the end of this report, show an average of the amounts available in study C-2BR and study C-650D, for pre-1927 appropriative and other rights, for pre-1938 appropriative and other rights, and for pre-1954&1955 appropriative and other rights.

The table below is produced from the averages for pre-1938 and other rights. It averages amounts available in Wet, Above Normal, Below Normal, Dry and Critically Dry years. It shows water available in July only in wet years, in August in no years, and very little available in September.

Year Type	Months of diversion							
	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
Wet	4435	3914	2396	396	5	119	338	11603
AN	3644	1741	392	0	0	101	280	6157
BN	3003	2586	1262	8	0	74	296	7229
Dry	1795	1249	434	25	0	32	195	3730
Critical	562	355	200	0	0	9	92	1218

Decision 1275, approved by the Board in 1967, originally excluded July, August, and September from the allowed season of diversion for the State Water Project. Decision D1291 discusses the reasons:

> Decision D 1275 excluded July, August, and September from the authorized seasons of diversion from the Delta. The reason for excluding these months, discussed in the decision beginning on page 26, was that the studies introduced by the Department at the hearing (Exh. 72 and related exhibits) showed that unappropriated water would have been available in the Delta during these months in only a few years during the 30-year period of study and then only in small quantities.
>
> The Department contended in its petition that greater quantities of unappropriated water than were indicated by its previous studies will be available in the Delta for several years because the actual in-basin use of water will be less than the assumed in-basin rights due to the fact that some rights are still in a development period and all in-basin rights will not be utilized simultaneously at maximum rates.
>
> The Department's exhibits and testimony demonstrated that for several years substantial quantities of unappropriated water will probably occur in the Delta during July, August, and September that were not indicated by the evidence which was the basis for deleting these months from the seasons of diversion in Decision D 1275.

The Department of Water Resources produced the following table of water available for export in five of the 15 years between 1952 and 1967.

	July	August	September
1952	985	296	441
1956	410	250	568
1958	632	411	693
1965	252	340	606
1967	1,358		

These numbers were based on new assumptions about consumptive use in the Delta which were never checked. The State Water Board decision only stated that, "the magnitude of the quantities assures that there will be substantial water available in the Delta with an average frequency of one year in three even if the assumptions are in error by relatively large percentages."

On the basis of this rather speculative math, the State Water Rights Board allowed diversions of unstored water by DWR during the months of July, August, and September, as well as the U.S. Bureau of Reclamation.

We now have a much better knowledge of hydrology in the Delta, and there are sophisticated computer models of Delta flows. These numbers have never been compared with numbers from Dayflow, and should be.

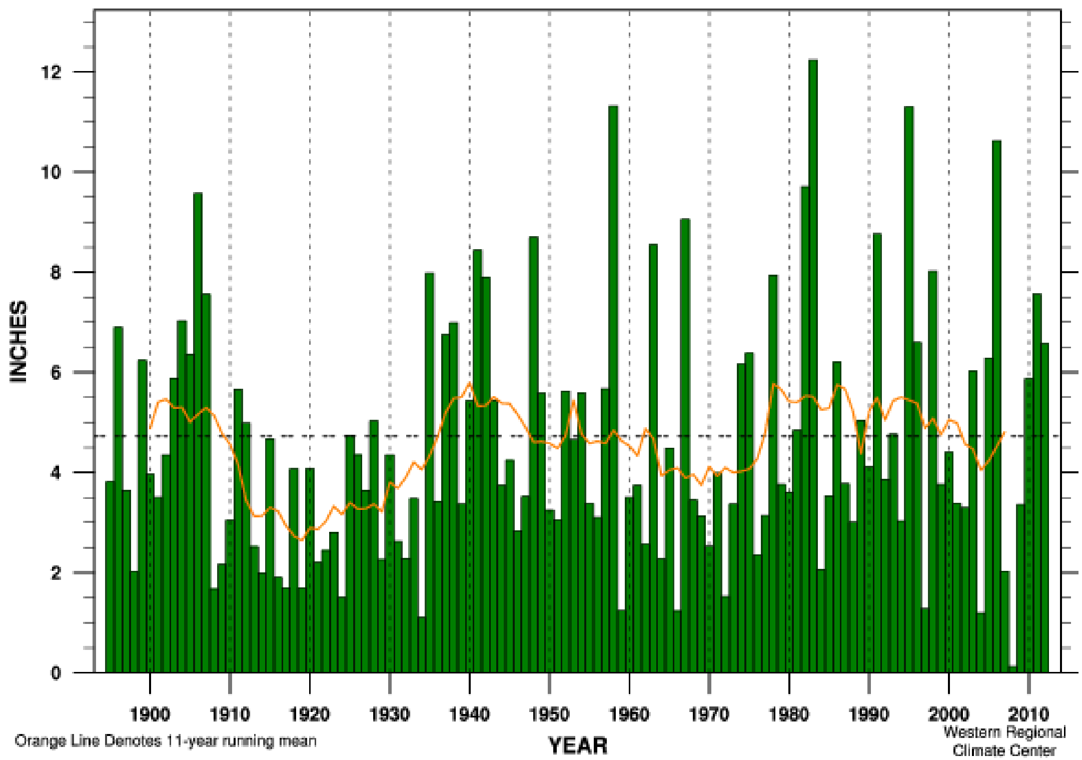
Shifts in Precipitation in Delta Watersheds

The charts below, from the Western Regional Climate Center, show shifts in precipitation in the Sacramento-Delta region. From 1975 to the present, there is a reduction in precipitation in the spring and fall, and an increase in the winter. As noted by Killam and Bui et. al., examination of regional data shows similar seasonal trends throught the state, including the Sierras [3],[4] The decreases in precipitation and shifts in runoff exacerbate impacts of water diversions by reducing Delta inflows and outflows in the spring, summer, and fall.

[3] Killam, D., A. Bui, S. LaDochy, P. Ramirez, W. Patzert and J. Willis. 2011. Precipitation trends in California: Northern and central regions wetter, southern regions drier. Unpublished. Cited in Temperature and precipitation trends in California: Global warming and Pacific Ocean influences, LaDochy and Ramirez et. al. (See reference 20.)

[4] Regional precipitation data with linear trends also available from Western Regional Climate Center, California Climate Tracker. Available at http://www.wrcc.dri.edu/monitor/cal-mon/frames_version.html

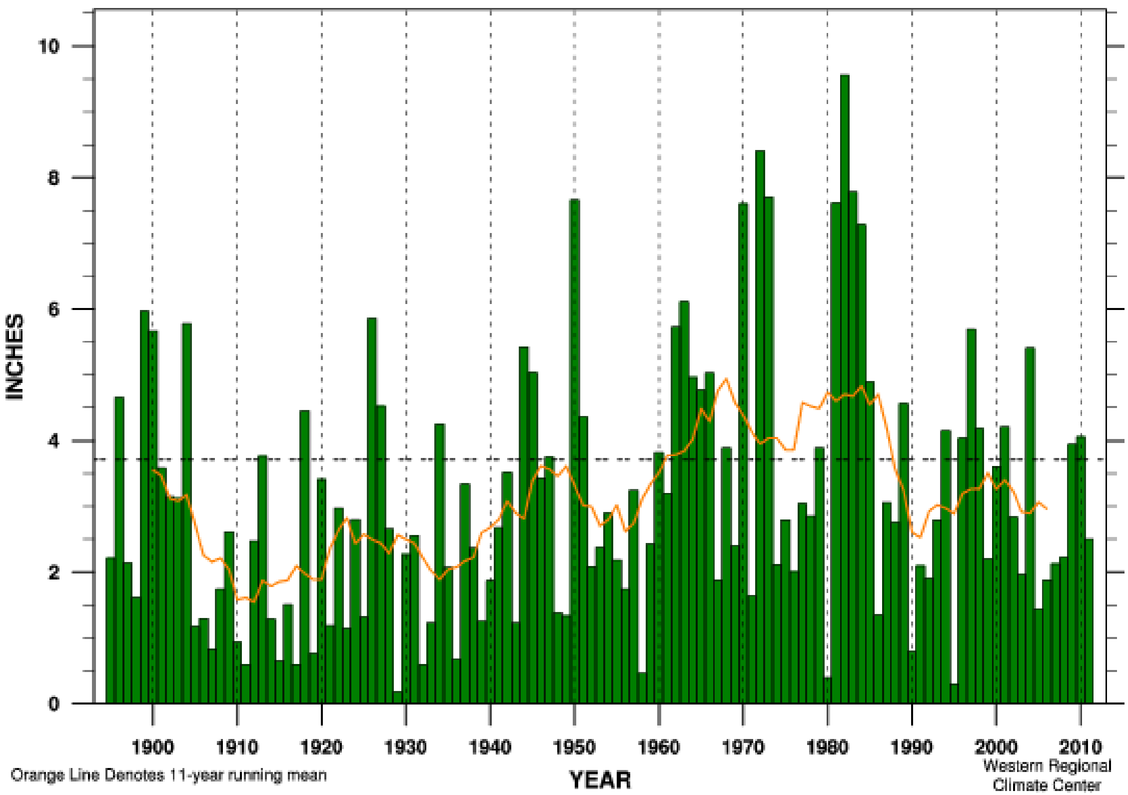
Sacramento-Delta Region
Precipitation Mar-May



Linear Trend 1895-present		+ 0.87 ± 1.30 in.	(+ 18 ± 27%) per 100 yr		
Linear Trend 1949-present		+ 1.25 ± 3.66 in.	(+ 26 ± 77%) per 100 yr		
Linear Trend 1975-present		- 1.25 ± 8.67 in.	(- 26 ± 183%) per 100 yr		
Wettest Year		12.24 in. (258%)	in 1983	MEAN	4.73 in.
Driest Year		0.12 in. (2%)	in 2008	STDEV	2.61 in.
Mar-May	2012	6.57 in. (138%)		RANK	96 of 118

Sacramento-Delta Region

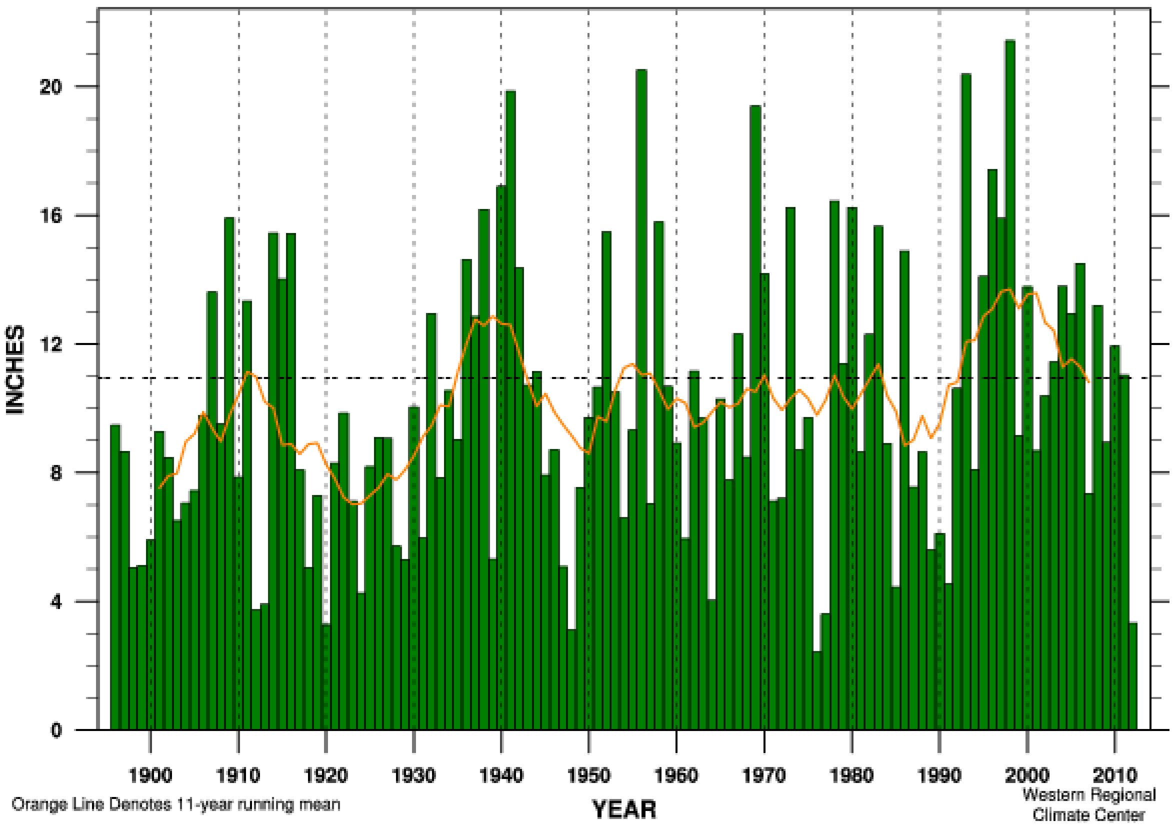
Precipitation Sep-Nov



Linear Trend 1895-present	+ 1.17 ± 1.05 in.	(+ 31 ± 28%) per 100 yr		
Linear Trend 1949-present	- 1.01 ± 2.97 in.	(- 27 ± 80%) per 100 yr		
Linear Trend 1975-present	- 3.87 ± 6.73 in.	(- 104 ± 181%) per 100 yr		
Wettest Year	9.56 in. (257%)	in 1982	MEAN	3.71in.
Driest Year	0.18 in. (4%)	in 1929	STDEV	2.21in.
Sep-Nov 2011	2.50 in. (67%)		RANK	54 of 117

Sacramento-Delta Region

Precipitation Dec-Feb



Linear Trend 1895-present	+ 2.72 ± 2.26 in.	(+ 24 ± 20%) per 100 yr	
Linear Trend 1949-present	+ 1.52 ± 6.14 in.	(+ 13 ± 56%) per 100 yr	
Linear Trend 1975-present	+ 4.87 ± 14.74 in.	(+ 44 ± 134%) per 100 yr	
Wettest Year	21.42 in. (195%)	in 1998	MEAN 10.94 in.
Driest Year	2.42 in. (22%)	in 1976	STDEV 4.49 in.
Dec-Feb 2012	3.33 in. (30%)		RANK 4 of 117

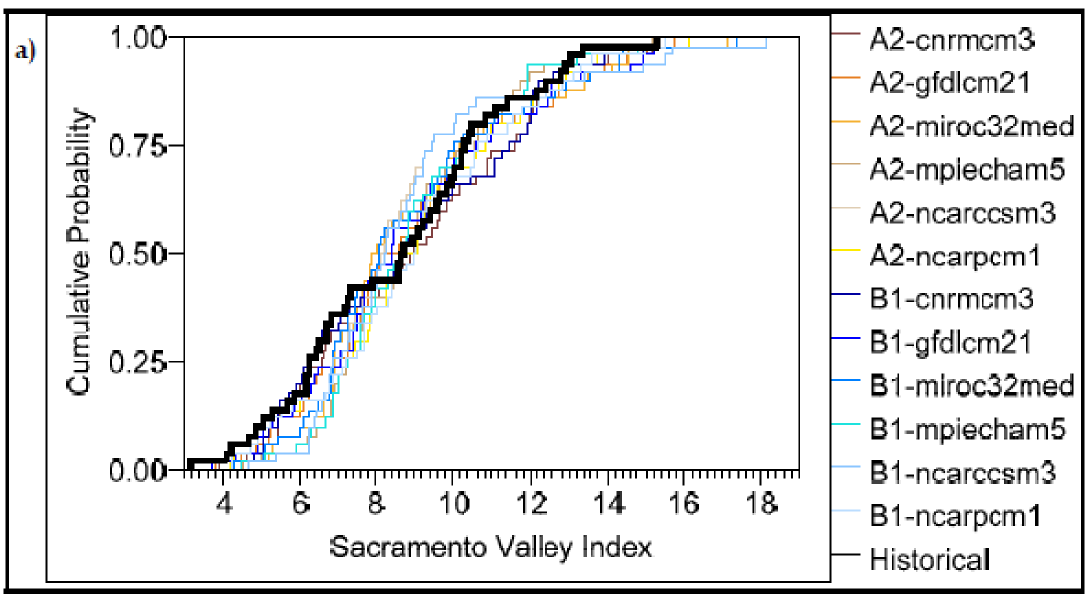
Projected Increases in the Frequency of Dry Water Years Under Climate Change

Many studies project an increase in the frequency and severity of droughts in California under climate change.

As part of the 3rd California Climate Change Assessment in 2012, the California Climate Change Center released a study by Sarah Null and Josh Viers at UC Davis, Water and Energy Sector Vulnerability to Climate Warming in the Sierra Nevada: Water Year Classification in Non-Stationary Climates.

The study used the six global climate models from the California Climate Assessment, and made projections under the SRES A2 (medium-high) and B1 (low) greenhouse gas emissions scenarios that were used in that assessment. (see Appendix.) The study usedthe same Variable Infiltration Capacity model that DWR uses for downscaling, with Bias-Corrected Spatial Disaggregation.

The main difference between the non-stationary study and modeling by the Department of Water Resources for assessments of climate change impacts on water supply, is that the non-stationary study did not correct model outputs to the historical hydrology.   Instead, researchers ran the models without climate forcing, and compared the results to the historical hydrology.   The graph below shows the cumulative probability of the different models compared with the observed 1951-2000 hydrology.



ANOVA and t-tests using a 95 percent confidence level found that results were not significantly different from historic hydrology.   The graph and the statistical tests show that the models do a good job of capturing historic hydrology.   This was one of the criteria for model selection.[5]

The results of the models under the A2 and B1 scenarios show a marked shift in climate.   Most of the models show major increases in dry and critically dry years, and decreases in wet and below-normal

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[5] Climate Change Scenarios And Sea Level Rise Estimates for the California 2009 Climate Change Scenarios Assessment, A Paper From the California Climate Change Center. Cayan et. al.   op. cit.

years. The histograms on the next page shows the changes in the frequency of water year types for the Sacramento Valley Index.

All of the models show a significant increase in dry and critically dry years by the latter half of the century, with a corresponding decrease in wet and above normal years. Many of the models also show an increase in dry and critically dry years in the first half.

The table below shows water year types, averaged over all six GCM models, for the two scenarios.

Table 6. Percentage of Years in Each Water Type by Modeled Time Period and Emissions Scenario (italicized values are percent change from historical period)

	SVI					
	1951-2000 (%)		2001-2050 (%)		2051-2099 (%)	
	A2	B1	A2	B1	A2	B1
Critical	8.7	8.3	11.3 *(2.7)*	6.7 *(-1.7)*	18.4 *(9.7)*	14.0 *(5.6)*
Dry	7.7	10.0	12.0 *(4.3)*	15.7 *(5.7)*	19.4 *(11.7)*	20.1 *(10.1)*
Below Normal	23.3	21.3	23.3 *(0.0)*	17.3 *(-4.0)*	18.7 *(-4.6)*	19.4 *(-1.9)*
Above Normal	21.0	22.7	16.7 *(-4.3)*	20.7 *(-2.0)*	12.9 *(-8.1)*	18.4 *(-4.3)*
Wet	39.3	37.7	36.7 *(-2.7)*	39.7 *(2.0)*	30.6 *(-8.7)*	28.2 *(-9.4)*

The medium-high emissions scenario (A2) projections showed dry and critically dry years in the Sacramento Valley increasing to 23% of all years between 2000 and 2050, and to 38% of all years in the latter half of the century. Under this scenario, the incidence of dry and critically dry years would more than double.

The projections also showed a decrease in wet years.

In the Sacramento Valley, the A2 projections showed wet and above normal years decreased to 53% of all years in 2000-2050, and to 41.5% of years by the latter half of the century.

The lower greenhouse gas emissions scenario (B1) showed similar but less dramatic shifts.

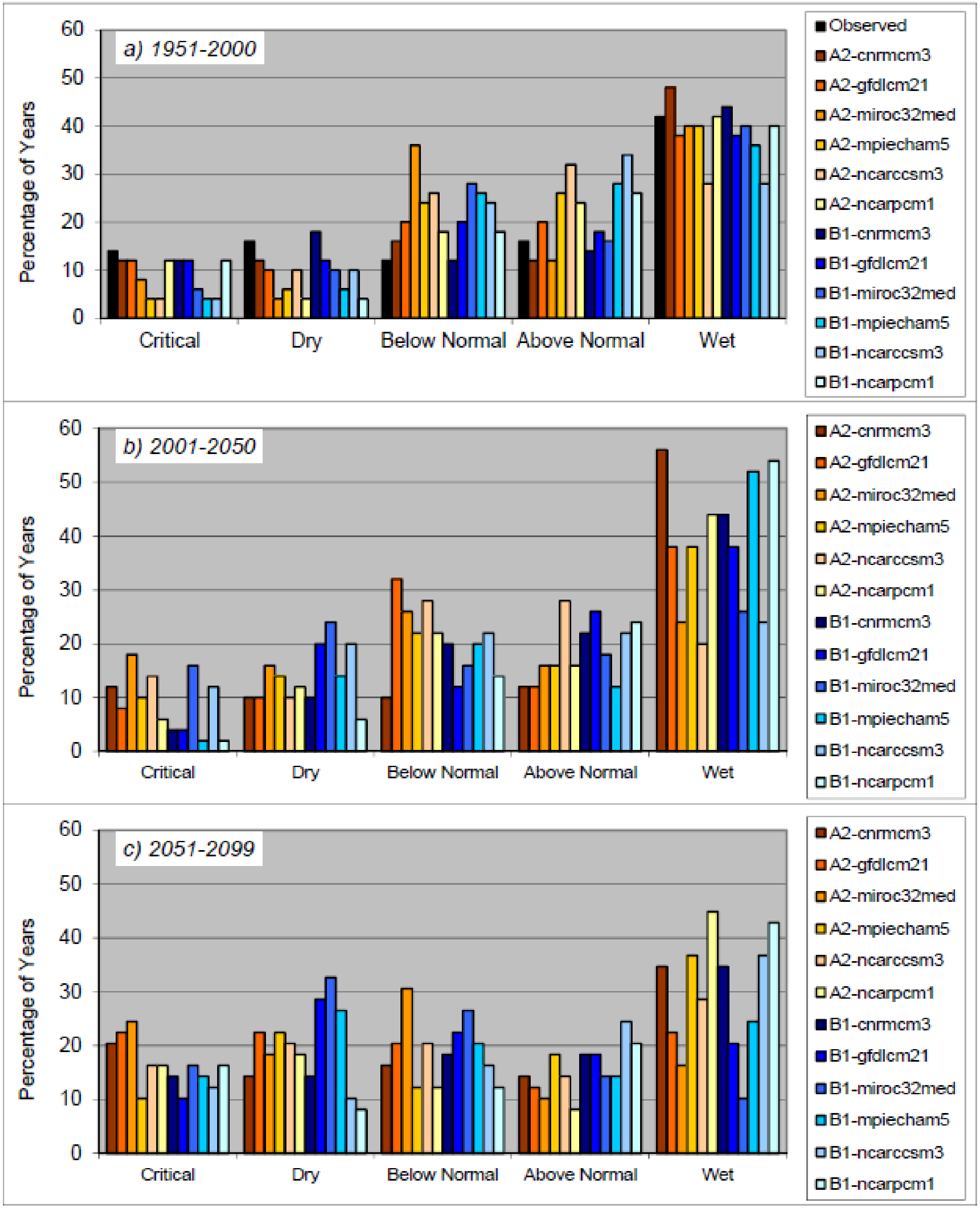


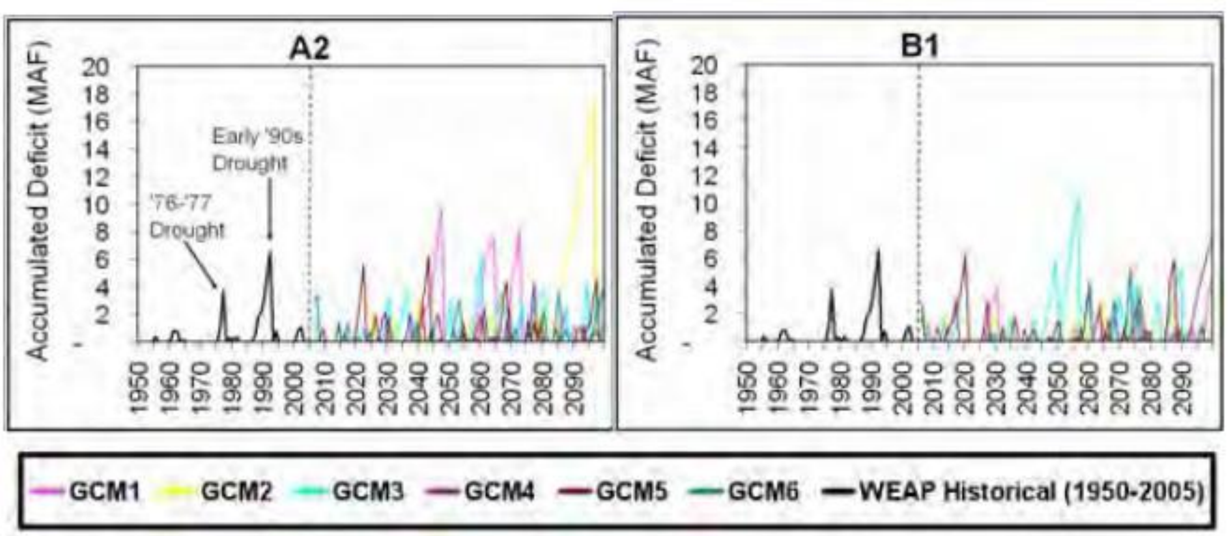
Figure 6. SVI Relative Frequency Histograms for (a) 1951-2000, (b) 2001-2050, and (c) 2051-2099

An earlier, study done by Brian Joyce, Vishal Mehta and David Purkey from the U.S. Center for the Stockholm Environmental Institute, Larry Dale from Lawrence Berkeley National Lab, and Michael Hanemann from the California Climate Center, was released as part of the second

California Climate Change Assessment in 2009, also showed significant increases in the frequency and severity of droughts. See Climate Change Impacts on Water Supply and Agricultural Water Management In California's Western San Joaquin Valley, and Potential Adaptation Strategies, August 2009.[6]

This study used the same set of twelve global climate models / climate change scenarios as the 2009 and 2012 California Climate Change assessment. The study used a application of the Water Evaluation and Planning (WEAP) system developed for the Sacramento River basin and Sacramento Delta. WEAP is an integrated rainfall / runoff and water resources modeling framework that was developed in Stockholm, and has been used for water resources planning around the world. WEAP has also been used in climate modeling for the 2009 California Water Plan, and is being used in preparing the 2013 California Water Plan.

WEAP has the advantage that it does not rely on perturbation of historical precipitation or runoff patterns for projections. This allows the model to capture major shifts in historical patterns. The study found marked increases in the frequency of droughts, and under the A2 scenario, a mega-drought towards the end of the century. The graph below shows the results for different models.



In sum, two recent studies using two different methods of downscaling showed major changes in the structure of droughts in California. Both indicated an increase in the frequency and severity of droughts. This information indicates that current stresses on the Delta due to over-export of unstored water are likely to increase with climate change.

[6] Climate Change Impacts on Water Supplies and Agricultural Water Management in the Western San Joaquin Valley and Possible Adaptation Strategies, Brian A. Joyce, Vishal K. Mehta, David R. Purkey, Larry L. Dale, and Michael Hanemann. California Climate Change Center, August 2009. Available at http://www.energy.ca.gov/2009publications/CEC-500-2009-051/CEC-500-2009-051-F.PDF

Potential reductions in runoff in Delta watersheds due to climate change

The US Geological Survey released a paper in February using the A2 scenario with the Global Fluid Dynamics Lab (GFDL) climate model. [7] The study was done by R.T. Hanson and other researchers at USGS in collaboration with Daniel Cayan, who oversaw the modeling for the California Climate Adaptation Strategy.

The paper uses the GFDL A2 scenario for predictions. This is a drier scenario which was used in the California Climate Adaptation Strategy. On the next page is a graph of predicted river flows in the Central Valley. The USGS models predict a 16-17% reduction in Sacramento River flows from 2020-2030 and 2040-2050, and a 34% reduction by 2080-2090. Similar reductions are predicted for the Tuolumne River.

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[7] R.T. Hanson et. al., "A method for physically based model analysis of conjunctive use in response to potential climate changes," Feb 4, 2012. Available at http://ca.water.usgs.gov/projects/cvhm/Hanson_etal_2012_WRR.pdf.

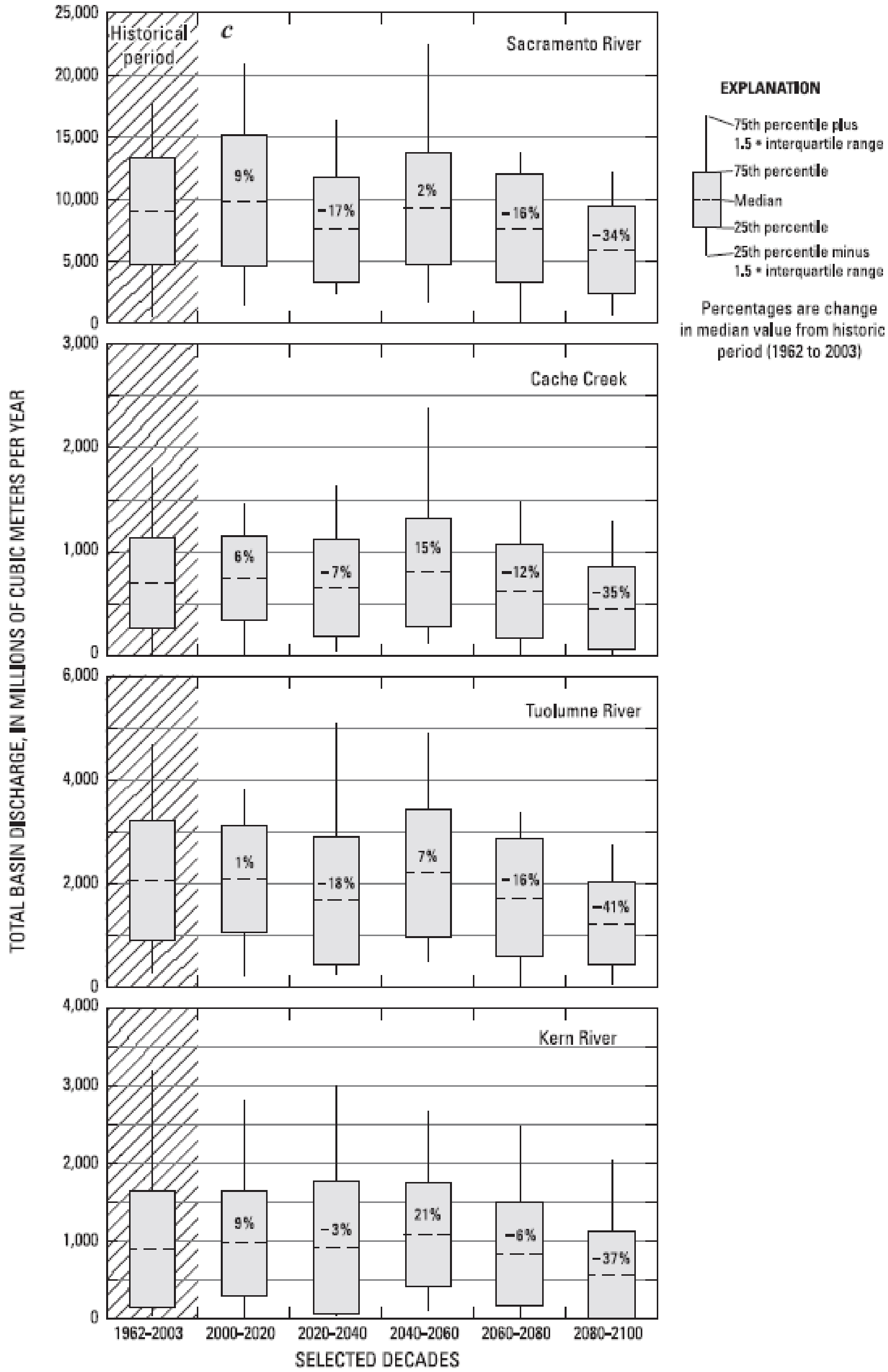


Figure 3. (continued)

The maps below show details of the reduction in river inflows from the USGS modeling. The different basins are color-coded, based on flow. There is a marked reduction in flows in all basins in the Central Valley by the end of the century.

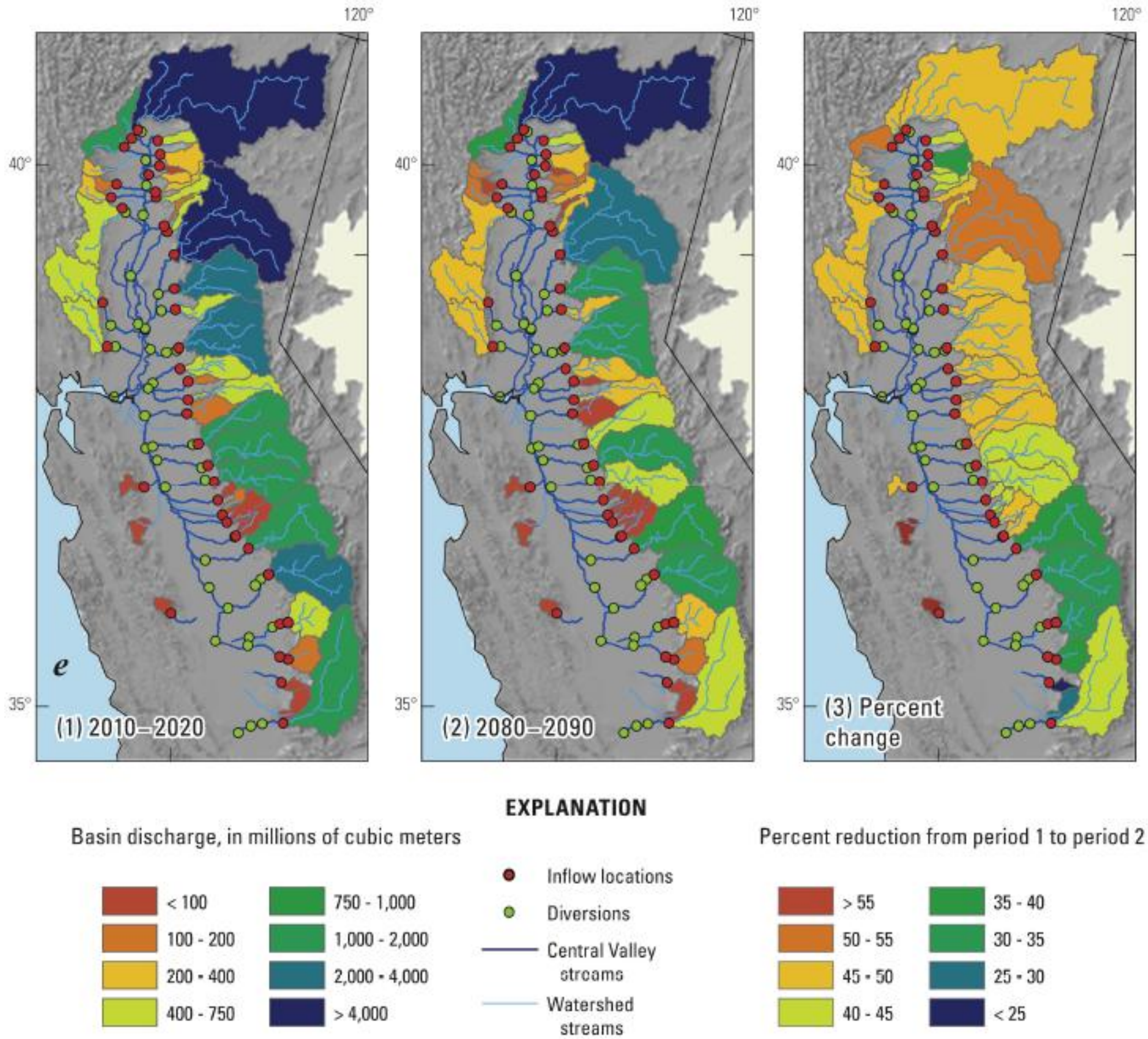


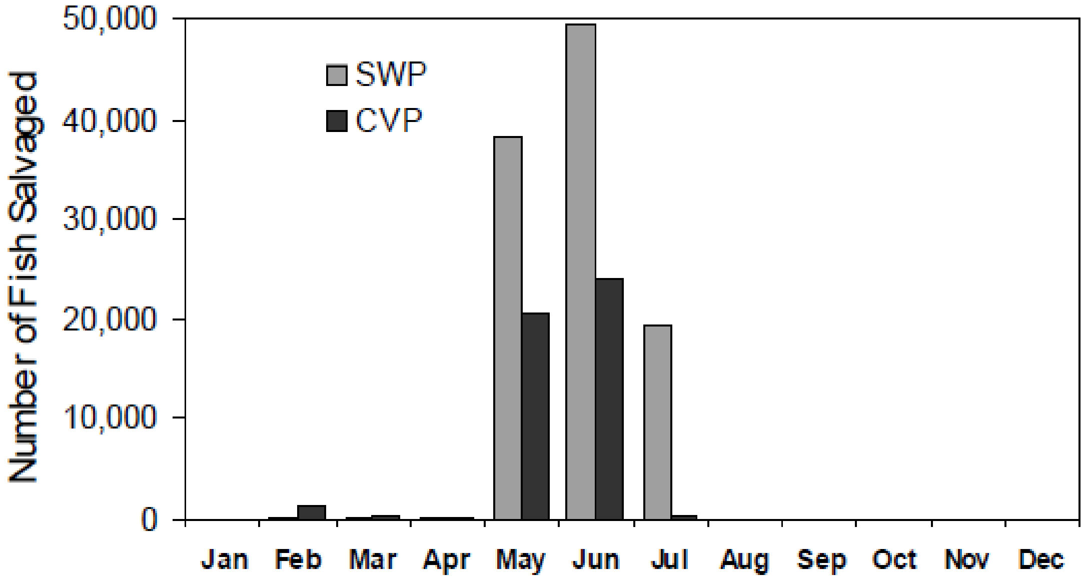
Figure 3. (continued)

Summer conditions leading to collapse of pelagic fish populations

Toxic algal blooms started in the Central Delta in 1999, and were associated with significant reductions in Delta inflows and outflows in late spring through fall. A study by Dr. Peggy Lehman of the Department of Water Resources found that large blooms of toxic algae in the

Delta appear to be linked with low flows and high air and water temperatures.[8] A more recent study linked the blooms to high water temperatures.[9]

Low flows also caused increased entrainment -- red light levels of Delta Smelt salvage were exceeded in May, June, and July of 1999.



Feyer, Sommer, and Slater[10] (2009) noted that threadfin shad exhibit a critical recruitment break between summer and fall, and speculated that there might be a tie to Microcystis blooms in the estuary:

> However, there did appear to be a complete "disconnect" between summer salvage density and FMT CPT, suggesting that factors occurring during the summer-to-fall transition might be one possible critical period. There are two factors in particular that are of concern for threadfin shad during this time period, dissolved oxygen and the toxic algae Microcystis aeruginosa, both of which occur in the center of threadfin shad distribution. Episodes of low dissolved oxygen concentration commonly occur in the San

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[8] Peggy Lehman et. Al., Initial impacts of Microcystis aeruginosa blooms on the aquatic food web in theSan Francisco Estuary, Hydrologica, 2010. Incorporated by reference.

[9] Mioni, C.E., Kudela, R.M., Baxa, D. (2012) Harmful cyanobacteria blooms and their toxins in Clear Lake and the Sacramento-San Joaquin Delta (California). Surface Water Ambient Monitoring Program (10-058-150). Final Report, March 31, 2012. Incorporated by reference.

[10] Feyer, Sommer, and Slater, Old school vs. new school: status of threadfin shad (Dorosoma petenense) five decades after its introduction to the Sacramento-San Joaquin Delta, San Francisco Estuary and Watershed Science, 7(1), 2009. Incorporated by reference.

Joaquin River and have been known to cause die-offs of threadfin shad. Such events are difficult to characterize and quantify but might be responsible in part for the sudden declines in abundance sometimes observed from one year to the next. In recent yearsthere have been dense blooms of M. aeruginosa geographically centered where threadfin shad are most abundant (Lehman and others 2008). The blooms also occur during the critical late summer/early fall when newly spawned fish are recruiting to the population (Lehman and others 2007).

Conclusion

Climate change is fundamentally shifting Sacramento River flows and Delta inflows, in a way that was not forseen when the original diversion permits in the Sacramento River and the Delta by the U.S. Bureau of Reclamation and the Department of Water Resources were issued by the State Water Rights Board in 1960 and 1967.

Not only has there been a significant reduction in precipitation in California in the spring and fall, as well as snowpack, there has been a maturity of water rights in the areas of origin. The assumption that there was unstored water available in the Delta for for export in the months of July, August, and September was always questionable, and it is likely that these developments have eliminated any surplus water in these months.

Rather than attempt to resovle these issues entirely by setting water quality targets for these months, which involves a great deal of uncertainty, given the range of future scenarios due to climate change, it would be more protective of the rights of the areas of origin to bar exports of unstored water in the Delta for those months in which studies show that it has not been available for the past two decades.

This assures the areas of origin that water exported during these times will actually be stored water.

Water quality targets can then focus on what quantities of stored water that will leave necessary bypass flows in the Sacramento River and the Delta.

Appendix. Tables of water remaining in the Delta. From the North Delta Water Agency.

Table B – Water Remaining in the Delta after Satisfaction of all Pre-1927 Appropriative and Other Rights

(Before water quality requirements are satisfied)[1]

(In thousands of acre-feet)

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
1924[2]	511	103	0	0	0	0	215	829
1925	3,950	2,980	1,004	0	0	101	386	8,421
1926	3,816	1,091	46	0	0	62	310	5,325
1927	5,199	3,122	1,862	116	0	156	432	10,887
1928	4,024	1,771	254	0	0	128	354	6,531
1929	1,076	987	273	0	0	70	282	2,688
1930	1,953	1,202	370	0	0	170	412	4,107
1931[2]	410	76	0	0	0	0	154	640
1932[2]	1,897	2,687	1,768	206	0	36	231	6,825
1933[2]	1,324	1,056	891	0	0	18	250	3,539
1934[2]	927	214	0	0	0	0	188	1,329
1935	6,629	3,826	1,894	0	0	117	421	12,887
1936	3,522	2,703	1,486	25	0	141	342	8,219
1937	3,990	3,537	1,593	4	0	86	457	9,667
1938	7,122	6,688	4,584	1,069	30	291	602	20,386
1939	1,132	356	0	0	19	63	292	1,862
1940	7,142	2,660	1,045	0	0	204	406	11,457
1941	6,479	4,772	2,557	636	0	195	471	15,110
1942	4,894	4,141	3,163	614	0	246	536	13,594
1943	4,231	2,686	1,425	21	0	172	501	9,036
1944	1,362	1,559	496	0	0	122	374	3,913
1945	2,412	2,608	1,340	41	0	167	548	7,116
1946	2,536	2,423	650	0	0	197	404	6,210
1947	1,577	421	213	0	0	126	535	2,872
1948	3,871	3,417	2,200	0	0	185	455	10,128
1949	2,380	1,648	240	0	0	104	240	4,612
1950	3,010	2,112	922	0	0	155	778	6,977
1951	1,915	2,141	358	0	0	228	518	5,160
1952	6,569	6,538	3,630	668	0	361	536	18,302
1953	2,240	2,591	2,033	193	0	350	551	7,958
1954	4,078	1,845	312	0	0	275	497	7,007
Total	**102,178**	**73,961**	**36,609**	**3,593**	**49**	**4,526**	**12,678**	**233,594**
Average	**3,296**	**2,386**	**1,181**	**116**	**2**	**146**	**409**	**7,535**
Number of Deficient Months	**0**	**0**	**4**	**20**	**29**	**3**	**0**	**56**

[1] Includes satisfaction of all assumed Riparian and Pre-1927 Appropriative and Other Rights of local water users along the Sacramento River above Sacramento and in the Delta Uplands and Lowlands to the extent of the available supply and before water quality requirements are met.

[2] Denotes Critical Year.

Table C – Water Remaining in the Delta after Satisfaction of all Pre-1938 Appropriative and Other Rights
(Before water quality requirements are satisfied)[1]

(In thousands of acre-feet)

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
1924[2]	376	100	0	0	0	0	78	554
1925	3,167	2,612	806	0	0	29	220	6,834
1926	3,322	888	39	0	0	13	157	4,419
1927	4,196	2,718	1,642	98	0	63	268	8,985
1928	3,454	1,443	183	0	0	49	202	5,331
1929	704	763	232	0	0	43	152	1,894
1930	1,559	935	351	0	0	106	260	3,211
1931[2]	230	67	0	0	0	0	33	330
1932[2]	1,505	2,335	1,652	201	0	5	100	5,798
1933[2]	864	755	766	0	0	3	131	2,519
1934[2]	636	90	0	0	0	0	67	793
1935	5,446	3,328	1,774	0	0	56	270	10,874
1936	3,047	2,412	1,308	20	0	84	202	7,073
1937	3,136	3,173	1,383	0	0	44	304	8,040
1938	6,505	6,326	4,177	966	36	158	432	18,600
1939	832	262	0	0	0	22	152	1,268
1940	6,525	2,316	933	0	0	121	242	10,137
1941	5,360	4,410	2,169	523	0	87	302	12,851
1942	4,029	3,528	2,743	512	0	123	317	11,252
1943	3,518	2,280	1,169	0	0	66	298	7,331
1944	1,022	1,289	395	0	0	31	209	2,946
1945	1,970	2,234	1,151	36	0	104	377	5,872
1946	1,999	2,082	551	0	0	92	242	4,966
1947	1,160	350	26	0	0	30	364	1,930
1948	3,000	3,055	1,778	0	0	49	290	8,172
1949	1,796	1,317	204	0	0	21	99	3,437
1950	2,422	1,817	888	0	0	87	390	5,604
1951	1,440	1,723	295	0	0	121	348	3,927
1952	5,799	6,127	3,280	563	0	168	366	16,303
1953	1,639	2,010	1,594	111	0	167	380	5,901
1954	3,155	1,483	156	0	0	111	326	5,231
Total	**83,813**	**64,228**	**31,645**	**3,030**	**36**	**2,053**	**7,578**	**192,383**
Average	**2,704**	**2,072**	**1,021**	**98**	**1**	**66**	**244**	**6,206**
Number of Deficient Months	**0**	**0**	**4**	**22**	**30**	**3**	**0**	**59**

[1] Includes satisfaction of all assumed Riparian, Pre-1927, 1927-38 Appropriative and Other Rights of local water users along the Sacramento River above Sacramento and in the Delta Uplands and Lowlands, and the assumed 1927 Right of the United States at Shasta Dam to the extent of the available supply and before water quality requirements are met.

[2] Denotes Critical Year.

Table D – Water Remaining in the Delta after Satisfaction of all Pre-1954 Appropriative and Other Rights

(Before water quality requirements are satisfied)[1]

(In thousands of acre-feet)

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
1924[2]	87	0	0	0	0	0	0	87
1925	2,980	2,501	639	0	0	0	25	6,145
1926	3,135	708	0	0	0	0	0	3,843
1927	4,009	2,665	1,497	0	0	0	71	8,242
1928	3,274	1,344	0	0	0	0	0	4,618
1929	524	604	0	0	0	0	0	1,128
1930	1,372	817	5	0	0	0	51	2,245
1931[2]	0	0	0	0	0	0	0	0
1932[2]	1,330	2,241	1,403	0	0	0	0	4,974
1933[2]	677	651	526	0	0	0	0	1,854
1934[2]	463	0	0	0	0	0	0	463
1935	5,259	3,213	1,529	0	0	0	0	10,001
1936	2,860	2,306	1,121	0	0	0	60	6,347
1937	2,949	3,078	1,228	0	0	0	0	7,255
1938	6,325	6,231	4,112	0	0	0	96	16,764
1939	661	0	0	699	0	0	241	1,601
1940	6,345	2,213	680	0	0	0	45	9,283
1941	5,180	4,315	2,102	266	0	0	110	11,973
1942	3,842	3,413	2,666	244	0	0	88	10,253
1943	3,331	2,165	1,060	0	0	0	71	6,627
1944	867	1,173	131	0	0	0	13	2,184
1945	1,783	2,143	975	0	0	0	187	5,088
1946	1,819	1,986	285	0	0	0	43	4,133
1947	973	38	0	0	0	0	174	1,185
1948	2,820	2,960	1,728	0	0	0	94	7,602
1949	1,609	1,219	0	0	0	0	0	2,828
1950	2,235	1,712	557	0	0	0	200	4,704
1951	1,253	1,608	0	0	0	0	157	3,018
1952	5,619	6,032	3,209	298	0	2	175	15,335
1953	1,452	1,895	1,523	0	0	0	190	5,060
1954	2,975	1,388	0	0	0	0	136	4,499
Total	**78,008**	**60,619**	**26,976**	**1,507**	**0**	**2**	**2,227**	**169,339**
Average	**2,516**	**1,955**	**870**	**49**	**0**	**0**	**72**	**5,463**
Number of Deficient Months	**1**	**4**	**11**	**27**	**31**	**30**	**11**	**115**

[1] Includes satisfaction of all assumed Riparian and Appropriative and Other Rights water users along the Sacramento River above Sacramento and in the Delta Uplands and Lowlands with priorities prior to January 1, 1954, including the assumed 1927 and 1938 Rights of the United States at Shasta Dam and in the Delta, to the extent of the available supply before water quality requirements are met.

[2] Denotes Critical Year.

Table E – Water Remaining in the Delta after Satisfaction of all Pre-1955 Appropriative and Other Rights

(Before water quality requirements are satisfied)[1]

(In thousands of acre-feet)

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
1924[2]	114	0	0	0	0	0	0	114
1925	3,030	2,446	555	0	0	0	11	6,042
1926	3,185	651	0	0	0	0	0	3,836
1927	4,059	2,552	1,413	0	0	0	34	8,058
1928	3,316	1,288	0	0	0	0	0	4,604
1929	574	547	0	0	0	0	0	1,121
1930	1,422	761	0	0	0	0	24	2,207
1931[2]	30	0	0	0	0	0	0	30
1932[2]	1,375	2,181	1,319	0	0	0	0	4,875
1933[2]	727	601	442	0	0	0	0	1,770
1934[2]	505	0	0	0	0	0	0	505
1935	5,309	3,163	1,445	0	0	0	28	9,945
1936	2,910	2,256	1,037	0	0	0	0	6,203
1937	2,999	3,007	1,144	0	0	0	55	7,205
1938	6,367	6,160	4,036	590	0	0	193	17,346
1939	701	0	0	0	0	0	0	701
1940	6,387	2,158	596	0	0	0	21	9,162
1941	5,222	4,244	2,030	157	0	0	65	11,718
1942	3,892	3,363	2,589	135	0	0	79	10,058
1943	3,381	2,115	976	0	0	0	60	6,532
1944	891	1,118	53	0	0	0	5	2,067
1945	1,833	2,080	891	0	0	0	139	4,943
1946	1,861	1,928	201	0	0	0	20	4,010
1947	1,023	9	0	0	0	0	126	1,158
1948	2,862	2,889	1,619	0	0	0	51	7,421
1949	1,659	1,163	0	0	0	0	0	2,822
1950	2,285	1,663	473	0	0	0	152	4,573
1951	1,305	1,563	0	0	0	0	111	2,979
1952	5,661	5,961	3,140	56	0	0	127	14,945
1953	1,502	1,845	1,452	133	0	0	142	5,074
1954	3,017	1,317	0	0	0	0	88	4,422
Total	**79,404**	**59,029**	**25,411**	**1,071**	**0**	**0**	**1,531**	**166,446**
Average	**2,561**	**1,904**	**820**	**35**	**0**	**0**	**49**	**5,369**
Number of Deficient Months	**0**	**4**	**12**	**26**	**31**	**31**	**11**	**115**

[1] Includes satisfaction of all assumed water rights of local water users along the Sacramento River above Sacramento and in the Delta Uplands and Lowlands, and the United States at Shasta Dam and in the Delta with priorities prior to January 1, 1955 to the extent of the available supply before water quality requirements are met.

[2] Denotes Critical Year.

Adaptive Management of Fall Outflow for Delta Smelt Protection and Water Supply Reliability

I. INTRODUCTION

In 2008, the US Fish and Wildlife Service (Service) issued a Biological Opinion (BiOp) on Central Valley Project (CVP)/State Water Project (SWP) operations that concluded that aspects of those operations jeopardize the continued existence of delta smelt and adversely modify delta smelt critical habitat. Among other requirements, the Reasonable and Prudent Alternative (RPA) that was issued with the BiOp calls for the adaptive management of fall Delta outflow (hereafter "Fall outflow") following "wet" and "above normal" water-years. The Service determined that the Fall outflow element of the RPA is required to alleviate both jeopardy to delta smelt and adverse modification of delta smelt critical habitat. The Fall outflow action is expected to improve habitat suitability and contribute to a higher average population growth rate of delta smelt.

The RPA prescription is expressed in terms of X2, the nominal location of the 2 ppt isohaline (Jassby et al. 1995). The RPA calls for Delta outflow to be managed such that fall X2 must average either 74 km or 81 km upstream from the Golden Gate during each of September and October, respectively, if the water year containing the preceding spring was classified as wet or above normal. There is an additional storage-related requirement to enhance outflow in November that does not have a specific X2 target. The RPA states that the performance of the action shall be investigated with a research and monitoring program containing a feedback loop allowing it to be adjusted from learned information (i.e., adaptive management).

At the time the BiOp was issued, the Bureau of Reclamation (Reclamation) responded with a "provisional acceptance" letter. In 2009-10, Reclamation and the Service developed and initiated a package of studies designed to increase understanding about Fall X2 and support a passive form of adaptive management.

Reclamation has further reviewed the science underlying the Fall outflow requirement in order to better understand the uncertainties and to consider how efficient adaptive management might proceed. Based on those considerations, and because the costs of implementing the Fall outflow action are high, Reclamation has drafted a framework for active adaptive management. By adopting a more aggressive, active approach, Reclamation hopes to achieve more rapid learning – thereby finding the best and most efficient action faster – while alleviating adverse modification of delta smelt critical habitat and avoiding jeopardy.

The adaptive management plan includes a description of how adaptive management works and how an aggressive scientific studies element can responsibly be incorporated into it, a statement of management goals, and a draft of the set-up elements. Since a starting point for the management is logically required, Reclamation has reviewed the rationale for the action and considered initial management alternatives.

This plan implements critical recommendations made by the National Academies of Science panel in its March 2010 report (available at http://www.nap.edu/catalog.php?record_id=12881). By laying out a framework for rigorous, science-based adaptive management, we hope the plan will enable us to learn what we need to know about the effects of Fall outflow, so that the most appropriate conservation action can be identified and implemented at lowest possible water cost.

We have addressed a number of questions, issues, and recommendations made by various stakeholders and the California Department of Water Resources. Their advice was solicited in order to help improve the quality and implementability of this plan. Reclamation appreciates the constructive input that was received.

This plan is designed to formalize and strengthen the adaptive management process that was begun with the 2010 draft studies plan. It will require ongoing development during implementation. The plan presented here provides a framework for work that is to follow. We are completing plans for augmented monitoring first, in order to place crews in the field annually beginning this year. We expect development and implementation of the more difficult modeling components to occur on an ongoing basis.

This plan deals with only one aspect of the broad issue of Delta outflow. As one of the primary determinants of the characteristics of the ecosystem, Delta outflow patterns are important year-round, and affect many species. Delta outflow is a topic of discussion in several ongoing public processes, including the Bay-Delta Conservation Plan development, the Delta Stewardship Council's Delta Plan development, the State Water Resources Control Board's Delta Flow Criteria proceedings, and the Environmental Protection Agency's advance notice of proposed rulemaking for water quality issues in the Bay-Delta. We expect that as these processes move forward, linkages and interactions that arise between fall outflow management for delta smelt and other aspects of outflow management will be addressed as circumstances and Reclamation's regulatory obligations require.

II. BACKGROUND

A. Delta smelt

Delta smelt is undoubtedly the most estuary-dependent native fish species that lives in the San Francisco Estuary (Moyle et al. 1992; Bennett 2005). Most delta smelt complete the majority of their annual life cycle in the low salinity zone (LSZ) of the estuary and use the freshwater portion of the estuary only for spawning and juvenile rearing (Figure 1; Dege and Brown 2004, Bennett 2005). Because it is endemic to the San Francisco Estuary, the continued existence of the species is dependent upon its ability to successfully grow, develop, and survive in the LSZ.

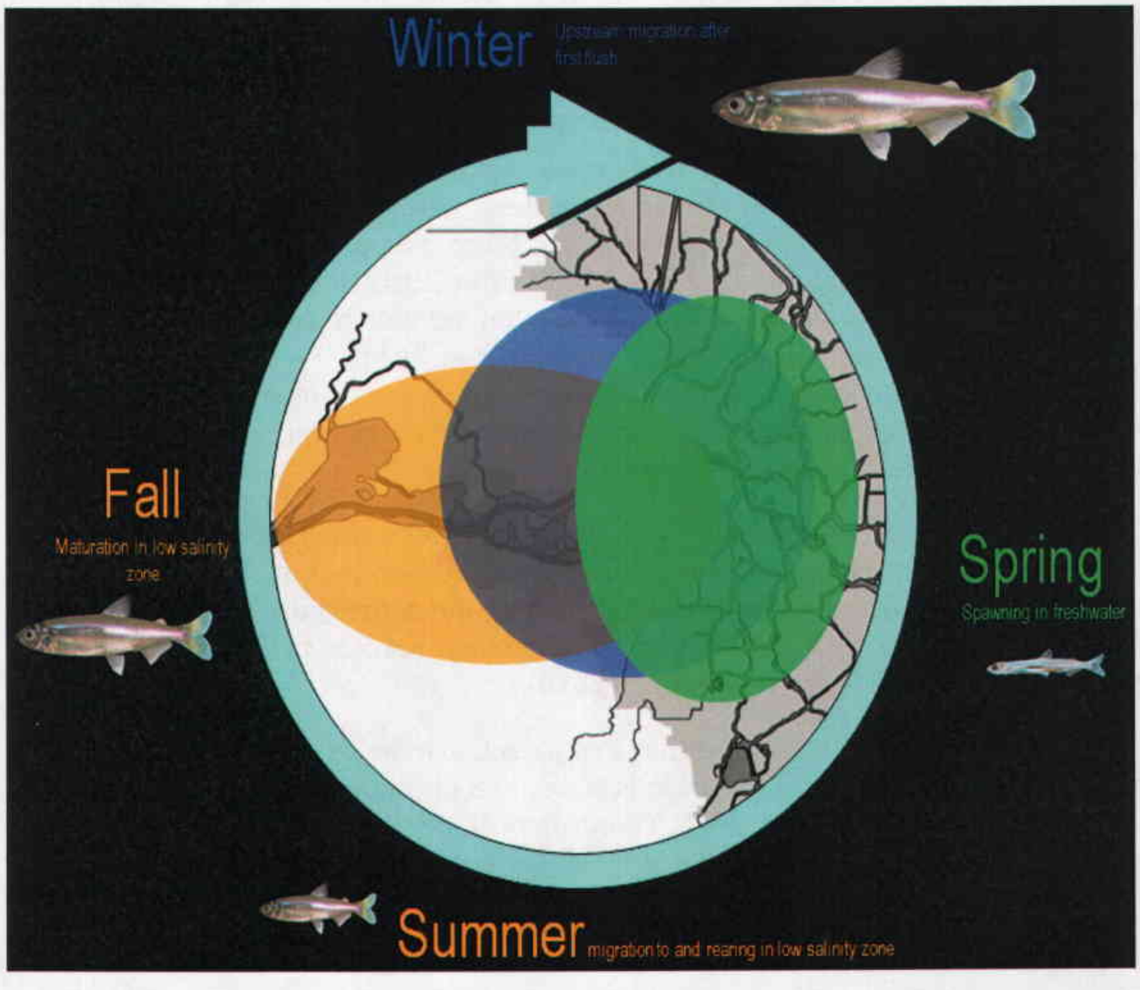


Figure 1. Simple conceptual diagram of the delta smelt life cycle (modified from Bennett 2005).

Delta smelt distribution and life history was first described by Moyle et al. (1992). A number of recent studies have examined delta smelt habitat use in more detail.

Bennett (2005) described general patterns of delta smelt habitat use by life stage. Dege and Brown (2004) described the effects of outflow on the distribution of larval and young juvenile delta smelt and noted the initial upstream and eventual close association between young delta smelt distribution and X2. Feyrer et al (2007, 2010) described the habitat associations of delta smelt during fall months (September-December) based on forty years of sampling data collected by the Fall Midwater Trawl Survey. Nobriga et al. (2008) described habitat associations during summer months (June-July) based on the forty plus years of sampling data collected by the Summer Townet Survey. Kimmerer et al. (2009) expanded on these studies by examining the habitat associations of delta smelt for each of the major IEP fish monitoring surveys. Finally, Sommer et al. (2011) examined delta smelt distribution shifts from fall through the spring months. Together, these studies demonstrate that most delta smelt reside in the low salinity zone in the summer and fall, with a center of distribution at approximately the 2 psu isohaline, but move upstream during winter and spring months when spawning and early development occur in freshwater.

Sommer et al. (2011) also noted the year-round presence of delta smelt in an upstream freshwater region of the system in the general Cache Slough/Sacramento Deep Water Shipping Channel, suggesting that there is a portion of the delta smelt population that may not utilize the low salinity zone. Historically, delta smelt were also present in the south Delta in the summer, but are now found there only in the winter and spring (Nobriga et al. 2008, Sommer et al. 2011). Fisch (2011) determined that individuals collected from this region were not genetically unique relative to delta smelt captured from other regions of the system; rather, there is a single, panmictic delta smelt population in the estuary.

Against a background of highly variable abundance, delta smelt have suffered a long-term abundance decline (Figure 2; USFWS 2008, Sommer et al. 2007; Thomson et al. 2010). The decline spans the post-1966 portion of the "post-reservoir period" described in Baxter et al. (2010) and was particularly marked in the "POD [Pelagic Organism Decline] period" (Baxter et al. 2010).

Long term trend analyses confirm that a step decline in pelagic fish abundance marks the transition to the POD period (Manly and Chotkowski 2006, Moyle and Bennett 2008, Mac Nally et al. 2010, Thomson et al. 2010, Moyle et al. 2010) and may signal a rapid ecological regime shift in the upper estuary (Moyle et al. 2010, Baxter et al. 2010).

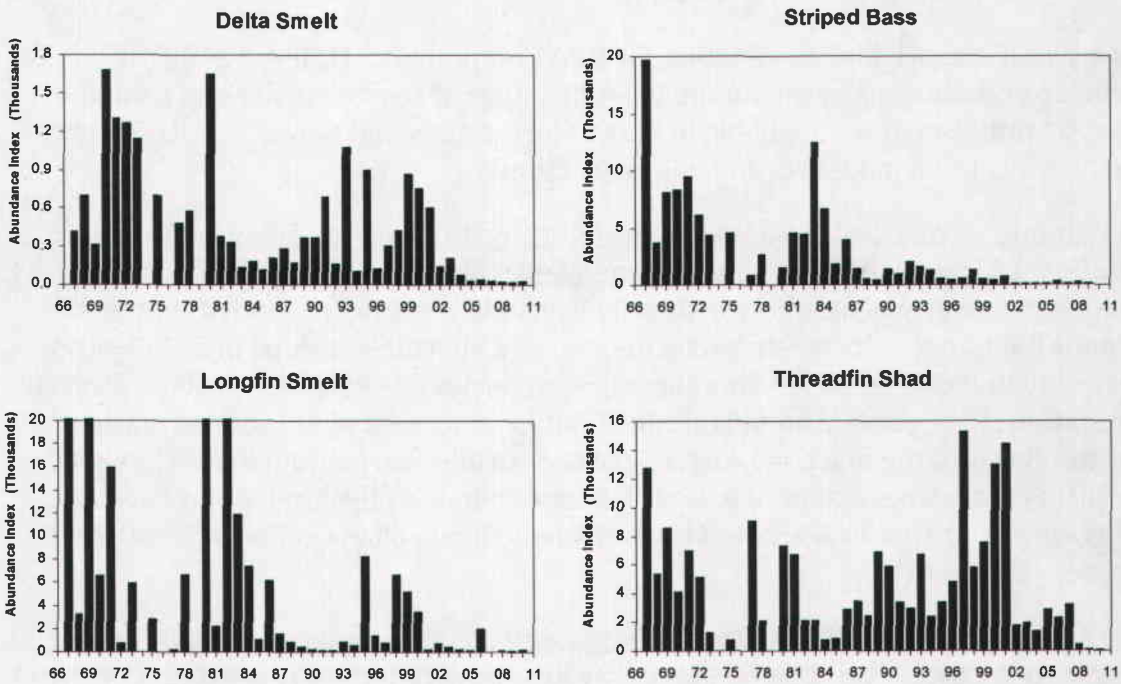


Figure 2. Trends in abundance indices for four pelagic fishes from 1967 to 2010 based on the Fall Midwater Trawl, a California Department of Fish and Game survey that samples the upper San Francisco Estuary. No sampling occurred in 1974 or 1979 and no index was calculated for 1976. Note that the y-axis for longfin smelt represents only the lower 25% of its abundance range to more clearly portray the lower abundance range.

The decline of delta smelt has been intensively studied as part of the POD investigation (Baxter et al. 2010; Sommer et al. 2007). The POD investigators have concluded that among several causes habitat degradation predominates.

> "We hypothesize that degradation of habitat is the fundamental cause of delta smelt decline and that it affects the species mainly through effects on growth and subsequent reproductive potential rather than immediate mortality. Both abiotic and biotic aspects of habitat suitability have declined over time. This has led to smaller, less healthy adults, which have lower per capita fecundity. These ecosystem challenges have probably been exacerbated by periodic high entrainment loss. We hypothesize that habitat degradation has reduced carrying capacity. Thus, entrainment losses at historical levels could have increased in importance because the population is smaller. Large-scale water diversion may also influence delta smelt carrying capacity through seasonal effects on Delta outflow" (Baxter et al. 2010, p. 54).

B. The 2008 Outflow RPA Action

As we read the original explanation for RPA Component 3 (USFWS 2008), it develops conclusions based on the following lines of reasoning derived from the best scientific analyses available in 2008. More details and newer results are given in the conceptual model section below (Section 4).

(1) Abiotic, or physical habitat used by delta smelt during the fall months has diminished in availability because of changes in water project operations. An analysis of historical monitoring data by Feyrer et al. (2007) revealed that the abiotic habitat of delta smelt can be defined as a specific envelope of salinity and turbidity that changes over the course of the species' life cycle. Over time, project operations have pushed and maintained fall X2 upstream of the wide expanse of Suisun Bay into the much narrower Sacramento and San Joaquin River channels, reducing the spatial extent of habitat falling within the physical habitat envelope. This may be further exacerbated by predicted climate change effects (USBR 2008; Feyrer et al. 2011).

(2) There is a discernible effect of good-quality abiotic habitat availability and delta smelt abundance. Fall habitat suitability has shown a long-term decline (Feyrer et al. 2007). Variation in abiotic habitat variables in the fall explained about 20% of the variance in subsequent juvenile abundance.

(3) The BiOp also asserted that restricted habitat area is likely to increase the probability that stochastic, localized, catastrophic events might affect a large fraction of the population.

The BiOp concluded that an outflow action was needed to (1) alleviate adverse modification of delta smelt critical habitat, and (2) avoid jeopardizing the continued existence of delta smelt. Based on the analysis contained in the BiOp and RPA, Component 3 of the RPA set requirements that X2 average 74 km in each of September and October following wet years and 81 km in the same months following above normal years "to mitigate the effects of X2 encroachment upstream in current and proposed action operations, and provide suitable habitat area for delta smelt" (BiOp page 373). Component 3 also includes a storage pass-through requirement in November. The effect of the November requirement is to enhance outflow above what the projects would normally provide when there is early precipitation, but does not require that a specific X2 objective be met.

The RPA also called for the adaptive management of the fall action, and prescribed that a team be convened to develop and implement a plan. The team, which became known as the Habitat Study Group (HSG), first convened in 2009. The HSG developed a package of studies to support fall outflow management, and completed a draft report of its activities in 2010. With Reclamation funding, the HSG studies were begun in 2010 under the administration of the Interagency Ecological Program (IEP) as part of the IEP POD investigation (Baxter et al. 2010).

C. Review of RPA Action

We have reviewed the basic rationale provided in the BiOp, bringing to bear information that has become available since the BiOp was completed. New information includes the 2010 POD synthesis (Baxter et al 2010), some newly published studies bearing directly on outflow effects and other issues, preliminary results from ongoing studies, commentaries from several review panels, complaints about the RPA that were raised by the State and Federal water contractors in letters and in litigation, and commentaries by DWR and NRDC that were provided to us in May 2011.

The main questions Reclamation asks in this review are the following. What kind of action seems appropriate, given the present array of available information? What are the most important specific uncertainties that affect management decisions pertaining to Fall Outflow?

We consider the available information in five sections, each of the last four building on those before it: (1) delta smelt habitat; (2) X2 as a surrogate for delta smelt habitat; (3) evidence for associations between habitat and abundance; (4) Delta hydrology, X2 and delta smelt habitat in the fall; and (5) the specific X2 action prescribed in the BiOp. Additional details are provided in the conceptual model section below (Section 4).

(1) Delta smelt habitat

As described above, seasonal movements and use of habitat by delta smelt have been captured by IEP long-term monitoring studies and reported in multiple studies (Moyle et al. 1992, Dege and Brown 2004, Bennett 2005, Feyrer 2007, Nobriga et al. 2008, Sommer et al. 2011). Two studies (Feyrer et al. 2007; 2011) have characterized the abiotic habitat of delta smelt using the Fall Midwater Trawl (FMWT) data set. Since 1967, the FMWT has trawled at 100+ fixed stations across the estuary each month from September through December. We have assumed, as Feyrer and colleagues did, that what constitutes suitable abiotic habitat in the POD period is the same as what constituted abiotic habitat during the post-reservoir period. Feyrer et al. (2007; 2010) found that delta smelt inhabit a wide range of salinity and turbidity levels, but the probability of observing a delta smelt is greatest at low salinities, centering on about 2 psu, and at relatively high turbidity levels. They analyzed the FMWT data using a generalized additive modeling approach, which is a commonly-used tool in ascertaining the habitat associations of fishes and other organisms. Generally, the method is a semi-parametric extension of a generalized linear model and is effective for describing non-linear relationships between predictor and response variables. The same method was used by Nobriga et al. (2008) and Kimmerer et al. (2009) in their studies of delta smelt habitat.

Sommer et al. (2011) found that one measure of smelt distribution, the center of distribution, is strongly correlated with X2 (Figure 3. see also Dege and Brown 2004) during the fall months (Figure 3). These relationships appear surprisingly robust even though the FMWT survey has been criticized for not sampling with respect to the tide (see conceptual model (Section 4) below for more details about implications).

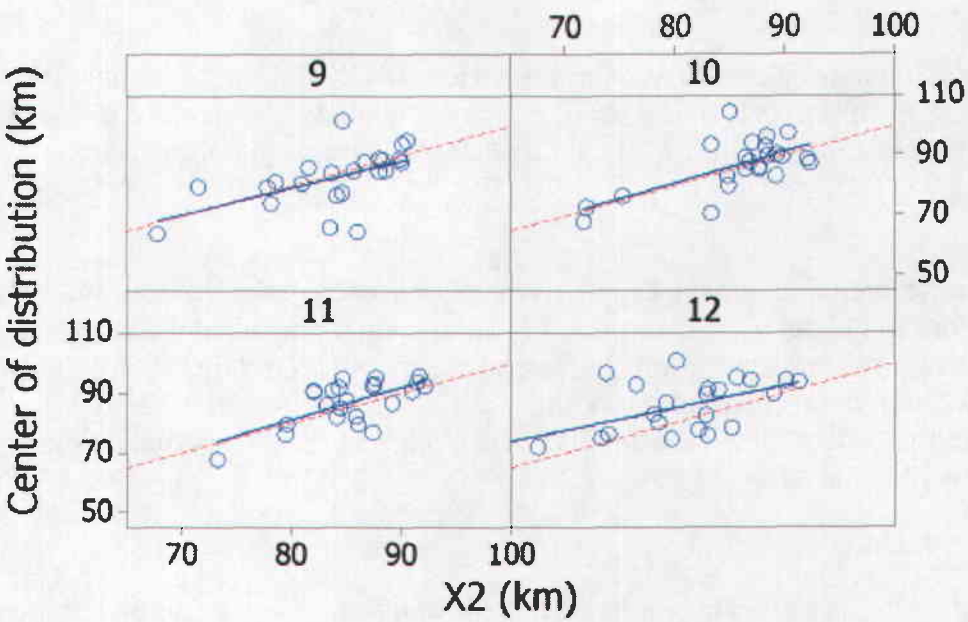


Figure 3. Center of delta smelt distribution during the fall months plotted against X2. Figure is from Sommer et al. (2011, their Figure 3) which has the following caption: "Monthly distribution of adult delta smelt in relation to salinity for the FMWT survey. The fish distribution data represent the centroid of the distribution from the FMWT (Dege and Brown 2004). Salinity is based on X2, the location of the 2-psu isohaline (Jassby and others 1995). The units for each data series represent the distance in kilometers from the Golden Gate Bridge. Hence, smaller values represent a seaward location and larger values represent a landward location. The red dotted lines show when the centroid and X2 values are equal. Centroid values above the red line represent fish distributions upstream of X2: centroid values below the line represent distributions downstream of X2. The blue lines show the fitted lines for the data, based on GLMs."

One issue that we cannot tackle in time to inform this document, but will be addressing as we proceed, arises from the fact that the FMWT samples at fixed geographical points without reference to the phase of the tides. The FMWT sampling plan thus represents an Eulerian approach that is being applied to what might be thought of as a Lagrangian problem, to the extent that delta smelt position themselves with respect to the moving body of water rather than fixed landmarks in order to stay in preferred physical habitat. The reality is probably nuanced. Because delta smelt are pelagic and tend to hold position with respect to a particular water mass over time, we have long thought that they must be "tidally surfing" in the presence of residual downstream flow. That is, they presumably ride the flood tide upstream, then seek refuge in the boundary layer near the bottom, or in littoral areas, during the ebb tide to avoid being swept too far downstream by the combination of net delta outflow and the ebb tide. However, summer/fall net flows are on the order of 1 cm per second downstream (Kimmerer pers com. 2011), a rate which delta smelt can easily overcome by swimming upstream, so tidal surfing is not necessary to maintain position. Recent work by Burau and Bennett (unpublished) may confirm the expectation that delta smelt strongly tidally surf upstream on the flood tide during periods of high net outflow.

Feyrer et al.'s (2007, 2011) approach has been criticized for being able to explain only approximately one quarter of the variance in presence-absence of delta smelt within the overall data set. The critics have asserted that this means that salinity and water clarity are unimportant, because other factors that were not considered in the analysis must explain the remaining three quarters of the variance in the data set.

We agree that adding pertinent additional factors might improve the model, but it is incorrect to interpret the percentage of variance explained as an indication that salinity and turbidity are unimportant (e.g. Abelson 1985, D'Andrade and Dart 1990, Bridgeman et al. 2009). Feyrer et al. (2011) demonstrated that the strong association between delta smelt occurrence and these factors was consistent over the history of the FMWT survey. Kimmerer et al. (2009) demonstrated that the result was also robust whether the response variable was occurrence or abundance. Moreover, in general, this degree of variance explanation is extremely common in studies on other species and in other systems where similarly strongly predictive habitat features have been identified (e.g. Kupshus 2003; Maravelias 1999; Stoner et al. 2001).

(2) X2 as a surrogate for delta smelt habitat

Feyrer et al. (2010) used the FMWT series to develop an abiotic habitat index, which incorporated both quantity and quality of habitat as defined by salinity and water clarity. The annual abiotic habitat index is a unitless quantity that can be thought of as the surface area of the estuary standardized for salinity and water clarity conditions preferred by delta smelt. This annual index exhibits a stepped relationship with X2 (Figure 4). The steep, stepped portion of the curve occurs over X2 ranging between about 85 km and 74 km, with less change outside this range.

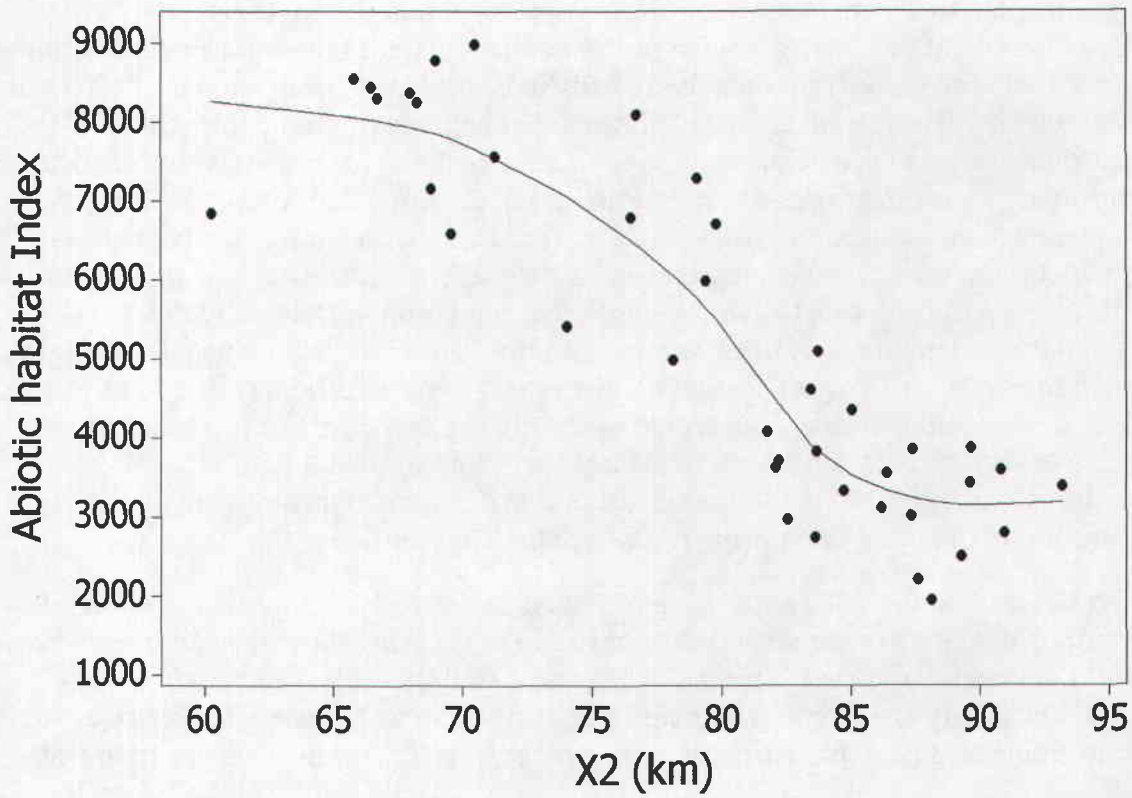


Figure 4. Delta smelt abiotic habitat index plotted against X2. Figure re-drawn from Feyrer et al. (2010). Curve is a LOESS smooth.

Across this 12-km range of X2, the habitat index increases approximately 2-fold. The habitat change is due to geography, in particular to change in the water surface area along the axis of the estuary. This range in X2 corresponds to a geographic area that straddles the confluence of the Sacramento and San Joaquin rivers, which is located at approximately 80km. When X2 is located downstream of the confluence there is a larger area of suitable habitat because the low salinity zone encompasses the expansive Suisun and Grizzly Bays and Suisun Marsh, which results in a dramatic increase in the habitat index (Figure 5). Newer hydrodynamic modeling results using the 3-dimensional UnTRIM Bay-Delta model show that the area occupied by the low salinity zone (defined as average daily salinity conditions of 1-6 ppt) is almost 5,000 hectares (12,000 acres) larger when X2 is 74 km than when it is 85 km (Figure 6, M. MacWilliams, unpublished) and varies in concert with the annual fall habitat index. X2 can thus be used to predict the annual habitat index defined by Feyrer et al (2010).

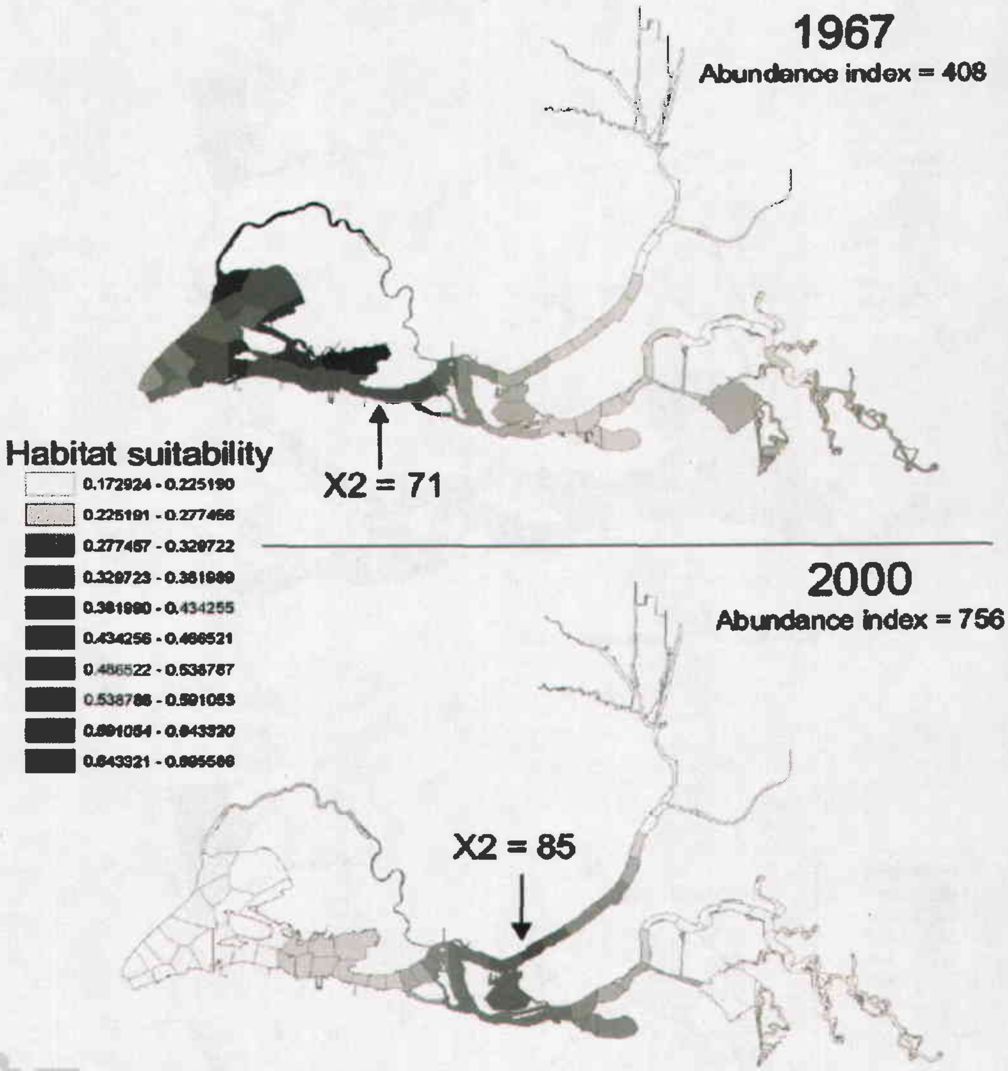
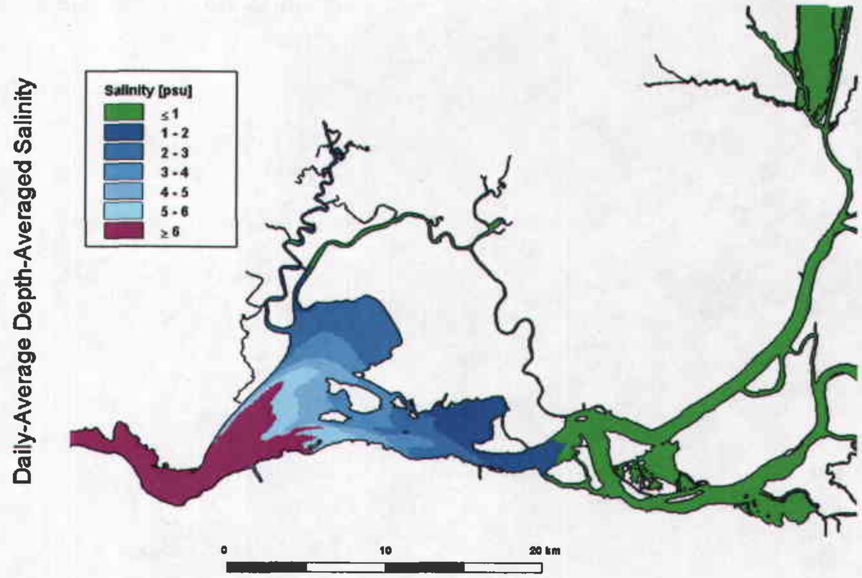


Figure 5. Spatial distribution of habitat suitability for delta smelt under different X2 conditions. Figure taken from Feyrer et al. (2010).



a) a) b)

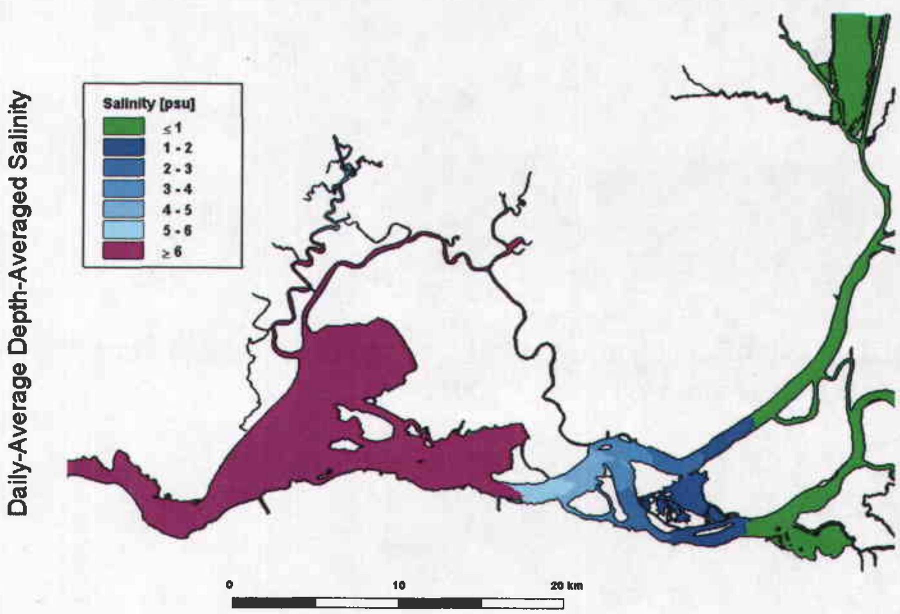


Figure 6. Spatial distribution of the low salinity zone (blue shades) under different X2 conditions: a) when X2=74 km (low salinity area = 9139 ha) and b) when X2=85 km (4262 ha) (Source: M. MacWilliams, unpublished).

This X2-habitat curve has been criticized for not considering biological features of habitat. According to this criticism, the habitat index does not represent the true realized habitat occupied by delta smelt. While it is true that a complete description of habitat includes physical, chemical, and relevant biological characteristics, physical and chemical characteristics are necessary preconditions for suitability. The ability of salinity and turbidity to reliably predict where delta smelt will be found during the fall months indicates that these variables are useful descriptors of habitat. Biotic factors, including food supply, that characterize an area become an important issue only after abiotic conditions are such that smelt can reside in the area without incurring excessive physiological costs or other detrimental effects.

(3) Evidence for a link between habitat and abundance

Two key papers demonstrate lines of evidence of an association between delta smelt abundance and summer and fall habitat conditions. After identifying long-term declines in habitat suitability, Feyrer et al. (2007) hypothesized that habitat changes might affect recruitment. Their analysis revealed a significant long-term decline in delta smelt abiotic habitat suitability and a substantial spatial constriction of habitat space. Incorporating abiotic habitat covariates into a basic stock-recruit model linking the abundance of sub adult delta smelt (FMWT) to juvenile production (TNS) improved the fit of the model. Models that included the abiotic habitat variables accounted for approximately 20% more of the variance in the data set than those without the abiotic habitat variables (r-squared values improved from 0.39 to 0.59). Model selection with AIC indicated that the models with the abiotic habitat variables were superior to the models without them. The salinity variable had the strongest effect.

(4) Delta hydrology, X2, and delta smelt habitat

Average X2 is largely determined by water project operations before winter storms begin in the fall. Since 1967, average fall X2 has moved upstream (Figure 7). In the last decade of the post-reservoir period there was substantial interannual variation in fall conditions. After wetter springs, there were often flood control releases in the fall months that moved X2 downstream for weeks. In the POD period very little interannual variation has been observed in the fall, and fall outflow conditions resemble what formerly occurred after drier springs regardless of actual spring hydrology (Figure 7).

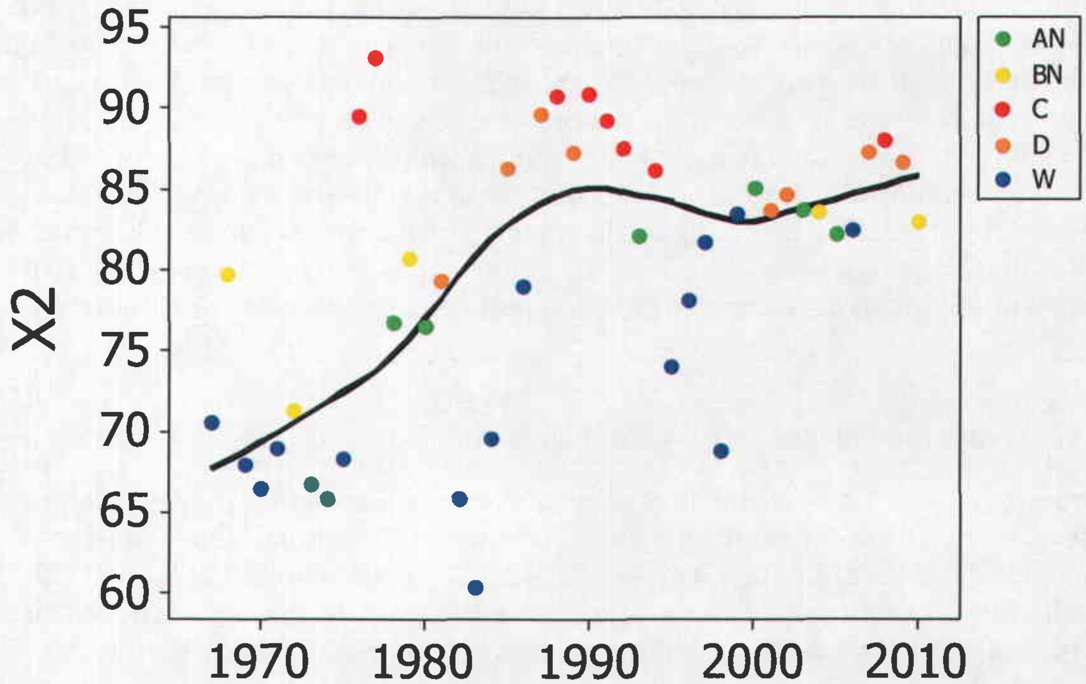


Figure 7. Time series of average fall X2 (km, September – December) since 1967. Symbols: water year type of the preceding spring for the Sacramento valley (W: wet, AN: above normal, BN: below normal, D: Dry, C: critically dry). A LOESS smooth is fitted to the data. (Source: F. Feyrer, unpublished. See also Figure 3 in Winder and Jassby 2010 and Figure 26 in Baxter et al 2010.).

Since 1967, the upstream shift in X2 has resulted in a decline in the average delta smelt abiotic habitat index, with the effect most pronounced in wet or above normal years (Figure 8; Feyrer et al. (2011) calculates a 78% decline from 1967 to 2008). This decline in delta smelt habitat has coincided with the long-term decline in delta smelt abundance (Feyrer et al. 2010). Operations modeling to evaluate the effects of project operations indicated that reduced and homogeneous fall outflow conditions will persist into the future (USBR 2008). Feyrer et al. (2011) concluded that the effects of future project operations in combination with climate change are likely to lead to further declines in delta smelt habitat in all water year types.

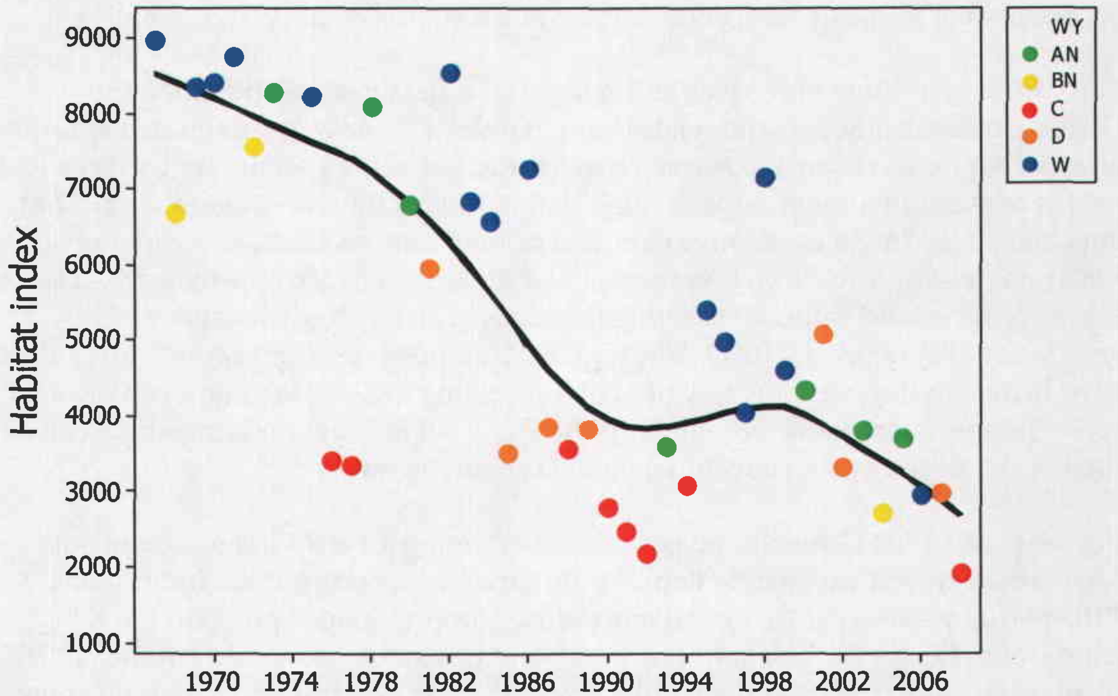


Figure 8. Delta smelt habitat index time series. A LOESS smooth is fitted to the data.

(5) Specific X2 prescription

The justification provided in the 2008 BiOp was to "mitigate the effects of X2 encroachment upstream in current and proposed action operations, and provide suitable habitat area for delta smelt" (BiOp page 373). The basic question is: how to achieve mitigation? It has been demonstrated in both the BiOp and the discussion above that project operations have affected average X2 during the fall (September-December). A closer examination of the data using Kendall trend tests reveals that there are significant positive trends in X2 for September, October, and November but not December in wet and above normal years.

Late fall and winter precipitation often drives X2 downstream in December, and to a lesser extent November (USBR 2008). Moreover, delta smelt may start moving into fresher water in December (Figure 3). For this reason, December has not been considered further. November has some frequency of both early precipitation and flood control releases (USBR 2008). While November has seen significant average reduction in outflow since the post-reservoir period, average outflow in November is still more frequently elevated than in either September or October. September and October have exhibited little variability in X2 in the POD period, and have seen larger changes in monthly average X2 compared with the post-reservoir period.

Consequently, limiting the fall outflow action to the first two fall months appears to be reasonable for protecting delta smelt while also protecting water supplies.

The choice of outflow objectives and related X2 objectives in September and October is constrained by the relationship between outflow and habitat. Feyrer et al.'s habitat index (Figure 4) reveals two habitat index tiers separated by threshold values containing a steep slope: a "high" habitat index tier corresponding to X2 at approximately 74 km or downstream, and a "low" tier for X2 at approximately 86 km or upstream. The curve is empirical and these figures are approximate. That there are threshold values separating these tiers is likely a consequence of geography (Feyrer et al. 2011). The high habitat index tier corresponds to X2 close to or in Suisun Bay, with the low tier corresponding to X2 in the more constrained river channels upstream. Potential mechanisms behind these relationships will be further discussed in the conceptual model section below.

Feyrer et al.'s (2011) results suggest that positioning X2 at 74 km or less in falls after wet years approximately doubles the expected abiotic habitat index above POD-period values (Figure 4) and more closely approximates pre-POD fall X2 conditions (Figure 7). The shift to a persistent upstream positioning of the fall LSZ in all water year types and the resulting reduction in delta smelt fall habitat is one of the most striking changes in the system during the POD years. Reestablishing X2 at 74 km or less is expected to restore delta smelt habitat and produce subsequent abundance benefits.

The use of an 81 km target for falls after above-normal years provides about 50% more of the abiotic habitat benefits than maintaining X2 at 86 km, and at present represents a reasonable intermediate action to restore late post-reservoir period salinity conditions in the fall.

D. Conclusions

It seems clear that outflow affects the quality and extent of abiotic smelt habitat. It also seems clear that restoring lost abiotic habitat availability is likely to produce subsequent-abundance benefits to delta smelt, probably by raising the carrying capacity. We are also left with important unanswered questions that bear on the management of fall outflow. What are the key underlying ecological mechanisms that link outflow to delta smelt abundance, and how important and manageable is each link? How does fall outflow fit in with other drivers of delta smelt abundance? Are there more water-efficient ways to provide the necessary benefits?

Answering these questions is important to good management. In the succeeding sections of this document, we address how to reduce these uncertainties while implementing the outflow action using an adaptive management approach.

III. ADAPTIVE MANAGEMENT OF FALL OUTFLOW

A. Basic Management Framework

Adaptive management is management undertaken in the face of uncertainty. Because large uncertainties about outcomes are a common feature of most natural resource management action, this management approach is strongly embraced by the Delta Plan under development by the State's Delta Stewardship Council as well as by the Bay Delta Conservation Plan under development by Reclamation and other Federal and State agencies. The plan for adaptive management of fall outflow presented here follows the Department of Interior (DOI) Technical Guide for adaptive management strategies (http://www.doi.gov/initiatives/AdaptiveManagement/) fairly closely. The DOI Guide defines the general adaptive management approach as a looped process with six steps (Figure 9).

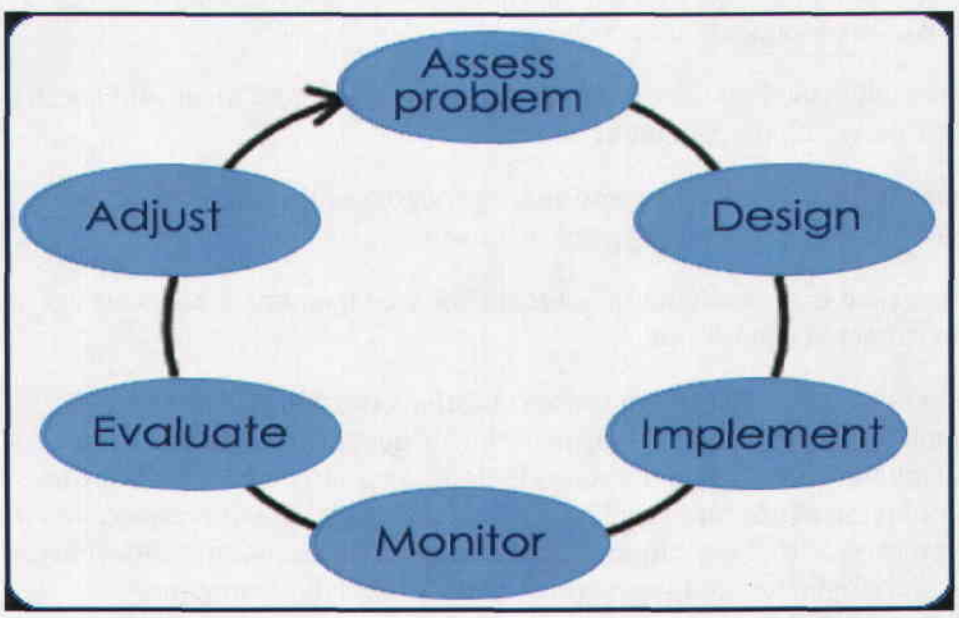


Figure 9. Adaptive management cycle (reproduced from DOI Adaptive Management Technical Guide).

The loop is initially entered in a "set-up phase" at the "assess problem" step. The set-up phase establishes key components of the adaptive management process including management goals and objectives, potential management actions, predictive conceptual and numerical models, and monitoring and research plans. The set-up phase is followed by the iterative phase which uses these components in an ongoing cycle of "learning and doing," with the "doing" based on what is learned and the "learning" aimed at improving the doing. Because of its critical management relevance, the fall outflow adaptive management strategy is based on a fast-paced annual cycle which closes the feedback loop every year and corresponds to the annual delta smelt life cycle. This implies that field and possibly laboratory data would be collected annually, regardless of water-year type and whether fall outflows were augmented. After each year's experience, a workshop and expert panel review would be used to assess what had been learned to date and what adjustments to the action and investigation should be considered.

While the steps in this loop are intuitively obvious, implementing a workable system to achieve learning can be a major challenge. In particular, the key to successfully navigating the sequence DESIGN → IMPLEMENT → MONITOR → EVALUATE lies in establishing management objectives that have the following features. Objectives must be "SMART":

1. Specific and unambiguous, with clear metrics and target conditions;
2. Measurable, with elements that can be readily observed, to promote evaluation of the management action;
3. Achievable, and based on the capabilities of the physical, political, and social system within which management occurs;
4. Results-oriented, with resource end-points and/or conditions, such as habitat conditions, representing their achievement;
5. Time-fixed, such that resolving the outcome of management choices occurs within an expected time-frame.

Defining objectives that satisfy all of these conditions is difficult in most real-world adaptive management situations. One of the hardest problems raised by consideration of fall outflow management lies in defining a satisfactory population-level delta smelt objective that can be reliably measured. Delta smelt are rare, and a simple calculation reveals that we cannot expect to detect an abundance difference in the FMWT after a single year of flow augmentation unless the abundance difference is very large. Other biologically important differences might not be detectable without many observations. To help overcome this difficulty, it is necessary to consider using every investigational tool that can responsibly be applied.

The term 'active adaptive management' (e.g. Walters 1986) has been used to describe the use of experimental manipulation embedded in management action as a learning tool. The advantage of an active approach is potentially much more rapid learning quickly leading to more effective management, but it also requires a much greater level of involvement and commitment by managers, scientists, and stakeholders. The potentially high water costs of implementing fall outflow actions and concomitant need to learn about the effectiveness of outflow management alternatives as quickly as possible strongly recommend the active approach. Lack of control and replicate "treatments" preclude true "experiments," but carefully designed flow adjustments and temporal and spatial comparisons as described below offer a greater likelihood of rapid learning and management adjustments than the previously envisioned more passive approach.

This document is a successor to the 2010 HSG Adaptive Management Plan (USFWS 2010). The HSG approach fell firmly in the 'passive' adaptive management category. The first package of HSG studies, which mostly focused on bottom-up questions related to outflow, was funded in 2010 and brief study descriptions are included in the 2010 POD work plan (Baxter et al. 2010).

This plan incorporates the investigations laid out in the 2010 plan. The new plan relies on both investigation of relevant ecological processes and on direct experimental manipulation of Delta outflow within the confines of the management action. It also includes a comparison with an upstream area (Cache Slough Complex, CSC) that is inhabited year-round by delta smelt (Sommer et al. 2011) and targeted for restoration in the draft Delta Plan and draft Bay Delta Conservation Plan. In combination, the use of these approaches provides a more efficient means than was available in 2010 to improve the conceptual model and test predictions about the consequences of management choices.

B. Elements of the 2011 Adaptive Management Plan

The preceding discussion reviewed the background for Fall outflow management and the basic adaptive management framework.

The succeeding sections of this document lay out plan elements that observe the conventions of adaptive management as described in the DOI Guide for the initial "set-up" phase. It is expected that these elements will be refined over the coming years during annual iterative cycles.

(1) SET-UP ELEMENT: GOALS AND OBJECTIVES

The goals of the fall outflow adaptive management plan are as follows.

I. To manage fall outflow for conservation benefits to delta smelt while minimizing water supply impacts.

II. To increase understanding about the effects of adjusting Fall outflow on the physical and biological environment, how those effects propagate through the ecosystem to affect delta smelt, and how to provide conservation benefits to delta smelt at least water cost.

As described above, objectives provide specific intermediate targets to aid in achieving the goals of the plan. The initial objectives of the fall outflow adaptive management plan emphasize achievement of conservation benefits to delta smelt, improved water efficiency, and improvement in understanding of the underlying basis for the action.

1) Use enhanced Delta outflow in wetter falls to increase the geographic area of the low-salinity zone, increasing the availability of high-quality LSZ physical habitat for delta smelt.

2) Restore LSZ connectivity to Suisun Bay in wetter falls, especially including Grizzly Bay and Honker Bay, to provide delta smelt access to the channel and shoal habitats in that area and allow access to Suisun Marsh sloughs.

3) Ensure higher annual and seasonal variability in salinity regimes in eastern Suisun Bay to reduce density of *Corbula* adults, thereby reducing the impacts of *Corbula* grazing on phytoplankton biomass and capture of selenium into the food chain year-round.

4) Use practical experience of managing enhanced fall outflow during wetter falls to improve efficiency of fall outflow water operations, including exploring utility of spring-neap outflow throttling and other possible methods to improve water efficiency of the action.

5) Improve understanding of turbidity dynamics by completing field studies of Delta sediment suspension and transport processes, and improve numerical modeling of hydrodynamics and sediment transport.

6) Improve understanding of delta smelt growth, health, and fecundity in order to evaluate the roles of delta outflow and other processes occurring through the summer and fall in determining the state of delta smelt at the onset of the spawning migration.

7) Improve understanding of plankton and benthos dynamics in Suisun Bay and the western Delta to support investigation of physical processes that may affect the abundance and accessibility of food for delta smelt and other species during the summer and fall.

8) Improve understanding of nutrient and contaminant dynamics that may be affected by outflow variability and the location of the LSZ during summer and fall, to support investigation of their potential influences on delta smelt growth, health, and fecundity.

(2) SET-UP ELEMENT: INITIAL MANAGEMENT ACTION AND ALTERNATIVES

The starting point for management includes the initial action and its alternatives. The choice depends on two main considerations. First, the management approach, including the manner in which the alternatives are deployed for study, must provide necessary conservation benefits to delta smelt. The second is that the management alternatives and the approach to deploying them must provide opportunities for learning. Both considerations limit the universe of possibilities.

We have relied on the analysis, discussion, and literature cited earlier in this document to conclude that although there are important uncertainties associated with the outflow prescription in the RPA, it is almost certain to provide improved fall habitat conditions for delta smelt and likely to result in better recruitment. Hence, the initial conservation action adopted in this plan is to have the projects operate to meet the targets identified in the 2008 RPA.

2011 Operations

Water year 2011 was quite wet, with precipitation falling throughout the winter and spring, even into June. The year has been officially classified as "Wet" by the State of California. On July 21, 2011, Reclamation transmitted a memorandum describing its proposed operations for fall 2011. Those operations implemented the 74 km fall outflow action as described for falls after hydrologically "wet" years in the 2008 RPA. The Service responded on July 22 that the proposal was consistent with Component 3 of the RPA.

The letter summarizes Reclamation's relevant features of operations that affect outflow and X2, including total Delta inflow, combined exports, expected Delta outflow, and expected X2. The proposal is premised on additional assumptions about consumptive use within the Delta that are based on historical demand patterns, with consumptive use declining through October to a point where they can be neglected in November. Moreover, the proposal was prepared without full feedback from DWR, so assumptions were made about DWR actions during the fall that may have to be revisited later. Because of the unusually wet hydrology, Reclamation expects that X2 will be close to the target of 74 km at the end of August, making the transition from August to September seamless.

August:

"In order to meet that average through the month of September, Reclamation anticipates the CVP and SWP will begin to modify combined operations for the second half of August. Based on a 50 percent exceedance hydrology, in the second half of August, Reclamation anticipates average daily combined inflows to the Delta of 25,000 cubic feet per second (cfs), combined exports of about 11,400 cfs and net Delta outflow of 11,800 cfs that will move X2 near the 74 km target. Because of the high level of exports and reservoir releases for multiple purposes during this period, Reclamation has forecasted no water cost to either the CVP or SWP during the month of August."

September:

"Reclamation intends that the CVP and SWP will operate in September to maintain monthly average X2 no greater than 74 kilometers (km). In order to meet that average through the month of September, Reclamation anticipates the CVP and SWP will begin to modify combined operations for the second half of August. Based on a 50 percent exceedance hydrology, in the second half of August, Reclamation anticipates average daily combined inflows to the Delta of 25,000 cubic feet per second (cfs), combined exports of about 11,400 cfs and net Delta outflow of 11,800 cfs that will move X2 near the 74 km target. Because of the high level of exports and reservoir releases for multiple purposes during this period, Reclamation has forecasted no water cost to either the CVP or SWP during the month of August.

Reclamation's current forecast projects an average outflow of 11,400 cfs to maintain X2 at 74 km. Reclamation is forecasting a continued average inflow to the Delta of about 25,000 cfs based on the 50 percent exceedance hydrology. Under these conditions, combined exports will be maintained near 11,000 cfs. Because of the high level of exports and reservoir releases for multiple purposes during this period, Reclamation has forecasted no water cost to either the CVP or SWP during the month of September."

October:

"Reclamation intends that the CVP and SWP will also operate in October to maintain a monthly average X2 position no greater than 74 km. In October, Reclamation is forecasting an average daily inflow of 18,200 cfs into the Delta. Combined average exports are expected to be reduced to approximately 6,300 cfs. The main reason for this reduction in total exports as compared to September is that the SWP has indicated that they will likely reduce reservoir releases on the Feather River from 7,000 cfs to 1,750 cfs in mid-October to avoid triggering a requirement to maintain those higher releases through the winter to prevent the dewatering of salmon redds in the Feather River. With the reduced reservoir releases, combined exports will be correspondingly reduced to maintain average X2 at 74 km. Reclamation believes Delta outflow required to maintain X2 at 74 km in October could be less than 11,400 cfs and that the initial calculation of outflow required is only an estimate. Assuming Delta outflow of 11,400 cfs is required to maintain average X2 at 74 km, and that DWR will reduce its Feather River releases to 1,750 cfs, then Reclamation estimates reduced exports of up to 300,000 acre-feet (AF) by the SWP. If Delta outflow of 10,000 cfs proves to be sufficient to maintain average X2 at 74 km in October, the SWP would incur an estimated reduction of exports of about 210,000 AF for October. In addition, if DWR's river releases at Oroville Dam were to be set above 1,750 cfs, the SWP could increase exports while maintaining X2 at 74 km. Based on the 50 percent exceedance forecast and an outflow requirement of between 11,400 and 10,000 cfs, Reclamation estimates little or no water supply impact to the CVP for October." [Footnote describing Kimmerer-Monismith X2 estimator omitted.]

November:

"Specific November Operations:

A. Any accumulated CVP and SWP Sacramento Basin reservoir storage attributable to November runoff will be added to reservoir releases. To the extent possible, Reservoir releases will be adjusted as necessary to achieve no net increase of storage in the month of November. The total amount of runoff passed-through for release may be apportioned among the Sacramento River Basin CVP and SWP reservoirs in any combination, irrespective of the source of the reservoir inflow, as long as the combined total of releases equals the volume of November inflow into these reservoirs.

B. For purposes of calculating the average November outflow required under these proposed operations, the average required outflow will be set at one half the computed Delta inflow in November, but will be no less than an average of 5,700 cfs. Delta inflow will be calculated in a manner consistent with the technique used in the State Water Resources Control Board's water right decision D-1641. At the beginning of the month of November, outflow will be based on one half the then current 14-day running average Delta inflow and will be adjusted through the month to achieve an average monthly outflow that is one half the computed average inflow for November.

C. In the event there is a net increase in Sacramento Basin CVP and SWP storage during November, [excepting storage accrued while X2 is maintained at 74 km]*, the increase in reservoir storage shall be released in December in a manner consistent with the RPA as quoted above. If this situation should arise, Reclamation will notify the Service to discuss project operations into the month.

D. Nothing in this proposal should be construed to override potential flood operations at CVP and SWP reservoirs and facilities that operators judge to be required for health, safety, and protection of property. Reclamation will notify the Service if operations deviate from those outlined in this proposal due to any of these reasons.

[T]hese operations are intended to result in November Delta outflow that will vary in accordance with runoff from the Sacramento and San Joaquin River Basins. In the absence of significant November precipitation, this proposal would impose no additional reservoir releases at the CVP and SWP reservoirs beyond those needed to pass through projected November reservoir inflows, not requiring pumping reductions beyond those necessary to maintain a minimum Delta outflow of at least 5700 cfs, or other modifications to coordinated CVP and SWP operations beyond what is needed to meet any other relevant obligations, both upstream and in the Delta. With increasing November runoff, the proposed operations for this year would result in Delta outflow to increase until the 74 km X2 value required for September and October under the RPA is achieved. Runoff exceeding what is needed to achieve 74 km X2 could be retained in upstream reservoirs or exported consistent with D-1641 at the discretion of the CVP and SWP, as it would not be needed to achieve the outflow objectives of the action.

Reclamation intends that the CVP and SWP will operate in November to maintain a monthly average Delta outflow consistent with the methods described above. Applying these methods in November, Reclamation is forecasting that average Delta outflow for the month would be 8,500 cfs based on the 50 percent exceedance hydrology forecast. In a 90 percent exceedance hydrology forecast, Delta outflow is estimated to be around 7,000 cfs for the month of November. Reclamation would anticipate that a Delta outflow sufficient to maintain X2 at 74 km (11,400 cfs) would occur at about a 40 percent exceedance hydrology this fall."

The asterisk marks text not in the original memorandum. The bracketed text was added for clarification.

There are no operations planned for December. However, under one contingency of November operations described above, the inadvertent retention of runoff that should have been passed through, the excess water would be released in early December to complete the fall action. There is some uncertainty how much runoff might remain unspent at the end of November; experience will likely help refine implementation of the action.

Under the operations described above, the projects will achieve the X2 target in September and the first half of October at no cost, simply by augmenting Delta inflow with reservoir releases that are expected to be required to evacuate flood space by November 1. During the second half of October, Reclamation expects that the SWP will reduce Oroville releases to set Feather River flow at a low level when permit restrictions are in force, with a corresponding reduction in SWP exports following in order to maintain Delta outflow at a level sufficient to keep average X2 at 74 km for the month. November operations will depend on precipitation, and the exact mix of tributary flows that might contribute to Delta inflow in November is hard to predict at present.

<u>San Joaquin River contribution to Delta outflow</u>

The San Joaquin River is shallower and has higher nutrient concentrations than the Sacramento River (Ball and Arthur 1979; Jassby 2008). The San Joaquin River thus generally supports higher levels of phytoplankton biomass. There are several reasons, however, for assuming that very little of this biomass is likely to make its way to the western Delta and Suisun Bay during Fall 2011. First, the flows in the San Joaquin are likely to remain relatively high, so the standing stock of phytoplankton will be relatively low (Jassby 2005). Second, owing to the absence of a barrier at the head of Old River, a portion of the phytoplankton load will be diverted directly to the CVP/SWP export facilities before it can reach the Delta (Jassby 2005). Depending on flow, most of the remaining phytoplankton load will settle out and die once it reaches the Stockton Deepwater Ship Channel (Jassby 2005). Finally, during most of the two-month period during which X2 will be fixed at 74 km, total export pumping will be set at 6000 cfs or higher. This is likely to mean that the total south Delta export rate will be similar to or higher than San Joaquin flow. Under these circumstances, only a small fraction of the San Joaquin's water reaches the western Delta, and then only because of tidal mixing processes rather than net flow. We plan to carry out water "fingerprinting" studies of several scenarios during the next month to more thoroughly explore this question.

Considerations for Future Operations

This plan does not establish a specific sequence of management treatments beyond 2011. In keeping with the premises of adaptive management, we have considered the kinds of information that will be needed to make informed management decisions and how best to learn from experience this year, but the actual choice of future management actions will depend on both management imperatives and the findings of this year's investigation.

That said, we believe some key questions will be most efficiently answered by implementing the action in very different ways (within the boundaries of prudence) in otherwise similar years and contrasting the results. To establish this idea for the future, we propose that there should be one initial management alternative to the RPA prescription, and that it should produce the highest practicable contrast with the RPA. The best choice from a learning point of view would be an alternative in which the action is not taken at all, with X2 instead managed so that it remains in the 84-86 km range during the period in which the RPA targets would otherwise be in force. This would provide a 10-12 km X2 contrast that covers the steepest portion of Feyrer et al.'s curve. We realize, however, that this approach creates some additional unmitigable risk to the species. If this approach is unavailable, we will consult with USFWS to determine what lower-outflow alternative is acceptable.

Because we have observed an almost unbroken string of low-outflow Falls since 2000, it is clear that the most informative Fall outflow action in 2011 would be a high-outflow action. With 2011 now officially designated as a "wet" year, we recommend that the Fall 2011 action should be the 74 km "wet"-year action described in the 2008 RPA.

While a number of key variables has been historically monitored, new forms of monitoring have been identified as key elements of the plan. Both high-outflow and low-outflow management alternatives will have to be observed with the full monitoring system in place. As the adaptive management process evolves, therefore, we expect that it will be necessary to observe both high- and low-flow actions in otherwise similar years to resolve key management questions and achieve the first goal of this plan.

(3) SET-UP ELEMENT: LEADERSHIP AND COLLABORATIONS

Successful implementation of this plan requires effective leadership. After review of a large number of case studies, Walters (2007) concluded that (a) adaptive management plans have succeeded less often than they have failed, and (b) a common feature of those that have succeeded is that they were led by strong, single-minded individuals who had been granted the time and resources to ensure success. Citing Walters, the outside panel that reviewed an earlier version of this plan recommended the identification of a single, highly empowered leader to oversee implementation of the plan. "The fall outflow plan leadership team should include one individual who is given the freedom to ensure that the implementation and monitoring of the plan is her/his top priority and principal responsibility for the next year starting July 1, 2011." (Page 25)

We agree with this recommendation and are working to identify a full-time leader with the right qualities to act as a lead scientist for the plan. In the meantime, a "core group" of scientists and managers representing several State and Federal agencies has offered its services to lead further development of the plan and implementation of the fall 2011 studies.

The core group, eventually led by the lead scientist, will work to implement the studies associated with this plan under the management of the Interagency Ecological Program (IEP). The IEP has established scientific and monitoring expertise in the Delta and has for six years conducted the similarly complex and cross-cutting Pelagic Organism Decline (POD) investigation. The IEP represents an established cooperative endeavor of the State and Federal agencies with interests here. It provides a management superstructure within which the studies and decision-support system needed for this adaptive management plan can be developed under the supervision, and with the support, of agency policymakers.

We plan to release this plan to the public in the near future, and hope to foster cooperative participation among the agency and stakeholder entities that are interested in the plan. Ongoing litigation bearing on the subject of this plan has made it difficult to obtain cooperative participation from the water users, who are plaintiffs. However, we will continue to invite their participation, as we strongly agree with the review panel's recommendation that stakeholder participation be enlisted.

> "The Panel hopes that the research community, water users and NGOs may conduct supplemental monitoring to further our understanding of the ecosystem services provided by the Fall outflow manipulation. This has also been expressed as moving toward a 'single version of the truth' where the best-available science with a quantification of the inherent uncertainties is developed and separated from the difficult policy decisions that must be made (Nunes, 2011). The Panel expects that the 2011 manipulation will be significant enough to address some of the fundamental questions posed by Reclamation in the Draft AM Plan and presents an opportunity to invest in monitoring to draw defensible scientific conclusions. Whatever Fall action is adopted, the decision is likely to be criticized and contested. Previous attempts at these major manipulations have been scaled back or inadequate monitoring programs were implemented to deduce findings. This opportunity should not be lost." (page 13)

(4) SET-UP ELEMENT: MODELS ABOUT SYSTEM DYNAMICS AND DELTA SMELT RESPONSES TO FALL OUTFLOW MANAGEMENT

This plan relies on a Bay-Delta pelagic fishes conceptual framework developed by the IEP that identifies and interrelates fish abundance and key drivers that help to explain the pelagic organism decline (POD) (Sommer et al. 2007, Baxter et al. 2010). It also uses the subsequent adaptation of the POD conceptual models described in the 2010 HSG Adaptive Management Plan (USFWS 2010) as well as an ecosystem-based view of estuarine habitats that was presented by an expert group to the SWRCB in their proceedings to develop flow recommendations and which was reflected in the SWRCB's final report (SWRCB 2010). In the following sections we first briefly review the existing conceptual models and then provide a new conceptual model specifically designed for adaptive management of fall outflows in 2011. Results from monitoring and studies in 2011 will inform conceptual model refinement for future years.

a) Role of Quantitative Models

Numerical models quantifying and integrating many aspects of the conceptual models are currently under development (see monitoring and study plan section, and Appendix 2) and are expected to deliver results that will help guide fall outflow management in the coming years. Results from these models will, however, not be available for some time, and fall flow management in 2011 along with associated studies and monitoring will thus necessarily rely to a large degree on conceptual models. Development of quantitative models, and their integration with the Newman et al. life cycle model currently under development, will proceed on a parallel track with an expectation that one to several years will be required before products of sufficient quality and management applicability are available for use. The quantitative modeling framework included with a previous draft of this plan is provided as Appendix 2.

b) Existing Conceptual Models

Basic POD model - The basic POD conceptual model (Figure 10) focuses on the four POD fish species and is rooted in classical food web and fisheries ecology. It contains four major components: (1) prior fish abundance, in which abundance history affects current recruitment (i.e., stock-recruitment effects); (2) habitat, in which the amount of water (volume or surface area) with suitable conditions for a species has changed because changes in estuarine water quality variables, disease, and toxic algal blooms in the estuary affect survival and reproduction; (3) top-down effects, in which predation and water project entrainment affect mortality rates; and (4) bottom-up effects, in which consumable resources and food web interactions affect growth and thereby survival and reproduction. Each model component contains one or more potential drivers affecting the POD fishes.

Although the IEP framework recognizes bottom-up, top-down, and prior-abundance driver categories, it treats habitat-related drivers differently.

> "For the habitat component of the model, a key point is that habitat suitability affects all other components of the model. This is indicated by the overlap of habitat with all other components in [Figure 2]. Hence, changes in habitat not only affect pelagic fishes, but also their predators and prey, which, in turn, can also have effects on the habitat they occupy." (Baxter et al. 2010, p. 23)

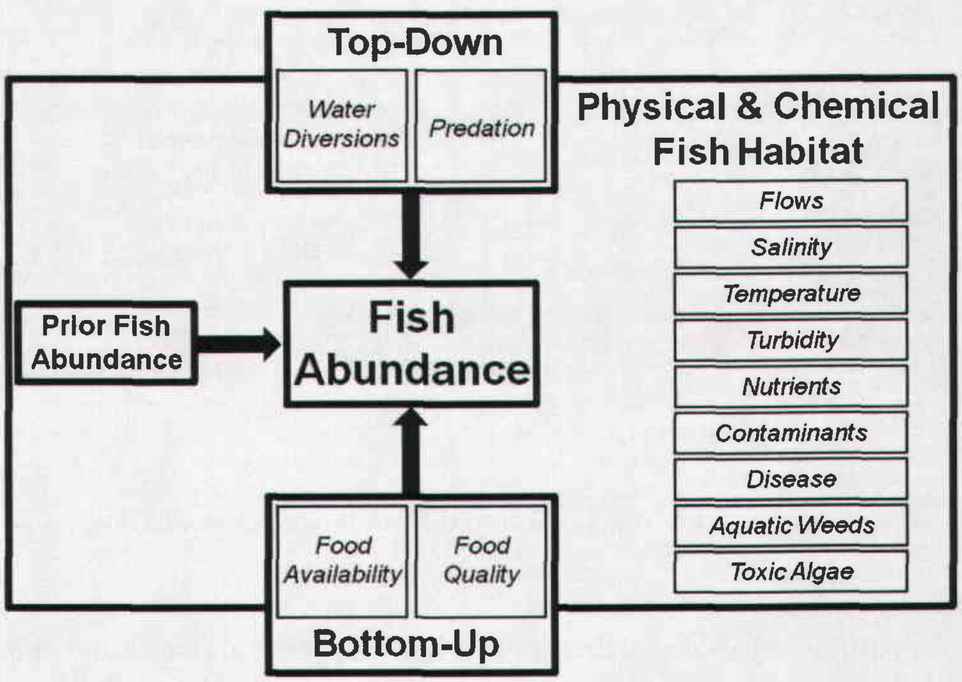


Figure 10. The basic conceptual model for the pelagic organism decline (updated from Sommer et al. 2007). Adapted from Baxter et al. 2010.

This treatment recognizes that habitat features may affect each of the other categories of drivers additively, antagonistically, or synergistically, producing outcomes that are not always easily predictable.

Delta smelt species model - We also rely on the delta smelt species model developed by the POD investigators which focuses on delta smelt (Figure 11; Baxter et al. 2010).

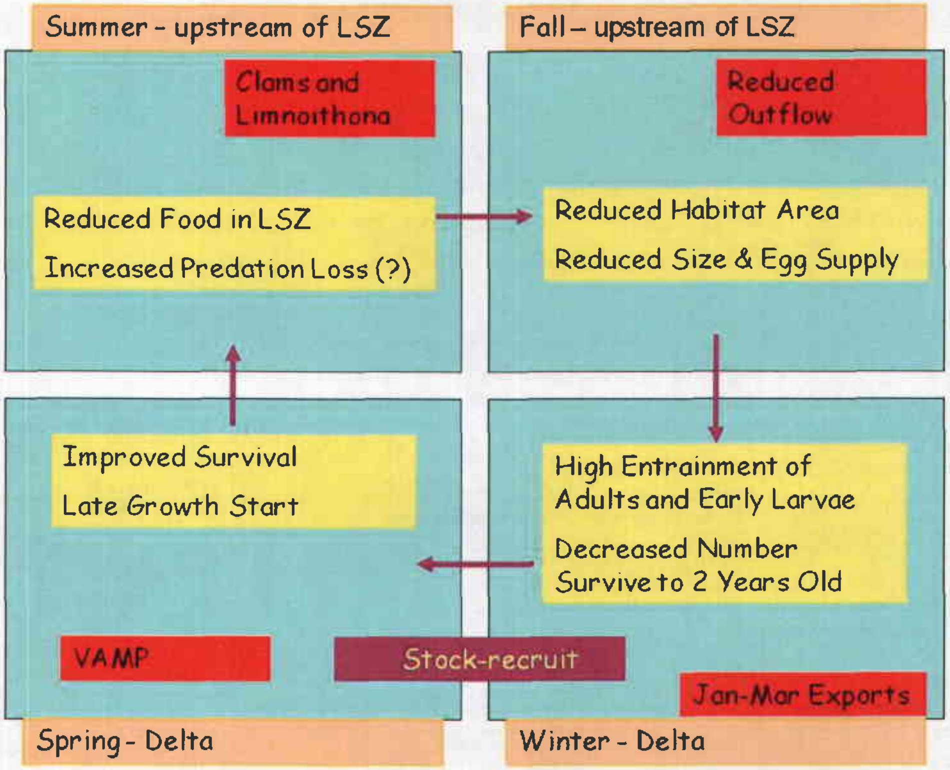


Figure 11. Delta smelt species model. Adapted from Baxter et al. 2010.

The model identifies key seasonal drivers in red, with proximal causes and effects in yellow. In fall, reduced habitat area is posited to affect the population through reduced growth and restricted egg supply rather than direct mortality. Fall effects therefore manifest themselves in potential limits on subsequent abundance, with the outcome depending on a variety of other seasonal factors.

Regime Shift Model – This more recently developed conceptual model focuses on the ecosystem of the upper estuary and posits that the POD is a manifestation of a rapid and comprehensive ecological regime shift that followed a longer-term erosion of ecological resilience in the estuary (Figure 12, see also Manly and Chotkowski 2006, Moyle and Bennett 2008, Baxter et al. 2010, Mac Nally et al. 2010, Thomson et al. 2010, Moyle et al. 2010). This conceptual model serves as a working hypothesis for future ecosystem investigations. Outflow, salinity, and turbidity are considered among the key "slow" environmental drivers in this conceptual model. The model posits that a more westward and variable salinity gradient favors native species (such as delta smelt), while a more eastward, constricted, and stable salinity gradient favors non-native and nuisance species (such as invasive jelly fish) and contributes to the erosion of the resilience of the original ecological regime. In this context, the fall outflow action would help restore resilience. This conceptual model also recognizes the step decline in turbidity in Suisun Bay that occurred after the sediment-flushing El Niño event of 1997–1998 (Schoellhamer 2011). Along with persistent high fall salinity in Suisun bay during the POD period, this sudden clearing may have also contributed to the POD regime shift and affected delta smelt fall habitat.

Old Regime	Environmental Drivers	New Regime
Variable, High	Outflow	*Variable, Lower*
To the west, Variable	Salinity gradient	*To the east, Constricted*
Complex, Variable	Landscape	*Simplified, Rigid*
Low, Variable	Temperature	*High, Uniform*
High, Variable	Turbidity	*Low, Less variable*
High P, low N	Nutrients	*Low P, High N (NH_4+)*
Few, Low	Contaminants	*Many, High*
Predation, Fishing	"Harvest"	*Predation and Entrainment*

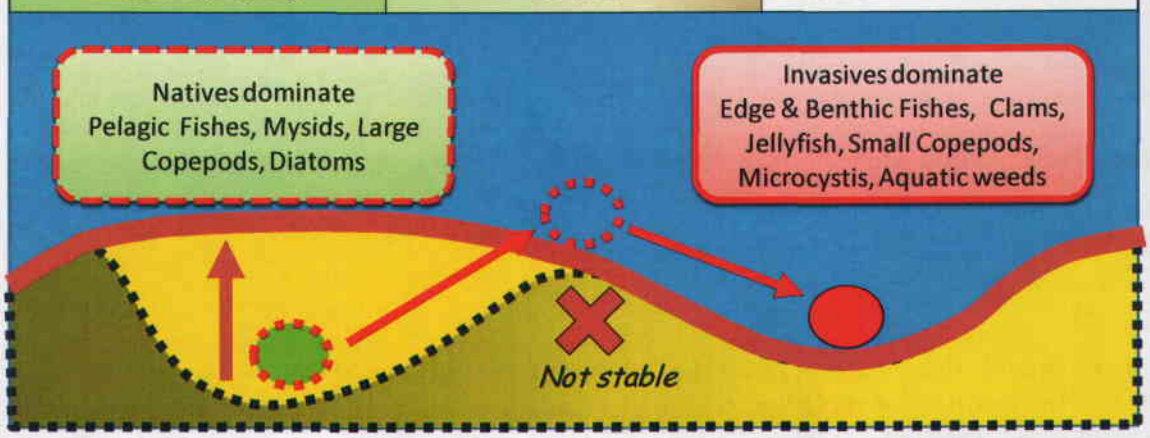


Figure 12. Regime shift model. From Baxter et al. (2010, their Figure 8 which has the following caption: "The ecological regime shift in the Delta results from changes in (slow) environmental drivers that lead to profoundly altered biological communities and, as soon as an unstable threshold region is passed, a new relatively stable ecosystem regime."

HSG Model - The 2010 HSG Adaptive Management Plan adapted the POD models to address key processes associated with habitat quality and quantity for delta smelt in the fall. This model represents habitat, bottom-up, and top-down drivers affecting delta smelt abundance, distribution, and health (Figure 13). Fall X2 is envisioned as a "filter" modifying the drivers and subsequent delta smelt responses. It implies that most of the potential effects of fall outflow are expected to occur through the processes that affect the growth and survival of juvenile and fecundity of adult delta smelt.

Figure 13. HSG model of effects of fall outflow on delta smelt through changes in habitat quantity and quality. Fall outflow affects (either directly or indirectly) the quantities on the left.

Estuarine Habitats Model - Peterson (2003) proposed an ecosystem-based view of estuarine habitats. A modified version of this view was presented by the Environmental Flows Group to the SWRCB in their recent proceedings to develop flow recommendations for the Delta. This group included regional technical experts including several members of the IEP POD team and others. Their view of estuarine habitats was reflected in the SWRCB's final report (SWRCB 2010) and provides the final piece for a new conceptual model for fall outflow adaptive management. In this view, the environment of an estuary consists of two integral parts:

(1) a stationary topography with distinct physical features that produce different levels of support and stress for organisms in the estuary, and

(2) a dynamic regime of flows and salinities. Organisms passively transported by flow or actively searching for a suitable salinity will be exposed to the different levels of support and stress that are fixed in space in the stationary topography.

Together these stationary and dynamic habitat features control the survival, health, growth and fecundity of estuarine pelagic species and ultimately their reproductive success (Figure 14).

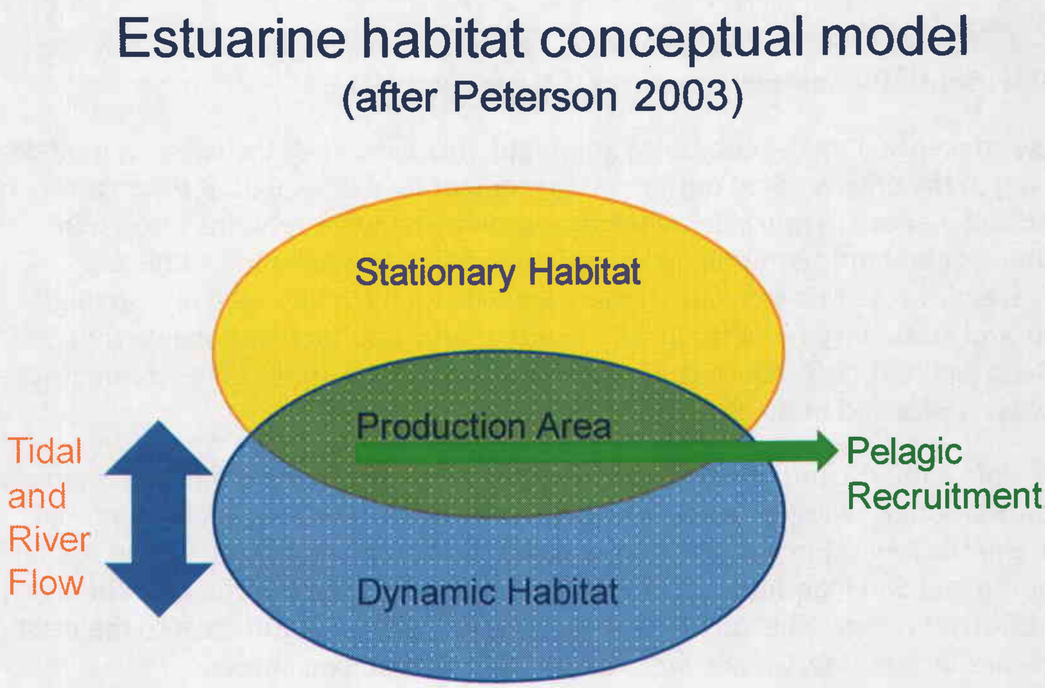


Figure 14. Estuarine habitat conceptual model presented to the SWRCB by the Environmental Flows Group (the full presentation is available at http://www.swrcb.ca.gov/waterrights/water_issues/programs/bay_delta/deltaflow/defg_presentation.shtml).

For the Delta, this dynamic and interacting view of estuarine ecology is reflected in the comments of UC Davis scientists to the SWRCB: "A vast ecological literature documents the significant roles of habitat complexity and variability in promoting abundance, diversity, and persistence of species in a wide array of ecosystems. This literature stresses the importance of both predictable and stochastic physical disturbances, timing and extent of resource availability, as well as the degree of connectivity among habitat patches, relative to the abilities of species to move between them. However, landscapes are not stable in their configurations through time and environmental fluctuations generally increase the duration and frequency of connections among patches of different kinds of habitat. This can increase turnover of resources, making the resources available to a shifting array of species. The variability implies that different processes interact at various scales in space and time, with the result that more species are present than would be characteristic of a hypothetical stable landscape (e.g., an agricultural landscape). Therefore, ecological theory strongly supports the idea that an estuarine landscape that is heterogeneous in salinity and geometry (depth, the configuration of flooded islands, tidal sloughs, floodplains, etc.) is most likely to have high overall productivity, high species richness, and high abundances of desired species." (Moyle et al. 2010).

c) A New, Spatially Explicit Conceptual Model For 2011

This new conceptual model combines and highlights aspects of the existing models pertaining to the effects of fall outflow management on delta smelt. It offers a way to describe and explore in more detail what is known and what remains uncertain about abiotic and biotic components of delta smelt fall habitat under different outflow scenarios. In this conceptual model, we distinguish between interacting dynamic and stationary (geographically fixed) abiotic habitat components that affect delta smelt, their predators, and their food resources in the river channels of the western Delta and in the Suisun region in the fall.

The dynamic habitat components are associated with different fall outflow regimes, while the stationary habitat components are associated with the specific physical structure of the low salinity zone when it is located in the confluence region of the Sacramento and San Joaquin Rivers (hereafter referred to as the "river confluence") or in the Suisun region. The Suisun region borders the river confluence to the west and includes Suisun Bay, Grizzly Bay, Honker Bay, and Suisun Marsh.

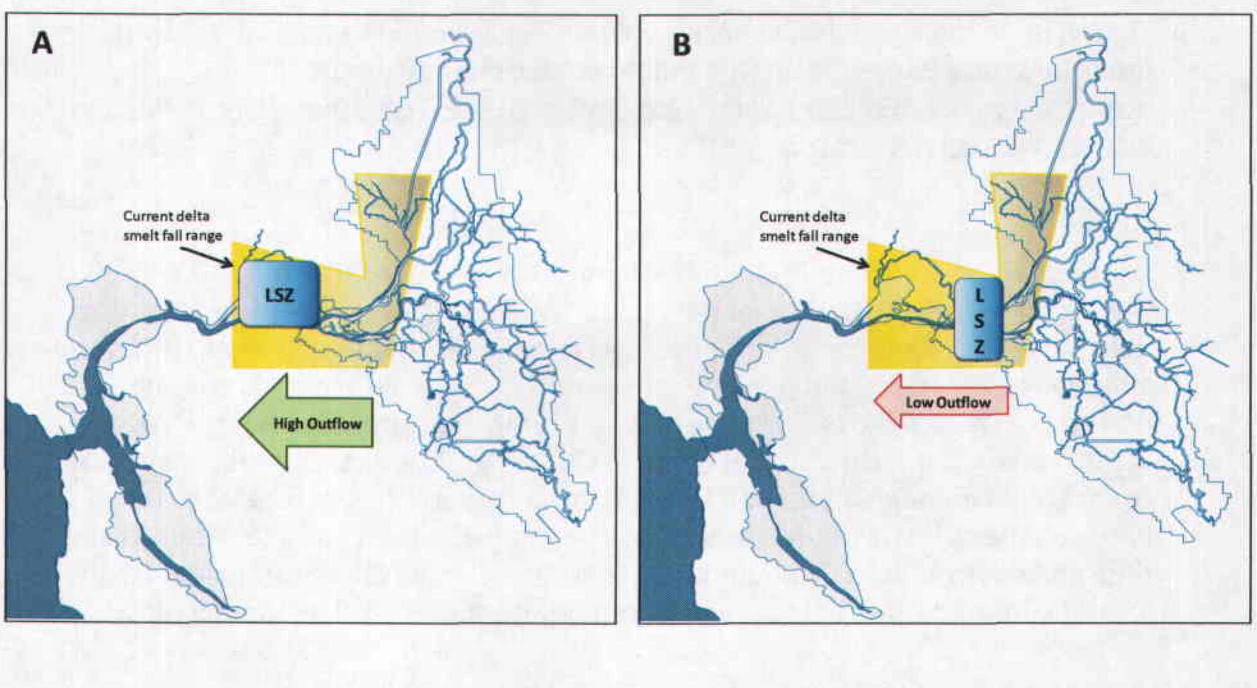


Figure 15: In the fall, delta smelt are currently found in a small geographic range (yellow shading) that includes the Suisun region, the river confluence, and the northern Delta, but most are found in or near the LSZ. **A:** The LSZ overlaps the Suisun region under high outflow conditions. **B:** The LSZ overlaps the river confluence under low outflow conditions.

The small current range of delta smelt (Figure 15) encompasses the Cache Slough complex and the lower portion of the Sacramento ship channel in the northern Delta, the river confluence in the western Delta, and the Suisun region. Historically, delta smelt also occurred in the central and southern Delta (Erkkila et al. 1950), but they are no longer found there in the summer and fall months (Bennett 2005, Nobriga et al. 2008, Sommer et al. 2011). Juvenile and sub-adult delta smelt occur mostly in the low salinity zone in the fall (LSZ, here defined as 1-6 psu) and are most abundant at 1-2 psu (Swanson et al. 1996, Bennett 2005, Sommer et al. 2011). While delta smelt can survive year-round in fresh water, the salinity levels in the LSZ seem best suited to the physiology of juvenile and sub-adult delta smelt. Delta smelt are generally not found at salinity levels above 14 psu and cannot survive at salinity levels above about 20 psu (Swanson et al. 2000).

In our conceptual model, the LSZ is a dynamic abiotic habitat component. Its size (surface area) and location varies with net freshwater outflow from the Delta. Under high outflow conditions, a broad LSZ overlaps a large part of the Suisun region (Figure 15 A) and the potential production area (see Figure 14) for delta smelt is relatively large and spread out across the deep and shallow areas of the Suisun region. Under low outflow conditions, a narrower LSZ overlaps the river confluence (Figure 15 B) and the potential production area for delta smelt is smaller and mostly confined to deep river channels.

Delta smelt and other organisms that seek the salinity levels of the LSZ or are transported by flow into this zone encounter and respond differently to different dynamic and stationary habitat features under high and low fall outflow conditions that place the LSZ in either the river confluence or in the Suisun region (Figure 16). This conceptual model focuses on the western part of the current delta smelt range. After describing this model, we will also briefly consider delta smelt habitat in the northern delta. This region has lower salinity levels, but resembles the LSZ in some of its other habitat features and, like the Suisun region, is an important target for habitat restoration (ERP 2011).

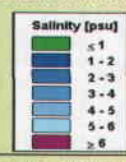
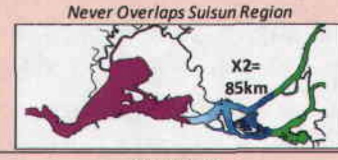
Suisun Region	Stationary Abiotic Habitat Components	River Confluence
Higher	Bathymetric Complexity	Lower
Higher	Erodible Sediment Supply	Lower
Many in South, Fewer in North	Contaminant Sources	Many
Fewer	Entrainment Sites	More
Variable Fall Outflow Regime	**Dynamic Abiotic Habitat Components**	**Static Fall Outflow Regime**
Higher After Wet Springs	Net Total Delta Fall Outflow	Always Low
Higher After Wet Springs	San Joaquin River Contribution to Fall Outflow	Always Low
After Wet Springs, Broad Fall LSZ Overlaps Suisun Region 	Location and Extent of the Fall LSZ (1-6 psu) 	Narrow Fall LSZ In River Channels, Never Overlaps Suisun Region 
Higher After Wet Springs	Hydrodynamic Complexity in the Fall LSZ	Always Lower
Higher After Wet Springs	Wind speed in the Fall LSZ	Always Lower
More Variable, Higher After Wet Springs	Turbidity in the Fall LSZ	Always Less Variable, Lower
More Variable, Maybe Lower After Wet Springs	Contaminant Concentrations in the Fall LSZ	Less Variable, Maybe Higher
LSZ Overlaps Suisun Region	**Dynamic Biotic Habitat Components**	**LSZ Overlaps River Confluence**
Higher	Food Availability and Quality	Lower
Variable	Predator Abundance	Higher
LSZ Overlaps Suisun Region	**Delta Smelt Responses**	**LSZ Overlaps River Confluence**
Broad, Westward	Distribution	Constricted, Eastward
Higher	Growth, Survival, Fecundity	Lower
Better	Health and Condition	Worse
May be Higher	Recruitment in the next Spring	Lower

Figure 16. Spatially explicit conceptual model for the western reach of the modern delta smelt range in the fall: interacting stationary and dynamic habitat features drive delta smelt responses.

Here, we are primarily concerned with delta smelt responses to the fall X2 flow manipulation described in the OCAP Biological Opinion and the opportunities for learning offered by the very favorable hydrology of 2011, but this conceptual model can also be used to explore effects of dynamic and stationary drivers on other species and to inform and refine the other conceptual models summarized above. Further, by applying this model to the San Francisco Estuary and in particular to the dynamics of the low salinity zone and delta smelt responses in its entire fall habitat including the northern Delta, we capture the effects of all likely drivers not only on delta smelt, but on much of the ecosystem as a whole. This will contribute not only to a refinement of the delta smelt species model, but also to a better understanding of the ecological "regime shift" conceptualized by Baxter et al. (2010).

Stationary abiotic habitat components: The POD and HSG models suggest four key stationary habitat components that differ between the river confluence and Suisun regions and may affect habitat quality and availability for delta smelt. Each of the four stationary habitat components is described below. It is important to note that while these features differ between the two regions, they are not uniform or static within each region – all vary within each region, and all change over time in response to dynamic drivers, albeit much more slowly than the dynamic habitat components. For example, bathymetry and erodible sediment supply can change as more sediment is transported into the region and deposited or eroded and flushed out to the ocean. Contaminant sources and entrainment sites are added or eliminated with changes in land and water use. Here we briefly summarize some of what is known and what remains uncertain about the four stationary habitat components in the river confluence and Suisun region.

- *Bathymetric complexity:* Differences in bathymetry and spatial configuration between the Suisun region and the river confluence affect nearly all other habitat features and interact strongly with the prevailing dynamic tidal and river flows to produce regionally distinct hydrodynamics. Overall, the Suisun region is more bathymetrically complex than the river confluence. The Suisun region includes deep and wide channel areas to the south, the large, shallow (less than 3–4 m), and open Suisun, Grizzly, and Honker bays in its center, and Suisun Marsh, the largest remaining tidal marsh in the estuary, to the north. In contrast, the only substantial shallow embayment in the river confluence is Sherman Lake which connects the mostly steep-sided and deep Sacramento and San Joaquin rivers near their mouths and there is only a very small amount of tidal marsh in this area.

- *Erodible Sediment Supply:* The amount and composition of the erodible sediment supply is an important factor in the regulation of dynamic suspended sediment concentrations and turbidity levels and quality in the water column. Suisun Bay features extensive shallow water areas such as Grizzly and Honker Bays that are subject to wind waves that resuspend bottom sediment and increase turbidity relative to the confluence (Ruhl and Schoellhamer 2004). Moreover, the bottom sediments in the shallow areas of Suisun Bay are composed mostly of easily erodible silts and clays, while the bottom sediments in the deep channels of the Suisun region and river confluence consist of silts and heavier sands (Schoellhamer 2011).The contribution of organic materials to the erodible sediment supply in Suisun region and the river confluence and its role are uncertain. It seems likely, however, that the large wetlands in the Suisun region and the shallow regions along its margins likely have higher benthic algal and aquatic plant productivity than deeper areas and thus likely contribute organic materials to the sediment supply that further affects the amount and source of turbidity in this region. Organic materials in the erodible sediments of the river confluence are likely of upstream riverine origin.

- *Contaminant Sources:* The large urban areas surrounding the estuary and the intensive agricultural land use in the Central Valley watershed and the Delta have resulted in pollution of the estuary with many chemical contaminants. Many of these pollutants (e.g. heavy metals, pesticides, etc.) are toxic to aquatic organisms and degrade the habitats of the estuary. Urban and industrial contaminant sources are located in the urban zones that surround the Delta and Suisun regions on all sides (Stoms 2010). Most wastewater treatment plants in and upstream of the Delta and Suisun regions have been upgraded to tertiary treatment which removes most inorganic nutrients and pathogens in addition to organic materials and also eliminates many pesticides and endocrine disrupting chemicals. However, the largest wastewater treatment plant in the Delta, the Sacramento Regional Wastewater Treatment Plant (SRWTP), continues to discharge effluent with high amounts of ammonium, pyrethroid pesticides, and other pollutants into the Sacramento River near the northern Delta border. The large Contra Costa wastewater treatment plant also discharges substantial amounts of ammonium and other pollutants into the western Suisun Bay near Carquinez Straight. Ammonium is converted to un-ionized ammonia at higher pH levels; un-ionized ammonia is toxic to animals. Ammonium has been found to suppress nitrate uptake and growth of phytoplankton in the Delta and Suisun Bay (Dugdale et al. 2007). In addition to man-made chemical pollution, blooms of the toxic cyanobacteria *Microcystis aeruginosa* have become a common summer occurrence in the central and southern parts of the Delta, including the river confluence and the eastern edge of the Suisun region. *Microcystis* produces chemicals that are toxic to many animals.

- *Entrainment sites:* Entrainment sites include agricultural water diversions and urban water intakes throughout the Delta and Suisun regions of the estuary, the state and federal water project pumps near Tracy, and two power plant cooling water intakes in the southern Suisun region (in Pittsburg and Antioch). Entrainment can cause direct mortality in fish screens, pumps, or pipes, or it can cause indirect mortality due to enhanced predation or unsuitable water quality associated with diversion structures and operations. Direct entrainment of delta smelt in the fall months is likely rare, although studies of entrainment effects of the power plants are ongoing. The plants are used mainly to satisfy peak electricity demands in the summer and fall months and could thus entrain delta smelt from the Suisun region, but the plants are not used very often and one of the plants will soon no longer use cooling water from Suisun Bay.

The starting distribution of delta smelt before winter migration is strongly influenced by salinity (Sommer et al. 2011). The winter spawning migration, which begins at the starting distribution and proceeds to points upstream, is typically initiated by "first flush" turbid river flows (Grimaldo et al. 2009; Sommer et al. 2011). A more eastward starting location may increase the risk of entrainment at the State and Federal water projects when "first flush" conditions trigger widespread upstream movement, but the extent of this risk is not known, and is under study.

Dynamic abiotic habitat components: In addition to stationary abiotic habitat components, the POD and HSG models also contain a number of dynamic components that change in magnitude and spatial configuration at daily, tidal, seasonal, and interannual time scales. Their interactions with each other and with stationary habitat components determine the extent and location of production areas for estuarine species. Chief among the dynamic components in this conceptual model is freshwater outflow that is the primary driver responsible for the location and extent of the dynamic LSZ in the fall. Other dynamic components are hydrodynamic complexity, wind speed, turbidity, and contaminant concentrations.

- *Total Delta outflow and San Joaquin River contribution in the fall:* The interaction of ocean tides with inflows from tributary rivers is the main dynamic driving force in estuaries and determines outflow to the ocean. Here, we briefly summarize the natural setting and the flow manipulations and landscape alterations that affect current outflow dynamics in the San Francisco estuary.

  The San Francisco estuary experiences twice-daily ebb and flood tides and strong fortnightly spring and neap tidal cycles. The estuary is located in a Mediterranean climate zone with highly variable precipitation and river flow patterns (Dettinger 2011). Winters are generally wet and summers are dry, but there is a large amount of interannual variability and California water managers distinguish between five different water year types (wet, above normal, below normal, dry, and critically dry). Historically, freshwater was "stored" as groundwater and in large seasonal and tidal wetlands along the rivers and in the estuary which buffered the seasonal inflow variation into the estuary to some degree. High flows during wet winters and springs recharged these natural freshwater reservoirs and their slow draining into the rivers allowed the Delta and the landward side of the Suisun region to remain fresh during summers and falls following wet springs (Enright and Culberson 2010).

  Large-scale disconnection of floodplains from river channels, draining of wetlands, filling of rivers with mining debris, and the beginning of groundwater depletion by pumping reduced the natural freshwater storage capacity of the system and increased seasonal and interannual flow variability in the late 1800s and early 1900s. Beginning in the first half of the 20th century, large dams were built on nearly all tributaries to the estuary to store water in large, artificial reservoirs for release during the dry season. Also, more and more water was diverted from the tributaries and the Delta itself and groundwater depletion became substantial. As a result, inflows into the Delta are now less variable within and between years than they would be under unimpaired conditions without reservoirs, flow diversions, and groundwater pumping. In general, late fall, winter, and spring inflows into the Delta are lower than under unimpaired conditions, while summer and early fall inflows are higher (Moyle et al. 2010). On an annual basis, San Joaquin River flows are reduced to a much greater extent than Sacramento River flows, and only a small amount of San Joaquin River water is actually discharged to the ocean in all but the wettest years. This is especially true in the fall months, when only a very small fraction of the entire water volume at Chipps Island is contributed by water from the San Joaquin River. According to hydrodynamic modeling using the Delta Simulation Model 2 (DSM2, see http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/models/dsm2/dsm2.cfm), water from the Sacramento River and water intruding from San Francisco Bay via Carquinez Straight are by far the dominant water sources during these months and throughout most of the year (Figure 17). Even with greater wet year fall outflows, the San Joaquin River contribution to total outflow will likely remain small.

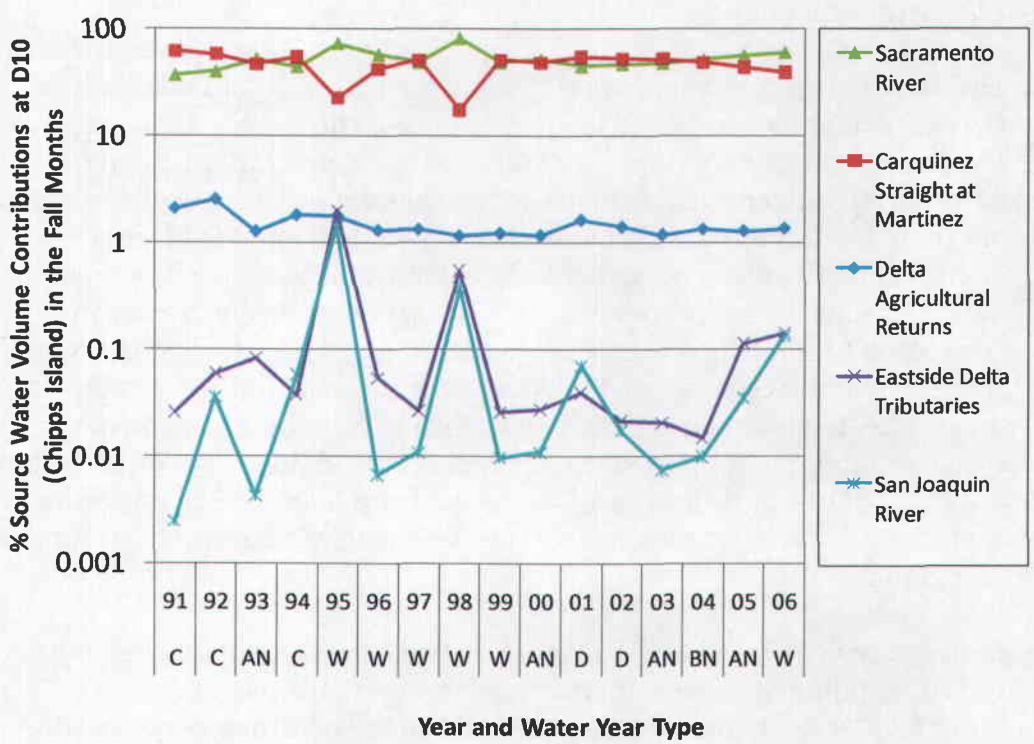


Figure 17. 1995-2006 times series of average seasonal water contributions from different sources to the total water volume at IEP-EMP station D10 at Chipps Island. Data: Volumetric water source "fingerprint" data for this station generated with the Delta Simulation Model 2 (DSM2, http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/models/dsm2/dsm2.c

fm). These data were provided to Anke Mueller-Solger by Bob Suits, DWR, in late 2006.

Annual net Delta outflows past Chipps Island increased in the first half of the 20th century due to increasing precipitation and less natural freshwater storage capacity, but declined in the second half due to water storage in reservoirs and increasing water diversions (Enright and Culberson 2009). Consistent with greater summer inflows due to reservoir releases and in contrast to outflows in all other months, summer outflows increased significantly over time (Enright and Culberson 2009). Long-term trends in early fall (September and October) outflows, on the other hand, do not follow the increasing trends in early fall inflows over the last eight decades (Enright and Culberson 2009). Fall (September through October) outflows increased until the mid-1970s, but decreased thereafter due to increasing inflow diversion through the Delta to the State and Federal Water Project pumps (Enright and Culberson 2009, Lund et al. 2008, Cloern and Jassby in prep.). Similarly low fall outflow levels never occurred after wet and above normal springs in the available data record from 1930 to 1990. In the POD period, fall outflows have been uniformly low, including in the fall months following the wet spring of 2006 (Figure 18, shaded period). This extreme level of disconnection of fall outflows from the interannual hydrological variability in the watershed is unprecedented in the entire historical data record.

The fall outflow management prescribed in the BiOp increases average fall outflows from the POD period average of about 5,200 cfs (95% confidence interval: 5,004 to 5,407 cfs) to approximately 11,400 cfs in September and October and 7,000 to 8,500 cfs in November following the wet spring of 2011 (see section I B). Approximately similar fall outflows would likely be required in other falls following wet and above normal springs in order to achieve the BiOp X2 objectives. While more than twice as high as during the POD years, the higher outflow levels in September and October 2011 would remain well below the average daily fall outflows during wet and above normal years from 1930-2009, even after excluding the extreme outflow years of 1982 and 1983 (Figure 17).

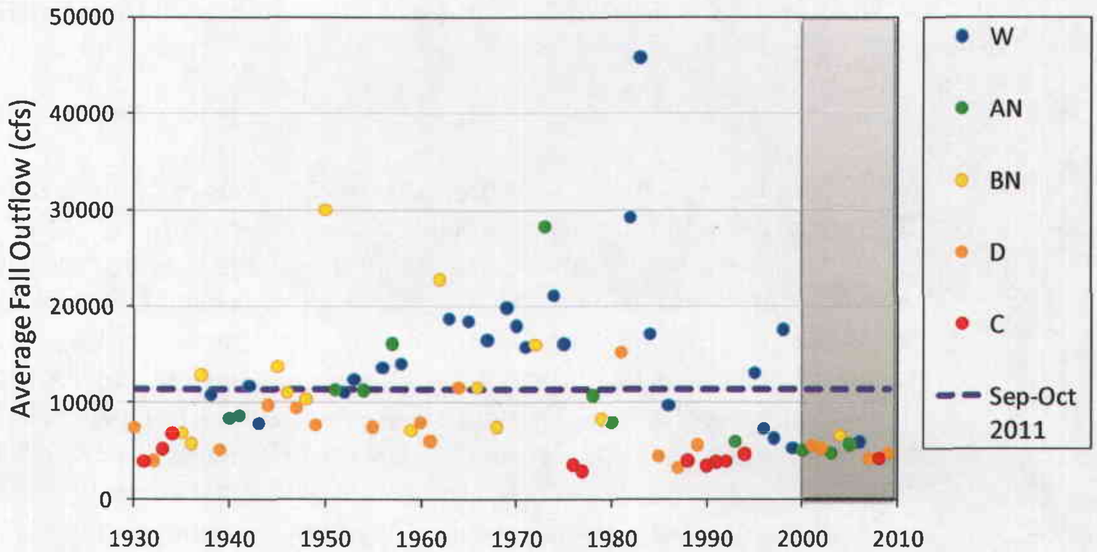


Figure 18. Time series of average daily net Delta outflow index in the fall (cfs, September – November) from 1930 to 2009. The shaded area shows the POD period. Symbols: water year type of the preceding spring for the Sacramento valley (W: wet, AN: above normal, BN: below normal, D: Dry, C: critically dry). Dashed purple line: projected average daily net Delta outflow level for September and October 2011. (Data source: Dayflow (http://www.water.ca.gov/dayflow/). Graphic: A. Mueller-Solger, unpublished.)

- *Location and extent of the fall LSZ:* Under the static fall outflow regime that has been typical for the POD period, outflows throughout much of the fall are always low and salinity intrudes far to the east (X2>80km, Figure XX, see also Figure 7), causing the LSZ to be constricted into a narrow band that overlaps the confluence of the deep Sacramento and San Joaquin river channels (Figure 6b). Prior to the POD period, a more variable fall outflow regime meant that high outflows in the spring were often followed by relatively high outflows in the fall of the same year (Figure 7 and Figure XX). Higher fall freshwater outflows do not allow salinity from the ocean to intrude into the river confluence. Instead, the LSZ is more westward (X2<80km) and much more spatially extensive than in low outflow falls (Figure 6a). In high outflow falls, it broadly overlaps the large shallow embayments of Suisun, Honker, and Grizzly Bays and reaches substantially into Suisun Marsh sloughs and wetlands. On an annual basis, the difference between X2 calculated for actual and unimpaired flows increased by 1.4% per year from 1932 to 2009 due to water management that resulted in a decline in outflow and allowed increasingly more salinity intrusion. The difference has been especially pronounced during the post-1960 droughts, with substantially greater salinity intrusions than the estuary experienced historically, including during the Dust Bowl drought of the 1930s (Winder et al. 2011).

- *Hydrodynamic complexity in the fall LSZ*: Hydrodynamics are driven by the interaction of dynamic river flows, ocean tides, and wind with the stationary bathymetry and spatial configuration. Hydrodynamics in the estuary are generally fairly well understood and have been modeled with a variety of modeling tools (see, for example, DSM2; CDWR 2008; CDWR 2005; Close et al., 2003)There remains much uncertainty, however, about the interaction of hydrodynamics with the stationary habitat components in the Suisun and river confluence regions and their combined effect on other dynamic habitat components including turbidity, contaminants, and biota. The diverse channel configurations and variable depths of the shallow regions and marshes in the Suisun region produce complex hydrodynamic features such as floodtide pulses in Grizzly Bay (Warner et al. 2004), tidal asymmetry (Stacey et al. 2010), lateral density fronts in Suisun cutoff (Lacy et al. 2003), and multiple null zones and turbidity maxima (Schoellhamer and Burau 1998, Schoellhamer 2001)see, for example, Wolanski 2007; Fischer et al., 1979).In contrast, the river confluence area has simpler bathymetry that lacks adjacent shallow embayments. . The greater hydrodynamic complexity in the Suisun region enables suspension and concentration of sediment particles (Ruhl and Schoellhamer 2004, Schoellhamer 2001), including inorganic sediment particles, organic detritus, and planktonic organisms, but detailed studies about these interactions are currently lacking. Greater residence times in the Suisun region may allow for the nitrification and uptake of river-borne ammonium to a degree that allows for more efficient algal nitrate uptake and growth. Greater mixing of the water column in these shallow areas and lateral exchange of water between deep and shallow areas may also prevent low dissolved oxygen conditions that can occur at the bottom of deep channels. Low dissolved oxygen conditions have been documented for the San Joaquin ship channel near Stockton and in some Suisun Marsh sloughs, but there have not been any thorough investigations of dissolved oxygen levels and dynamics in the Suisun region or the river confluence.

- Wind speed in the fall LSZ: The Suisun and river confluence regions of the San Francisco estuary often experience strong winds from the north and west. On average, wind speeds are high throughout most of the year including early fall, but lower in mid to late fall. The interaction of wind with river and tidal flows and the erodible sediment supply drives the resuspension of erodible bed sediments. Wind-wave resuspension is substantial in the shallow bays of the Suisun region and helps maintain generally high suspended sediment concentration and turbidity levels in these bays (Ruhl and Schoellhamer 2004). In contrast, wind likely plays a less important role in suspending sediments in the deep channels of the river confluence.

- Turbidity in the fall LSZ: In the San Francisco Estuary, turbidity is largely determined by the amount of suspended inorganic sediments in the water (Cloern 1987, Ganju et al. 2007, Schoellhamer et al. in press), although organic components likely also play an important role (USGS 2008). Sediment particles are constantly deposited, eroded, and resuspended, and are transported into, within, and out of the estuary. The amount of sediment that is suspended in the water column depends on the available hydrodynamic energy, which determines transport capacity, and on the supply of erodible sediment. In the late 1800s, enormous amounts of sediments were washed into the rivers in the estuary's watershed by hydraulic gold mining. A substantial portion of these sediments was deposited in the rivers and bays of the estuary because the transport capacity was not enough to wash them out to the ocean. In the 1900s, river-borne sediment supplies started to decline due to the end of hydraulic mining, sediment trapping behind newly constructed dams, and rip-rapping of river banks for flood protection. This meant that the eroding sediment pool was no longer rapidly replenished from upstream and started to wash out to the ocean, leaving behind thinning bed sediments and slowly declining turbidity levels. High flushing flows associated with two recent, strong El Niño-Southern Oscillation (ENSO) events led to the sudden and permanent clearing of the river confluence in 1983 (Jassby et al 2005) and the bays of the San Francisco estuary in 1999 (Schoellhamer 2011). In the western estuary, the onset of this clearing coincided with the onset of the POD period. It appears that turbidity from suspended sediments is now regulated by the bed supply of sediments, not by the transport capacity of the estuary, a situation that was not experienced in the estuary since before the gold rush.

  In spite of the depletion in erodible sediments, strong turbulent hydrodynamics in the Suisun region that are caused by strongly interacting tidal and riverine flows, bathymetric complexity, and high wind speeds continue to constantly resuspend large amounts of the remaining erodible sediments in the large and open shallow bays of the Suisun region. The Suisun region thus remains one of the most turbid regions of the estuary. Turbidity dynamics in the deep channels of the river confluence are driven more by riverine and tidal processes while high wind and associated sediment resuspension has little if any effect (Ruhl and Schoellhamer 2004). In Fall, fine erodible sediment has been somewhat winnowed from the bed and wind speed is less than spring and summer, so wind wave resuspension and suspended-sediment concentrations typically are low compared to other seasons. While generally lower than in the last century, turbidity in the river confluence can still increase dramatically during high flow events ("first flush") that bring in large amounts of suspended sediments from the watershed. In the fall, however, turbidity is usually lower in the river confluence than in the Suisun region (Bennett and Burau 2011). This is also consistent with preliminary analyses by W. Kimmerer (SFSU, pers. com.) that suggest that turbidity in the LSZ is higher when fall X2 is further downstream and the LSZ overlaps the Suisun region.

- *Contaminant Concentrations in the fall LSZ:* Chemical contaminants from agricultural and urban sources that are present in the estuary include pyrethroid pesticides, endocrine disruptors, and many traditional contaminants of concern. The estuary is also overly enriched with the nutrient ammonium (Johnson 2010). In the late summer and early fall, blooms of the cyanobacteria *Microcystis aeruginosa* can release toxic microcystins (Lehman et al. 2009). Agricultural contaminants are delivered into the LSZ from winter to summer in storm-water run-off, rice field discharge, and irrigation return water (Kuivila and Hladik 2008). The amount and types of agricultural contaminants that reach the LSZ vary seasonally, with more inputs from winter to summer than in the fall (Kuivila and Hladik 2008). Urban and industrial pollution from wastewater treatment plants and industrial discharges occurs more steadily throughout the year, although the amount of contaminant-containing urban storm-water run-off is largest in the winter and spring. In the fall, pollutant loading from stormwater is generally negligible and lower river flows mobilize fewer sediment bound contaminants than in other seasons. However, low flows also produce higher residence times and therefore enhance the possibility of accumulation and acute and chronic effects of contaminants from agricultural and urban sources. For example, the percentage of samples collected from the Delta and Suisun regions of the estuary that were acutely toxic to the amphipod *Hyalella azteca* was much higher in 2007, a relatively dry year (8.5 % of 340 samples), than in the wet year 2006 (1.7% of 353 samples) (Werner et al. 2010). Overall, regular toxicity monitoring conducted from 2006-2009 has shown relatively few incidences of acute *Hyalella* and delta smelt mortality (Werner et al. 2010 a and 2010 b, Weston et al. 2010)). However, sub-lethal, chronic effects at low, but persistent contaminant levels are likely a significant concern for delta smelt and other aquatic organisms throughout the estuary (Scholz et al. 2011). For example, a recent IEP study by Connon et al. (in review) assessed sublethal effects of ammonia exposure on delta smelt with novel molecular tools (DNA microarrays and qPCR). Results suggest that delta smelt are more sensitive to un-ionized ammonia, the toxic gas form of ammonium, than rainbow trout and ammonia primarily affects their cell membrane stability, but also energy metabolism and other physiological and neurological processes. In combination with other stressors, this can have a negative effect on health, condition, and overall fitness of delta smelt.

The river confluence is geographically closer to agricultural and urban contaminant sources as well as to the toxic *Microcystis* blooms than the Suisun region. The lack of large wetlands in the river confluence precludes removal of contaminants through wetland processes and the supply-regulated sediment transport regime does not allow for much contaminant burial in bed sediment. Overall, this may increase the risk of exposure to toxic contaminants in the river confluence compared to the Suisun region. On the other hand, the southern margin of the Suisun region is heavily urbanized and includes the Contra Costa wastewater treatment plant which discharges ammonium and other pollutants into the western Suisun Bay near Carquinez Straight. Ammonium is converted into nitrate as it moves downstream, but elevated levels are often found in both the river confluence and the Suisun region. Higher phytoplankton productivity in the Suisun region may drive up pH levels, which could lead to increased levels of toxic un-ionized ammonia. Higher benthic productivity and resuspension of sediments in the shallow areas of the Suisun region can mobilize sediment-bound contaminants and introduce and accumulate them in the food chain. Suisun Marsh is bordered by a large urban area along its northern margin and much of its wetlands are managed by duck clubs. Urban areas and duck clubs are known to pollute Marsh sloughs with chemical contaimants and high loads of organic matter. Contaminant exposure risk may thus be overall more variable and not always lower in the Suisun region than in the river confluence.

Dynamic Biotic Habitat Components: Estuarine fishes seek areas with a combination of dynamic and stationary habitat components that are well suited to their particular life histories. In addition to abiotic habitat components, this also includes dynamic biological components such as food availability and quality and composition and predator abundance and composition.

- *Food availability and quality:* Food production in estuaries is a dynamic process that involves the entire food web, from algae, microbes, and aquatic plants at the base of the food web to intermediate and higher trophic levels populated by invertebrates such as zooplankton and benthic consumers and vertebrates such as fishes and water birds. As in many other estuaries, higher trophic level production in the open waters of the Delta and Suisun regions is fueled by phytoplankton production (Sobczak et al. 2002). In contrast to many other estuaries, however, the San Francisco estuary has overall low phytoplankton production and biomass (Cloern and Jassby 2008). Phytoplankton production in the estuary is highly variable on a seasonal and interannual basis (Jassby et al. 2002, Cloern and Jassby 2009). The San Francisco estuary also has a large amount of spatial variability in food production and food web dynamics. Estuaries and rivers often have dynamic food and biogeochemical "hot spots" (Winemiller et al. 2010) that persist in one location for some time or move with river and tidal flows. There are usually also areas with low food production and biomass.

  Not all highly productive hot spots are beneficial for consumers. For example, summer-time blooms of the cyanobacteria *Microcystis aeruginosa* that now regularly occur in the estuary can be both toxic and of very low food quality for some species of copepods (Lehman et al. 2009, Ger et al. 2010). *Microcystis* blooms can suppress copepod production and possibly affect zooplankton community composition, thus altering food quality for zooplankton consumer such as delta smelt. Similarly, the growth suppression of some, but not all, algal species by ammonium may alter phytoplankton community composition and their nutritional quality for consumers such as copepods. For example, diatom spring blooms in Suisun Bay are suppressed by high levels of ammonium (Dugdale et al. 2007), while ammonium may fuel *Microcystis aeruginosa* blooms in the summer (Kendall 2010). *Microcystis aeruginosa* grow mostly in the freshwater regions of the Delta, but are transported into the low-salinity zone in the summer and fall months. *Microcystis* blooms have been a prominent part of the phytoplankton community in the delta during the POD period, but the high flows and cool conditions of 2011 are not expected to produce a substantial bloom this year.

The temporal and spatial variability of food production, biomass, and quality in estuaries is the result of the interaction of dynamic drivers such as biomass and nutrient inputs from upstream, estuarine hydrodynamics, salinity, turbidity, and trophic interactions with stationary habitat components such as the bathymetric complexity and spatial configuration of a particular geographic area. For example, an area with shallow, well-mixed, and nutrient-rich water should have greater growth of planktonic and benthic algae and associated zooplankton than an area with deep, stratified, and nutrient-poor water (Cloern 2007). Greater bathymetric complexity may lead to a greater concentration and resuspension of particles, including planktonic organisms, than in less complex situations. In the shallow areas of the Suisun region, relatively high residence times combined with adequate light availability at shallow depths may allow for the draw-down of ammonium from the Sacramento River that may then enable greater diatom growth on nitrate (Dugdale et al. 2007). Salinity also plays a role – for example, Lehman (2000) found that in the spring, phytoplankton biomass and cell diameter was greatest toward the landward, fresher end (0.6 ppt) of the LSZ. If this were also true for the fall, a larger area at this low salinity in the Suisun region could translate into considerably larger food resources at the bottom of the food chain under high flow conditions. In general, however, spatial and temporal variations in productivity, density, and composition of plankton organisms in the LSZ at small scales that matter to delta smelt in the fall remain poorly understood for both the Suisun region and the river confluence. These small scales include the small temporal scale for the swimming speed of delta smelt while foraging (perhaps ~1 body length per second) and and the small spatial scale of its feeding ambit (perhaps no more than several meters in an area of high food concentration (i.e. a food hot spot)) (W. Kimmerer, SFSU, pers. com.).

Estuaries are open systems and food inputs from rivers and the ocean are an important driver of food web dynamics in estuaries. Of the two main tributary rivers to the San Francisco estuary, the San Joaquin River has generally more phytoplankton and zooplankton production and biomass than the Sacramento River. San Joaquin River waters along with the plankton they contain rarely reach the LSZ under low outflow conditions in the fall because the San Joaquin River is largely diverted into the water projects under these conditions. Higher outflow conditions and altered water management may allow some of the San Joaquin River biomass loads to reach the Suisun region in falls following wet springs, thus subsidizing the food available to delta smelt in the LSZ. Food production and biomass is also known to be high in some of the sloughs in Suisun Marsh (Sobczak et al 2002, Mueller-Solger et al 2002). When the LSZ extends into these sloughs, delta smelt may benefit from the production directly in some of the more open sloughs. If Suisun Marsh is a source of plankton organisms for Suisun bay, delta smelt may also benefit from Suisun Marsh food subsidies to the Suisun Bay, however the role of Suisun Marsh as a food source or sink remains uncertain. The river confluence likely receives substantial amounts of riverine organic matter from upstream, but much of this organic matter is not very nutritious and supports less higher trophic level production than autochthonous phytoplankton and fresh wetland production (Mueller-Solger et al. 2002, Sobzack et al. 2002). On the other hand, large amounts of detrital organic matter transported into and produced in the system are utilized by heterotrophic microbes (bacteria and protists) and microbial production and respiration in the system is high (Sobczak et al. 2002). Microbial biomass in the LSZ appears to nutritionally benefit at least one zooplankton species in the LSZ, the invasive cyclopoid copepod *Limnoithona tetraspina* (Bouley and Kimmerer 2006). However, in spite of its high abundance in the LSZ, this copepod species is not a good food source for juvenile and sub-adult delta smelt due to its small size (Sullivan et al. 2010). In the LSZ, microbes are often so heavily grazed by the invasive clam *Corbula amurensis* that their biomass can only be maintained through subsidies from other regions less affected by the clams (Greene et al 2011).

The overbite clam *Corbula amurensis* invaded the Suisun and river confluence regions in the late 1980s. This invasion led to a dramatic decline in the productivity in and upstream of these regions (Jassby et al. 2002). However, *Corbula* recruitment is suppressed and densities are lower in years with higher outflows and a more westward LSZ and X2 (Peterson and Vayssieres 2010, Winder et al. 2011), such as the wet 2011 – preliminary IEP monitoring results from this spring and early summer show very low numbers of live *Corbula* in the Suisun region. Without high densities of large *Corbula* in the fall, the Suisun region may have higher phytoplankton biomass this fall than in years with more *Corbula* which, along with reduced *Corbula* predation on juvenile zooplankton, would benefit zooplankton production.

This could translate into more food resources for delta smelt if the low salinity zone overlapped the productive Suisun region.

The food web in the Suisun and river confluence regions has been further altered by successive invasions of several species of zooplankton and now more closely resembles East-Asian than North-American zooplankton assemblages (Winder et al. 2011). Non-native zooplankton species started replacing native species in the upper estuary in the 1970s when increasing inputs from Asian ballast water coincided with extended drought periods. Water management reduced freshwater inflow even further, increasing drought severity and allowing unusually extreme salinity intrusions (see above). Unprecedented high salinity levels and intensified benthic grazing by the clam *Corbula amurensis* that also benefitted from the more saline and lower outflow conditions in the western estuary allowed the non-native zooplankton species to outcompete native species and colonize the system (Winder et al. 2011). At least one of these species, the calanoid copepod Pseudodiaptomus forbesi, appears to be a good food source for delta smelt. In contrast, the small cyclopoid copepod *Limnoithona tetraspina* that has become highly abundant in the LSZ since 1994 is not a good food source for juvenile and sub-adult delta smelt due to its small size (Sullivan et al. 2010). Overall, much uncertainty remains regarding the nutritional value of the non-native zooplankton species for delta smelt and other fishes.

Jellyfish (gelatinous zooplankton) have also increasingly invaded the LSZ from the Ponto-Caspian region. The estuary is now home to three species of hydromedusae (*Blackfordia virginica, Maeotias marginata,* and *Moerisia sp.)* introduced to the estuary in the 1970s (Mills and Sommer 1995, Mills and Rees 2000, Rees and Gershwin 2000). These three species inhabit the fresh to brackish regions of the estuary, including Suisun Bay, the channels of Suisun Marsh, and the western Sacramento-San Joaquin Delta, and are seasonally abundant throughout late summer and fall. As a result, they overlap both spatially and temporally with delta smelt habitat in the fall, but their role in the LSZ including any effects they might have on delta smelt is only now starting to be investigated.

In summary, food resources for delta smelt in the fall LSZ vary considerably on many spatial and temporal scales. Many uncertainties also remain about the dynamics of food resources at the small scales that matter to delta smelt survival, growth, and health in the fall. Uncertainties also remain regarding the relative importance of food subsidies from upstream regions and food produced in the LSZ. Species invasions associated with extreme salinity intrusions during droughts have greatly altered the composition of the invertebrate community in the LSZ, with uncertain effects on delta smelt. Overall, food quantity and quality may be higher for delta smelt if the fall LSZ is in Suisun Bay than if it is in the river confluence, but many uncertainties remain.

- *Predator composition and abundance*: Predators are a natural biological component of ecosystems and most organisms are exposed to predation during some part of their lives. In general, a reduction in habitat size may increase the probability of predation in that habitat. Even for a rare species like delta smelt, reduced habitat availability may increase the probability of a stochastic event such as an encounter between the core population of delta smelt and a school of predators. In the San Francisco estuary, striped bass juveniles become piscivorous and occupy much the same areas as delta smelt in the fall. Predation on delta smelt by young striped bass may be enhanced in recent years by a general increase in size of striped bass young of year and the general decrease in size of juvenile delta smelt, although the abundance of juvenile striped bass has decreased in the open waters of the estuary (Thomson et al. 2010). Striped bass occur in both the confluence and the Suisun region. Higher turbidity in the shallow areas of the Suisun region may, however, reduce predation risk for delta smelt in these areas compared to the river confluence, where turbidity is generally lower. In addition, preliminary results indicate that open-canopied beds of the native submerged aquatic vegetation (SAV) *Stuckenia pectinata* (sago pondweed) may provide cover from predation, although this has not yet been observed for delta smelt (K. Boyer, SFSU, pers. com.). This relatively salt-tolerant SAV species currently occurs in shallow off-shore areas extending from the western margin of the river confluence west into Grizzly Bay (K. Boyer, SFSU, pers. com.). In the fresher, warmer and clearer waters in and upstream of the river confluence, the dominant SAV species is the non-native *Egeria densa*. Its denser canopies provide ideal conditions for ambush predators such as largemouth bass (L. Conrad et al., DWR, pers. com.). Largemouth bass are increasingly abundant in the central and northern Delta and may potentially exert significant predation pressure on delta smelt in the river confluence and the clearer areas of the Suisun regions, although this has not yet been documented. Sacramento pikeminnow, a native predator, occurs in both regions. Mississippi silversides, another introduced species, appear to prey on larval delta smelt in the spring, but are likely too small to prey on juvenile and sub-adult delta smelt in the fall (B. Schreier, DWR, pers. com.). High predator abundance has been documented in the river confluence at the release sites for fishes salvaged in the CVP and SWP fish facilities. Overall, predator abundance and associated predation risk for delta smelt may be generally high in the river confluence, but variable in the Suisun region. Much uncertainty remains, however, about the role and magnitude of predation in these regions.

Delta Smelt Responses: The POD and HSG models suggest that delta smelt may respond in several ways to outflow-related habitat changes in the fall. Specifically, access to areas of greater bathymetric complexity such as those found in the Suisun region likely offers multiple advantages to delta smelt, although many uncertainties regarding the mechanisms that link delta smelt responses to outflow conditions and the position of the LSZ remain. Note also that the responses of delta smelt may be muted depending on the status of the population. For example, severely low adult abundance is likely to generate relatively low recruitment regardless of habitat quality. At the extreme end of low abundance, delta smelt populations may be subject to Allee effects, which cause a downward spiral that may be difficult to reverse (Baxter et al. 2008). Summer survey data suggest that delta smelt population levels have improved somewhat in 2011, hopefully reducing the risk of Allee effects.

- *Distribution:* Prior to their upstream spawning migration in the winter, delta smelt are commonly found in the LSZ (Feyrer et al. 2007, Sommer et al. 2011). While they can survive in freshwater and at salinities up to about 20 psu Swanson et al. 2000), the LSZ seems best suited to their physiology at this life stage. Older life stages of delta smelt may not require the same high turbidity levels that larval delta smelt need to successfully feed, but are most likely able to discriminate level and types of turbidity (and salinity) to find waters that contain appropriate prey resources and that will provide some protection against predation. A westward LSZ (Figure 15 b) ensures delta smelt access to a larger habitat area that overlaps the more bathymetrically complex Suisun region with its deep channels, large shallow shoal areas, and connectivity with Suisun Marsh sloughs.
- *Growth, survival and fecundity:* Distribution across a larger area with high turbidity, more food, and open-canopied native SAV beds in falls when the LSZ overlaps the Suisun region may help delta smelt avoid predators and increase survival and growth (K. Boyer, SFSU, pers. com.) although evidence for this is currently lacking. Delta smelt are poor swimmers and may also benefit from the more variable hydrodynamics associated with the more complex bathymetry of the Suisun region which include more quiescent areas that may allow delta smelt to rest and feed in addition to areas with strong flows that delta smelt may utilize to move around the LSZ without expending large amounts of energy on swimming. Distance from entrainment sites and predation hot spots (artificial physical structures, scour holes in river channels, *Egeria* beds) may also help increase survival and health. Higher phytoplankton and zooplankton production in shallow areas of the Suisun region and in San Joaquin River water may provide better food resources for delta smelt than in the deep river confluence during high outflow years when *Corbula* numbers are low and food resources in San Joaquin river water reach the LSZ in the fall. Together, these habitat features may increase delta smelt growth, survival, and fecundity.

- *Health and condition:* Similar to the mechanisms listed for growth, survival and fecundity, a broader distribution across the bathymetrically complex Suisun region can affect health and condition. For example, more habitat may help delta smelt avoid, or reduce exposure to, toxic hot spots, limit entrainment to diversions and access better food resources, compensate for degraded physical habitat elsewhere.
- *Recruitment in the next spring:* Ultimately, the factors listed above may lead to greater recruitment of delta smelt. However, before they can recruit successfully, delta smelt need to find suitable spawning and larval rearing habitat upstream of the low salinity zone. In addition to summer and fall habitat conditions, successful recruitment thus requires suitable winter and spring conditions for migration, spawning, and larval rearing. These habitat conditions depend on the interplay of a different set of stationary and changing dynamic habitat features. Only if habitat conditions are met year-round will delta smelt be able to successfully maintain their life history and genetic diversity and thus, maintain a viable population in their original habitat into the future.

Delta Smelt In the Northern Delta: While the center of the delta smelt distribution in the fall is the low salinity zone, they also occur year-round in the northern Delta, but are no longer found in their historical range in the southern Delta in the summer and fall (Nobriga et al. 2008, Sommer et al. 2011). Because delta smelt are currently found in the northern Delta in the fall, this region also constitutes current delta smelt fall habitat. It is important to note, however, that habitat quality and resulting delta smelt survival, health, growth, fecundity and recruitment contribution to the total population may differ between this region and the low salinity region. The 2011 study plan includes a comparison of dynamic and stationary habitat features and delta smelt responses in the LSZ and northern Delta habitats.

The northern Delta range of delta smelt in the fall includes the Sacramento deepwater ship channel and the Cache Slough complex with its dead-end sloughs and the large, flooded Liberty Island. This region has a number of similarities in stationary habitat features with the Suisun region: compared to the mainstem Sacramento River, it is bathymetrically complex, turbid, productive, and has low entrainment risk and variable risk of toxin exposure and predation. Dynamic habitat features include strong tidal exchanges with the Sacramento River, variable contributions of highly productive tributary waters, and increasing salinity levels up to about 0.5 psu from the mainstem Sacramento River into the ship channel and the smaller sloughs. Like the Suisun region, the northern Delta region is also targeted for habitat restoration activities. Learning more about its habitat suitability for juvenile delta smelt in the summer and fall thus provides not only an informative comparison for the low salinity habitat investigation, but will likely also yield key insights for implementing more science-based habitat restoration in both areas.

At this time we hypothesize that while the salinity range may not be physiologically optimal in the northern Delta, the interplay of the dynamic and stationary habitat features in the northern delta may result in a secondary production area for juvenile delta smelt that geographically overlaps with optimal spawning habitat, thus eliminating the need for and the associated dangers of the spawning migration. It is important to note that genetically, delta smelt are a single, panmictic population that may have different migration patterns of subsets (contingents) within the population (Sommer et al. 2011), but no persistent genetic differentiation into subpopulations (Fisch et al. 2011).

If done in concert with the low salinity habitat restoration that is afforded by higher fall outflows in wet and above normal years such as 2011, additional habitat improvements for delta smelt spawning and rearing in the northern delta may have substantial benefits for the delta smelt population. On the other hand, northern Delta habitat restoration alone will likely not be enough for delta smelt recovery – the salinity in the northern Delta is too low. With the fall outflow adaptive management plan, we intend to test and refine these predictions and associated management strategies.

(5) SET-UP ELEMENT: PREDICTIONS

A key to the adaptive approach described in this document is that the alternative fall outflow scenarios explored in the new conceptual model for 2011 lead to a suite of expected responses about dynamic habitat drivers and biological responses at multiple levels of the ecosystem. As explained in the conceptual model section, the stationary habitat components are not static. We do not, however, expect any of the stationary habitat components to change rapidly or appreciably in response to fall outflow management.

Our expectations about dynamic habitat drivers and biological responses are presented in the form of quantitative and qualitative predictions in Table 1. The science plan detailed below is designed to test these predictions (there stated in the form of hypotheses and/or study questions) and provide additional quantitative results that will be used to better quantify the predictions and improve the level of certainty with which they can be made. Quantitative results will also be used to parameterize additional quantitative models and to develop predictions for additional dynamic response variables. Several important dynamic response variables are suggested by the conceptual model, but not yet incorporated into Table 1 because there is not yet enough data available to make qualitative or quantitative predictions. This includes predator density and predation rates, contaminant concentrations and effects, jellyfish dynamics, microbial dynamics, and delta smelt responses beyond the fall such as recruitment and future abundance trends.

It is important to note that delta smelt responses may not be detectable in the first years of the action, but may require many years of careful outflow management and persistent monitoring to become detectable with a sufficiently high degree of certainty. Delta smelt are currently so rare that Allee effects may prevent their recovery for quite some time. The low delta smelt numbers also make it is difficult to detect significant trends. In addition, as described in the POD and HSG models, delta smelt and the other POD fishes are subjected to multiple and often interacting stressors, in addition to the persistently low delta outflow and high X2 in the falls of the POD years. Recovery of delta smelt ultimately depends on a reduction in many stressors that currently degrade their habitat and will likely take years, if not decades, to fully manifest itself.

The 81 km and 74 km columns in Table 1 correspond to RPA X2 targets for "above normal" and "wet" water years and the high outflow variant (Figure 15A) of the variable outflow scenario described in the new conceptual model (left side of Figure 16). The 85 km column represents the "low habitat" tier in Figure 4 and the static low fall outflow scenario (Figure 15B and right side of Figure 16). These predictions provide a starting point for development of analyses that progressively evaluate the adequacy of the existing conceptual and quantitative models and suggest new or refined ones.

Table 1. Predicted qualitative and quantitative outcomes of X2 management in the fall based on 3 levels of the action. Numbers in the "Measurements and analysis " columns designate what will be measured, see table footnotes. These measurements are explained in more detail in the Science Plan section below.

Variable (Fall Months)	Predictions for X2 scenarios			Measurements and Analysis			Notes
	85 km	81 km	74 km	Monitoring Data	Studies Data	Analysis and Modeling	
Dynamic Abiotic Habitat Components							
Average Daily Net Delta Outflow	~5000 cfs?	~8000 cfs?	11400	M 1	S 1	A 1	
San Joaquin River Contribution to Fall Outflow	0	Very Low	Low	M 1	S 1	A 1	
Hydrodynamic Complexity in LSZ	Lower	Moderate	Higher	M 1	S 1	A 1	
Average Wind Speed in the LSZ	Lower	Moderate	Higher	M 2	S 2	A 2	
Surface area of the fall LSZ	~ 4000 ha	~ 5000 ha	~ 9000 ha	M 3-a	S 3-a	A 3-a	
Average Turbidity in the LSZ	Lower	Moderate	Higher	M 3-a	S 3-a	A 3-a	
Average Secchi Depth in the LSZ	Higher	Moderate	Lower	M 3-a	S 3-a	A 3-a	
Average Ammonium Concentration in the LSZ	Higher	Moderate	Lower	M 3-b	S 3-b	A 3-b	
Average Nitrate Concentration in the LSZ	Moderate	Moderate	Higher	M 3-b	S 3-b	A 3-b	
Delta Smelt Abiotic Habitat Index	3270 ± 220	4870 ± 243	7300 ± 285	M 1, M 3-a	S 1, S 3-a	A 1, A 3-a	
Dynamic Biotic Habitat Components							
Average Phytoplankton Biomass in the LSZ (excluding Microcystis)	Lower	Moderate	Higher	M 4-a	S 4-a	A 4-a	
Contribution of Diatoms to LSZ Phytoplankton Biomass	Lower	Moderate	Higher	M 4-a	S 4-a	A 4-a	
Contribution of Other Algae to LSZ Phytoplankton biomass at X2	Higher	Moderate	Lower	M 4-a	S 4-a	A 4-a	
Average Floating Microcystis Density in the LSZ	Higher	Moderate	Lower	M 4-a	S 4-a	A 4-a	
Phytoplankton biomass variability across LSZ	Lower	Moderate	Higher	M 4-a	S 4-a	A 4-a	
Calanoid copepod biomass in the LSZ	Lower	Moderate	Higher	M 4-b	S 4-b	A 4-b	
Cyclopoid copepod biomass in the LSZ	Lower	Moderate	Moderate	M 4-b	S 4-b	A 4-b	
Copepod biomass variability across LSZ	Lower	Moderate	Higher	M 4-b	S 4-b	A 4-b	
Corbula biomass in the LSZ	Higher	Moderate	Lower	M 5	S 5	A 5	
Delta Smelt (DS) Responses							
DS caught at Suisun power plants	0	0	Some	M 6	S 6	A 6	
DS in fall SWP & CVP salvage	Some?	0	0	M 6	S 6	A 6	
DS center of distribution (km)	85 (77-93)	82 (75-90)	78 (70-85)	M 6	S 6	A 6	
DS growth, survival, and fecundity in fall	Lower	Moderate	Higher	M 6	S 6	A 6	
DS health and condition in fall	Lower	Moderate	Higher	M 6	S 6	A 6	

Table 1 Footnotes:

M 1: Delta Flow Data- inflows, outflows, and estuarine hydrodynamics
M 2: Meteorological Data - wind speed, wind direction, precipitation, and solar radiation
M 3: Water Quality Data
- M 3-a Salinity, Turbidity, Temperature
- M 3-b Nutrients, Dissolved Oxygen, Organic Carbon, pH
- M 3-c Contaminants and Toxicity

M 4: Plankton Data
- M 4-a Phytoplankton and Microcystis
- M 4-b Zooplankton and Jellyfish

M 5: Benthic Macroinvertebrate Data

M 6: Fish Data
M 7: SAV Data
S 1: Delta hydrology and hydrodynamics studies
S 2: Water Quality studies
    S 2-a Salinity, Turbidity, Temperature
    S 2-b Nutrients, Dissolved Oxygen, Organic Carbon, pH
    S 3-c Contaminants and Toxicity
S 4: Plankton Studies
    S 4-a Phytoplankton and Microcystis
    S 4-b Zooplankton and Jellyfish
S 5: Benthic Macroinvertebrate Studies 6: Fish Studies
S 7: SAV Studies
A 1: Delta hydrology and hydrodynamics analyses
A 2: Water Quality analyses
    A 2-a Salinity, Turbidity, Temperature
    A 2-b Nutrients, Dissolved Oxygen, Organic Carbon, pH
    A 3-c Contaminants and Toxicity
A 4: Plankton analyses
    A 4-a Phytoplankton and Microcystis
    A 4-b Zooplankton and Jellyfish
A 5: Benthic Macroinvertebrate analyses
A 6: Fish analyses
A 7: SAV analyses

(6) SET-UP ELEMENT: SCIENCE PLAN

The science plan for adaptive management of fall outflow (simply referred to as the "science plan" in the remainder of this document) contains monitoring and research study elements that are intended for implementation in all years, whether a fall outflow augmentation is carried out or not. This document contains the initial science plan for 2011-2012. The science plans for future years (i.e. for the *iterative phase*) will be modified based on what has been learned in preceding years.

In the following sections, we first describe monitoring and field and laboratory studies intended to address hypotheses and questions derived from the conceptual model, test the predictions listed in Table 1, and provide numerical inputs to quantitative models. We then describe data analyses and quantitative modeling intended to improve the conceptual model and provide additional quantitative predictions.

While new field studies are especially designed to take advantage of the very wet conditions of 2011, the science plan also includes analyses of existing data intended to contrast the wet 2011 and other wet years with habitat and fish responses in previous wet years as well as in drier years. Newly developed models will be validated and tested with additional field and lab studies in future years (iterative phase).

In labor and cost terms, we are fortunate that a majority of the needed long-term monitoring is are already being done by the Interagency Ecological Program (IEP, see http://www.water.ca.gov/iep/ for detailed information about IEP monitoring and research). In addition, the IEP, the Delta Science Program (DSP, www.deltacouncil.ca.gov/delta_science_program/), and the Ecosystem Restoration Program have a long history of supporting, coordinating, and carrying out shorter-term, hypothesis and question-driven studies that address scientific questions with clear management relevance. Since 2005, the IEP has implemented a series of successive work plans investigating the decline of four pelagic fish species in the estuary (known as the Pelagic Organism Decline (POD) investigations). These comprehensive workplans have included tightly coordinated monitoring and study elements funded by the IEP, DSP, ERP, and others. The most recent published POD workplan (Baxter et al. 2010) included a number of studies funded after an open proposal solicitation that focused on the effects of fall outflow management on delta smelt. Along with the long-term monitoring and a number of new studies, these ongoing POD studies form the basis for the fall outflow science plan, while the POD workplan provides the broader multi-species habitat and ecosystem context for the fall outflow science plan.

A main objective for the fall outflow science plan is to ensure the high level of coordination of the existing monitoring and studies needed to carry out the comprehensive analyses, syntheses, and modeling needed for adaptively managing fall outflow and other important system variables to accomplish the co-equal goals of water supply and ecosystem protection.

MONITORING

The IEP and others have conducted fish, invertebrate, phytoplankton, and water quality monitoring surveys in the estuary for more than four decades. These surveys are carried out year-round from several times a week (e.g. Chipps Island fish trawls) to semi-annually (e.g. spatially intensive benthos surveys). In addition, many monitoring stations in the estuary and its watershed are equipped with continuously recording instrumentation for a variety of hydrological, meteorological, and water quality variables. Together, these monitoring surveys and stations play a key role in the fall outflow science plan.

The fall outflow science plan will not change the spatial or temporal sampling design of any long-term monitoring surveys, as continuity of historical time series and the ability to test hypotheses about effects of the action based on comparison of new data to historical data are important objectives of this plan.

Two key fish monitoring surveys conducted in the summer and fall recently extended their sampling area to include new stations in the Cache Slough complex and the Sacramento Deep Water Ship Channel in the northern Delta. These surveys also collect data for zooplankton, salinity, and turbidity at the fish sampling stations. Additional special surveys are currently conducting turbidity monitoring (USGS) and toxicity monitoring (UCD and UCB) in this region. Some delta smelt from this region apparently remain resident (see Sommer et al. 2011) and measures of growth, diet etc. of these fish can provide an informative contrast with those collected from the LSZ.

At this time, the 2011-12 Science Plan does not include any augmentation of delta smelt sampling during monitoring surveys because the current abundance of delta smelt is so low. Instead, the Science Plan proposes to make limited use of surrogate species, such as age-0 striped bass, threadfin shad, and Mississippi silversides, when delta smelt catches are low. This also extends the fall outflow science plan to include two other POD species (age-0 striped bass and threadfin shad), thus broadening its scope beyond a single target species. Importantly, we recognize that there are no true surrogate species for delta smelt, *i.e.* open water planktivores with a distribution narrowly centered on the LSZ in the fall. This limits the usefulness of data from surrogates for assessing delta smelt responses to fall outflow and other management actions (Murphy et al. 2011). Young striped bass have the greatest distribution overlap with delta smelt and feed on plankton organisms in their first year of life, but they are much better able to make use of benthic and near-shore prey than delta smelt and become piscivorous starting in the first and second year of life (Sommer et al. 2011). Interpretation of surrogate species responses to fall outflow management will thus proceed with great care and data obtained directly from delta smelt will always take precedence over data obtained from other species in informing future management adaptations. Data from other fish species is mostly used for comparisons.

The following data are currently slated to be collected during routine monitoring surveys to test and refine the predictions in Table 1 and collect additional information about the habitat components and biological responses contained in the conceptual model for this study. The monitoring efforts described below are numbered according to the numbers in the "monitoring data" column in Table 1. In some cases the monitoring is augmented by ongoing special studies which are described in more detail below.

M 1: Delta Flow Data

In the conceptual model described above, inflows, outflows, and estuarine hydrodynamics are the primary dynamic habitat components responsible for the location and extent of the dynamic LSZ in the fall. The IEP agencies operate numerous flow monitoring stations in the estuary and its watershed. Raw data collected at most of these stations is generally available in real time at DWR's California Data Exchange Center website (CDEC, http://cdec.water.ca.gov/). Additional short-term studies augment the monitoring data.

- Some 35 fixed stations located throughout the Delta and Suisun regions have instrumentation for continuous recording of flow and stage. Flow is measured Acoutstic Doppler Current Profiler (ADCP) technology. These stations are operated by DWR, USBR, and USGS.
- Daily average net Delta outflow for the preceding water year (Oct-Sep) is computed once a year by DWR's Dayflow program and made available at http://www.water.ca.gov/dayflow/. The program uses daily river inflows, water exports, rainfall, and estimates of Delta agriculture depletions to estimate the "net" flow at the confluence of the Sacramento and San Joaquin Rivers, nominally at Chipps Island. It is a key index of the physical, chemical, biological state of the northern reach of the San Francisco Estuary.

M 2: Meteorological Data

Wind is an important driver of hydrodynamics and turbidity while solar radiation is important for under-water visibility, seasonal phytoplankton production cycles, and physiological and behavioral responses to day-night cycles. The IEP agencies operate numerous weather stations in the estuary and its watershed. Raw data collected at most of these stations is generally available in real time at DWR's California Data Exchange Center website (CDEC, http://cdec.water.ca.gov/) and DWR's Irrigation Management Information System (CIMIS, http://www.cimis.water.ca.gov/cimis/). Additional short-term studies augment the monitoring data.

- Six fixed stations operated by IEP agencies in the Delta and Suisun region have instrumentation for continuous recording of air temperature, wind speed and direction and irradiance. Two more stations on the San Joaquin River (Vernalis and Mossdale) are slated for installation December 2011. Raw data from all of these stations are available at CDEC (see above). Stations in DWR's Irrigation Management Information System network provide additional data on air temperature, solar radiation, wind speed, wind direction, precipitation etc. around the estuary and in its watershed.

M 3: Water Quality Data

The IEP agencies, the San Francisco Bay Regional Monitoring Program (Bay RMP) conducted by the San Francisco Estuary Institute (SFEI), various dischargers with NPDES permits, and others conduct comprehensive water quality monitoring in the estuary at continuously recording fixed stations, along transects, and at fixed sites that are generally visited once a month by boat or from shore. Several of the monitored water quality constituents are key dynamic components of delta smelt habitat in the fall.

M 3-a Salinity, Turbidity, Temperature

- Salinity (as electrical conductivity, EC), temperature, and turbidity (nephelometric) are measured and recorded continuously (every 15 minutes) at dozens of fixed stations operated by DWR, USBR, and USGS. The raw data from these stations are usually available in real time at DWR's California Data Exchange Center website (CDEC, http://cdec.water.ca.gov/). CDEC also provides calculated real-time X2 estimates (station ID "CX2").

- The DWR-led IEP Environmental Monitoring Program (EMP, see http://www.water.ca.gov/iep/activities/emp) conducts monthly continuous transect sampling along routes connecting the EMP's discrete monitoring sites and the home port of its research vessels in Antioch. Water is continuously pumped from 1 m water depth to sensors that measure salinity (as specific conductance), temperature, and turbidity (nephelometric) Geographical position is recorded along with the monitoring data.
- The IEP EMP also measures temperature, EC, turbidity, and Secchi depth along with total suspended solids in grab samples collected at 25 stations that are visited monthly. The EMP also conducts vertical profile measurements of temperature and EC at these stations. In addition, vertical profile measurements are also conducted at two floating stations that follow the 2 psu and 6 psu isohalines along the axis of the estuary.
- The Bay RMP (USGS for SFEI, see http://sfbay.wr.usgs.gov/access/wqdata/index) includes monthly water quality transect surveys at 39 fixed sampling stations spaced 3 to 6 km apart along the axis of the estuary from South San Francisco Bay to Rio Vista on the Sacramento River. Four of these stations are located in the Suisun region and four are located in the Sacramento river portion of the river confluence region. These surveys include vertical profiles of temperature, EC, and total suspended solids (optical backscatter). These data have been collected regularly for more than two decades.
- EC, turbidity, and Secchi depth are also measured at discrete sites during fish sampling surveys described below. In particular, temperature, EC, turbidity, and Secchi depth data is collected at 138 stations during the fall midwater trawl fish sampling events. Summer and spring fish surveys (SKT and TNS, see below) also include discrete turbidity and Secchi depth measurements at each of their fish sampling sites and the Chipps Island trawl and Suisun Marsh surveys include Secchi depth, temperature and EC measurements.

M 3-b Nutrients, Dissolved Oxygen, Organic Carbon, pH

- Several fixed stations have instrumentation for continuous recording of dissolved oxygen and pH. A few stations also have instrumentation for continuous recording of organic carbon and anions, including nitrate. Raw data collected at most of these stations is generally available in real time at DWR's California Data Exchange Center website (CDEC, http://cdec.water.ca.gov/).

- The IEP EMP conducts monthly continuous transect measurements at 1 m water depth for dissolved oxygen along the routes connecting its discrete monitoring sites and the home port of its research vessels in Antioch.
- The IEP EMP measures nutrients (including ammonium, nitrate and orthophosphate), dissolved oxygen, organic carbon, and pH at stations that are visited monthly. This includes vertical profiles of dissolved oxygen. The EMP nutrient monitoring is augmented by additional stations associated with several ongoing special studies in the Suisun region and elsewhere in the estuary (described below).
- The IEP EMP also conducts spatially intensive, biweekly dissolved oxygen monitoring surveys along the San Joaquin ship channel from about June to November of each year. This includes surface and bottom measurements.
- The Bay RMP (USGS for SFEI, see http://sfbay.wr.usgs.gov/access/wqdata/index) measures nutrients during monthly water quality transect surveys at the 39 fixed sampling stations along the axis of the estuary described above.
- Routine nutrient monitoring is augmented by additional stations associated with several ongoing special studies in the Suisun region and elsewhere in the estuary (described below).

M 3-c Contaminants and Toxicity

The San Francisco Bay Regional Monitoring Program (Bay RMP) conducted by the San Francisco Estuary Institute (SFEI) is a comprehensive, coordinated contaminant monitoring program for San Francisco Bay and the Suisun region. A similar program for the Delta (Delta RMP) is currently under development by the Central Valley Regional Water Quality Control Board (CVRWQB), but has not yet been implemented. In its absence, there is a diffuse network of discharge permit driven contaminant monitoring in the Delta (Johnson 2010). In addition, the IEP sponsored a 4-year invertebrate toxicity monitoring effort conducted by UC Davis from 2006-2009 at selected the fish monitoring sites, but this has been discontinued. Results showed that toxicity to invertebrates was quite rare at these sites. An ongoing IEP- CVRWQB sponsored as well as a newly funded DFG-ERP study include monitoring of pyrethroid toxicity to invertebrates in the Cache Slough Complex, but there is no consistent contaminant monitoring effort in the western Delta and Suisun region.

M 4: Plankton Data

Phytoplankton, zooplankton, and benthic invertebrates have been regularly monitored in the estuary over several decades by the IEP agencies and others. While phytoplankton and zooplankton represent the food base for delta smelt and other pelagic fishes, benthic invertebrates are generally not consumed by delta smelt and the non-native benthic clams *Corbula* and *Corbicula* compete with the fishes for zooplankton and reduce phytoplankton biomass. In recent years, several IEP fish surveys have started monitoring zooplankton at fish survey stations. Jellyfish are also monitored by a few programs. Microbial organisms, benthic microalgae, and submerged and emergent aquatic vegetation and associated invertebrate and algal communities are currently not routinely monitored. *Microcystis aeruginosa* blooms are monitored with a qualitative surface bloom density ranking system during fish and water quality monitoring surveys.

M 4-a Phytoplankton and Microcystis

- Several fixed stations have instrumentation for continuous recording of chlorophyll *a* fluorescence which can be used as a surrogate for phytoplankton biomass. These sensors are regularly calibrated and maintained by DWR. Raw data collected at most of these stations is generally available in real time at DWR's California Data Exchange Center website (CDEC, http://cdec.water.ca.gov/).
- The IEP EMP conducts monthly continuous transect measurements at 1 m water depth for chlorophyll *a* fluorescence along the routes connecting its discrete monitoring sites and the home port of its research vessels in Antioch. An additional continuously recording spectrofluorometer (bbe FluoroProbe) that measures the relative contributions of green, brown, blue-green, and cryptophyte algae to total chlorophyll *a* was added to the EMP transect measurements in 2008.
- The IEP EMP also measures chlorophyll *a* concentrations and microscopically identifies and enumerates phytoplankton species in discrete grab samples collected at stations that are visited monthly.
- The Bay RMP (USGS for SFEI, see http://sfbay.wr.usgs.gov/access/wqdata/index) collects vertical chlorophyll *a* fluorescence profiles during monthly water quality transect surveys at the 39 fixed sampling stations along the axis of the estuary described above. It also collects discrete chlorophyll *a* and phytoplankton grab samples for microscopic identification and enumeration.
- *Microcystis aeruginosa* bloom distribution and density is currently assessed qualitatively (ranked visually) during several monitoring surveys (EMP, TNS, FMWT). Remote sensing based monitoring tools are still under development.

M 4-b Zooplankton and Jellyfish

- The IEP EMP includes a monthly zooplankton monitoring component conducted by DFG which collects, identifies, and enumerates macrozooplankton (mainly mysids), mesozooplankton (mainly copepods and cladocerans), and microzooplankton (rotifers, copepod nauplii)
- Several IEP fish monitoring surveys conducted by DFG (see below for details) also collect zooplankton at fish monitoring sites: the 20-mm survey has collected mesozooplankton samples at all its sites since 1995; the summer

townet survey has collected mesozooplankton samples at all its stations since 2005; The UCD Suisun Marsh has intermittently collected zooplankton samples and began doing so again in 2010. Macro- and mesozooplanktion monitoring is proposed for some of the DFG Fall Midwater Trawls stations. (See below for more details about these surveys).

- The DFG Bay Study identifies, counts and reports gelatinous plankton (jellyfish) from all its sampling stations (since 2000). The DFG Fall Midwater Trawl has enumerated jellyfish since 2001. The DFG Summer Townet Survey began enumerating jellyfish in 2007. The UCD Suisun Marsh survey has reported jellyfish since this survey began.

M 5: Benthic Macroinvertebrate Data

Benthic macroinvertebrates have been regularly monitored in the estuary over several decades by the IEP agencies. Benthic invertebrates are generally not consumed by delta smelt and the non-native benthic clams *Corbula* and *Corbicula* compete with fishes for zooplankton and reduce phytoplankton biomass. *Corbula* biomass is highest under high X2 and low outflow conditions.

- Grab samples for benthic macroinvertebrates including the clams *Corbula* and *Corbicula* will be collected once per month at 13 IEP EMP stations. All invertebrates will be identified and enumerated. In addition, clams will be weighed and measured to assess their biomass.
- Benthic macroinvertebrates will also be collected and enumerated during a spatially-intensive IEP survey using a general randomized tessellation survey design (GRTS) that is conducted by DWR and USGS in October and and May. An additional GRTS survey focusing on the confluence and Suisun region will be conducted by DWR in August 2011 to assess clam abundance and biomass before the fall months.

M 6: Fish Data

Fall outflow management is predicted to affect delta smelt and other fishes monitored in the estuary and its watershed. The IEP monitoring program includes 16 fish monitoring surveys in the estuary (Honey et al. 2004). Many of these surveys are required by OCAP Biological Opinions and deliver critical data for status and trends assessments and water project operations. IEP fish monitoring is carried out by five organizations: California Department of Fish and Game (DFG), California Department of Water Resources (DWR), University of California Davis (UC Davis), US Bureau of Reclamation (USBR), and US Fish and Wildlife Service (USFWS). Most of the fish monitoring surveys have been conducted for several decades. The oldest continuing surveys are the DFG's Summer Townet Survey (TNS, since 1959) and Fall Midwater Trawl survey (FMWT, since 1967). These two surveys routinely deliver key data on delta smelt abundance and distribution before (TNS) and during (FMWT) the fall season. Two other surveys, the DFG's Spring Kodiak Survey (SKT) and 20-mm Survey deliver data on adult and juvenile delta smelt abundance and distribution in the winter and spring. Additional delta smelt data is available from DFG's San Francisco Bay study, FWS's Delta Juvenile Fish beach seine survey and Chipps Island midwater trawl surveys, UCD's Suisun marsh survey, fish collected at the Suisun Bay powerplants, and fish collected at the Skinner and Tracy water project fish facilities (salvage).

- Delta smelt and other fish data will be collected by several IEP fish surveys. Delta smelt fall abundance and distribution data will be collected primarily by the IEP Fall Midwater Trawl (FMWT) Survey conducted by DFG. The FMWT survey samples 138 stations monthly September through December, including 6 new stations as of 2009 and 2010 in the Cache Slough complex and the Sacramento Deep Water Ship Channel. Additional information will come from the DFG San Francisco Bay Study (Bay Study, 52 stations monthly, year-round), the UCD Suisun Marsh Study (21 stations monthly, year-round), the USFWS Chipps Island Trawl (one location, 10 tows, 3 or more times per week, year-round), and the USFWS Delta Juvenile Fish Beach Seine Survey (57 sites sampled weekly, year-round). Pre-fall distribution and abundance information will be generated by the DFG 20 mm Survey (41 stations biweekly, mid-March through mid-July) and DFG Summer Townet Survey (TNS, 40 stations biweekly June through August), including 8 new stations in Cache Slough and the Sacramento Deep Water Ship Channel. Post-fall information will come primarily from the DFG Spring Kodiak Trawl Survey (SKT, 39 stations monthly, January through May (see Honey et al. 2004 for sampling details and IEP web pages (http://www.dfg.ca.gov/delta/) under 'Surveys, Studies and Programs' for more information and recent survey sampling enhancements).
- Delta smelt collected during the August TNS and FMWT (all months) monitoring surveys described above will be handled and stored appropriately to determine body condition and conduct otolith growth, otolith chemistry (looking for migratory or resident signature), and diet and overall health assessments. In addition, fish from January through March SKT samples will be assessed for fecundity and potentially indicators of repeat spawning. Much of this fish processing has not been done on a consistent basis historically and will be conducted by UC Davis scientists (Dr. Swee Teh, Dr. Jim Hobbs, and others). We will evaluate the utility and feasibility of these analyses for incorporation into routine monitoring. Fish collection, handling, and analyses will be carried out by staff from DFG and UC Davis. Delta smelt as well as selected age-0 striped bass, threadfin shad, and Mississippi silversides will be examined, prepared, and analyzed as follows.

The following will be done in the field, immediately after capture:

- Identify, measure length, (mm FL) and assign an individual code to each delta smelt and other target fishes.
- Measure fish weight (0.1 gr) for body condition, hepatosomatic index
- Visually assess injury and disease status for general health index
- Extract, examine, prepare, preserve and archive tissue for laboratory analysis:
    - Gills – extracted, weighed (0.1 gr) and preserved;
    - Liver – extracted, weighed (0.1 gr) and preserved for histopathic exam, glycogen content, lipid and fatty acid analysis;
    - Stomach – for content identification;
    - Gonads (if present) – weigh fresh, assess egg quality - to estimate fecundity, assess the likelihood of previous spawning or future spawning (i.e., multiple spawning in a season);
    - Genetic fin clip samples – to assess delta smelt population structure;
    - Head – preserved in 95%ETOH for otolith chemistry to determine salinity history and potentially migratory timing, otolith incremental growth;
    - Dorsal muscles (& possibly livers) – for stable isotope analyis.
    - Preserve and archive remaining carcass in buffered formalin.

STUDIES

As mentioned above, the IEP, DSP, ERP have a long history of supporting, coordinating, and carrying out short-term studies that address scientific questions with clear management relevance. The IEP POD workplans have attempted to coordinate and integrate studies funded by all three programs in order to answer questions about the POD. We view the fall outflow science plan as a logical part and extension of the POD workplans. The most recent published POD workplan (Baxter et al. 2010) includes a number of studies about fall outflow effects on other dynamic habitat variables and responses by delta smelt. These ongoing studies are included in the fall outflow science plan. New studies are added to address additional questions about the effects of fall outflow after the very wet spring of 2011 and to provide data for modeling efforts. The new studies include several that recently funded by the DSP and the ERP. These studies will be coordinated and integrated by the fall habitat study group.

Fall habitat studies focus on the western Delta and Susiun regions, but also include studies conducted in larger areas and in the northern Delta.

The following studies about habitat components and delta smelt responses listed in Table 1 are currently slated to be conducted as part of the fall outflow science plan. In addition, studies are also conducted to quantify habitat dynamics for components for which we could not yet make a prediction in Table 1. These are listed in Table 2, using the same numbering system as in Table 1. In many cases, data collected as part of these studies augments and complements data collected by the monitoring surveys described above. The ongoing and new studies described below are placed in categories that are numbered according to the numbers in the "studies data" column in Table 1.. Modeling studies are listed in the Analysis and Modeling sections.

Variable (Fall Months)	Measurements and Analysis			Notes
	Monitoring Data	Studies Data	Analysis & Modeling	
Dynamic Abiotic Habitat Components				
Contaminant Concentrations	M 3-c	S 3-c		
Dynamic Biotic Habitat Components				
Average Bacterioplankton Biomass in the LSZ		S 4-a		
Average Protozoan Plankton Biomass in the LSZ		S 4-a		
SAV cover, distribution, and species composition in the LSZ	M7	S 4-a		
Invertebrate Biomass and species composition associated with SAV in the LSZ		S 4-a		
Jellyfish biomass in the LSZ	M 4-b			
Jellyfish biomass variability across LSZ		S 4-b		
Delta Smelt (DS) Responses				
DS recruitment	M 6	S 6		
DS abundance	M 6	S 6		

Table 2: Additional variables investigated by special studies.

Abiotic Habitat components:

S 1: Delta hydrology and hydrodynamics studies – see S 2-a, below.
S 2: Water Quality studies

S 2-a Salinity, Turbidity, Temperature

Ongoing:

IEP 2011-XXX. Scott Wright, USGS, and others: "Delta sediment measurements to support numerical modeling of turbidity." The total three-year budget for the five-year project is $1,955,213. The purpose of the proposed work is to collect data that will support the development, calibration, and validation of numerical models of sediment transport and turbidity in the Sacramento-San Joaquin Delta. While some data on sediment transport and geomorphology exist for the Delta, there are major data gaps that preclude accurate specification of model boundary and initial conditions. Also, measurements are needed to constrain model parameters related to various physical processes, such as erosion rates and settling velocities. Data is provided immediately, provisionally, on an ongoing basis to facilitate model development in the near-term.

IEP 2011-XXX. Jon Burau, USGS, and others: "Measurement of boundary condition data in support of a sediment transport model and improved web-based data visualization software." The total budget for the five-year project is $1,884,291. The goals of this project are four-fold: (1) measure the flows and turbidity at four new sites to establish boundary conditions for numerical hydrodynamic and sediment transport models and to allow the computation of suspended solids flux into and out of the Delta and between regions within the Delta; (2) estimate the complete scalar field (including turbidity) along a transect between Mallard and Liberty Island for each slack water; (3) collect acoustic backscatterance data as a surrogate that can be calibrated to turbidity and suspended solids concentrations by replacing aging Sontek Sideward-Looking Acoustic Doppler Current Profilers (ADCP) at ten sites with RDI 600 kHz units; and (4) improve visualization of time-series data and scalar fields, including turbidity.

S 2-b Nutrients, Dissolved Oxygen, Organic Carbon, pH

IEP 2010-164 R,. Dugdale, SFSU, and others: "Spatial and Temporal Variability in Nutrients in Suisun Bay in Relation to Spring Phytoplankton Blooms". The goal of this study is to answer the two questions: How do nutrients vary in Suisun Bay temporally and spatially and how does this relate to spring phytoplankton blooms? What are the major sources of ammonium in Suisun Bay?
This study is an extension of earlier work on the effect of ammonia on phytoplankton blooms in the estuary. The purpose of this project is to quantify and better understand the variability of nutrients in Suisun Bay, their relation to spring phytoplankton blooms, and sources of ammonium.

IEP 2010-173. R. Dugdale, SFSU, and others: "Distribution, Concentrations and Fate of Ammonium in the Sacramento River and the Low Salinity Zone: Determination of Phytoplankton Uptake and Bacterial Nitrification Rates." Cost: $77,000. This research will quantify 2 key biological processes influencing river NH4+ distribution, bacterial nitrification (= NH4+ oxidation) and phytoplankton uptake, and in future years will investigate the degree of river flow-dependence on these processes. The first step is to develop a protocol for measuring water column nitrification using 15N-labeled NH4+ as a tracer. The protocol is then applied to archived river samples that will be incubated and collected in spring and summer 2010 (as part of the CALFED-funded "Two Rivers" project, Dugdale and Mueller-Solger, Lead-PIs) and the Fall 2010 IEP Foodweb (Parker, et al., 2010). C. Kendall, USGS, will also be involved by collecting samples for natural abundance stable isotope work, for independent estimates of nitrification and phytoplankton N uptake. This project addresses the questions: Can pelagic nitrification rates be measured (and validated to a degree) in the San Francisco Bay using 15N labeling, the NH4+ micro-diffusion technique and mass spectrometry? What are the rates of (a) bacterial/archaeal nitrification and (b) phytoplankton NH4+ uptake downstream from Sacramento to Suisun Bay in spring, summer and fall? Does the fate of NH4+ (i.e., uptake and nitrification) change with season, salinity and flow?

IEP 2010-174. A. Parker, SFSU, and others: "The influence of elevated ammonium (NH4) on phytoplankton physiology in the San Francisco Estuary Delta during fall: exploring differences in nutrients and phytoplankton in the Sacramento and San Joaquin Rivers and how variation in irradiance via changing river flow, modulates NH4 effects." Cost: $114,000. Elevated NH4 concentrations (>4 μmol L-1) appear to inhibit phytoplankton NO3 uptake. One outstanding question is whether the NH4 inhibition effect or the NO3 shift-up that follows NH4 exhaustion occurs at low irradiances characteristic of the natural system. Research in marine settings has demonstrated an irradiance response for phytoplankton DIN uptake, including a differential response for phytoplankton NH4 and NO3 uptake. Phytoplankton DIN versus irradiance relationships are not clear for the SFE or estuarine environments in general. This study addresses the questions: What are the rates of primary production and phytoplankton NO3 and NH4 uptake in the Sacramento and San Joaquin rivers during the fall period? What role does DIN composition and concentration play in modulating the above phytoplankton rates and phytoplankton species composition? How does river flow affect nutrient distribution and phytoplankton rates? Does the conceptual model of NH4 suppression of phytoplankton NO3 uptake and primary production hold under low-light conditions?

Variable	DS Response	DS Source	DS Life Stage	PI	At	$	Study ID	Type
Dynamic Abiotic Habitat Components								
Salinity	Feeding, survival, swimming behavior	FCCL	juvenile to adult	J. Lindberg	UCD	50,000		Ongoing
Turbidity	Feeding, survival, swimming behavior	FCCL	juvenile to adult	J. Lindberg	UCD	50,000		Ongoing
(... and predation)	Feeding behavior, oxygen consumption	FCCL	larval to juvenile	L. Sullivan	SFSU			Ongoing
Hydrodynamic complexity	??? (Has study with swimming at different flows etc been dione by Tina? Someone else?	FCCL	juvenile to adult					
Contaminants	Site-specific gene expression and TIEs after 7-d toxicity assays with water from Delta and Sulsn Marsh sites	FCCL	larval to juvenile	R. Connon	UCD			Ongoing
Dynamic Biotic Habitat Components								
Simulated predation (and turbidity)	DS Feeding behavior, oxygen consumption	FCCL	larval to juvenile	L. Sullivan	SFSU			Ongoing
Jellyfish predation	DS Ingestion by jellyfish	FCCL	larval to juvenile	L. Sullivan	SFSU			Ongoing
Silverside predation	DS genes in silverside guts	Field monitoring and studies	larval to juvenile	B. Schreier	DWR			Ongoing
Striped bass predation	DS genes in striped bass guts & microscopic gut content analysis	Field monitoring and studies	all	F. Feyrer	USBR			Ongoing
Copepod density	Feeding rate, oxygen consumption	FCCL	larval to juvenile	L. Sullivan	SFSU			Ongoing
Zooplankton food quality (different zooplankton species) (...& salinity)	Growth rate, fatty acid profile - (did Lindsey already do enough?). Behavioral response (Loge?)?	FCCL	juvenile to adult	Could use Nann Fangue's postdoc				
Stuckenia beds	Delta smelt abundance in Stuckenia beds	Field	all	K. Boyer	SFSU			New
New Delta Smelt Study Tools								
SmeltCam underwater towed imagin	DS abundance and distribution	FCCL & Field tests	all	Don Portz	USBR			Ongoing
JSATS tag development	Delta smelt swimming responses	FCCL	1- & 2-year old adul	F. Loge	UCD			Ongoing

Table 3: S6 Studies that directly link habitat components and delta smelt responses.

ANALYSES AND MODELING

The monitoring and study elements described above will provide data for comprehensive analysis and modeling efforts. These efforts are intended to test hypotheses and answer questions about responses of delta smelt to fall outflow management and affected habitat components. Example hypotheses and questions related to each habitat component in the conceptual model are listed below, along with the analysis and modeling approaches that will be used to address them. In many cases, these efforts bring together data collected by a variety of monitoring surveys and studies. In addition to data collected in 2011-12, the analysis and modeling efforts described here also rely heavily on historical data, where available. The numbering below corresponds to the "Analysis" column in Tables 1 and 2. There are no numbers for the stationary habitat components.

Stationary Abiotic Habitat Components

The stationary (geographically fixed) abiotic habitat components in the fall outflow conceptual model are bathymetric complexity, erodible sediment supply, contaminant sources, and entrainment sites. They differ between the two regions in which the LSZ is placed in the fall through the outflow management prescribed in the BiOp – the Suisun region during falls following wet springs and the river confluence during falls following dryer springs. These components are not expected to be affected by fall outflow management. They are not static, but they change much more slowly than the dynamic habitat components. Importantly, their interactions with the dynamic habitat components are expected to produce different delta smelt responses when the LSZ is in the Suisun region compared to when the LSZ is in the river confluence. In order to assess these interactions, the stationary habitat features need to be clearly documented.

Fortunately, good, recent data and documentation exists for bathymetry and bed sediment volume (Schoellhamer 2011), the location of entrainment sites, and contaminant sources (Johnson 2010). The study plan thus merely contains a data portal element for this information and notes that bathymetry surveys need to be repeated at regular intervals. Because less is known about bed sediment composition across the bays of the Suisun region, the science plan also contains a study element to address the questions: How does bed sediment composition vary among and within the shallow and deep areas of the Suisun region and river confluence? What are the sources of the bed sediments in the Suisun region and river confluence? *("fingerprinting" of sediment cores)*

Dynamic Abiotic Habitat Components

A 1: Delta hydrology and hydrodynamics studies

A 2: Water Quality analyses

Hypothesis: The amount of abiotic habitat for delta smelt varies with X2. Questions: Does fall turbidity vary with fall X2? How does X2 affect habitat volume/area based on salinity and water clarity? How does X2 affect the habitat of delta smelt predators such as striped bass and largemouth bass? Does X2 affect the abundance and distribution of submerged aquatic vegetation (SAV) such as Egeria?
Does SAV proliferation affect delta smelt spawning habitat?

Hypothesis: High fall X2 exacerbates contaminant effects. Questions: How does fall X2 affect the distribution, concentration, and effects of ammonia and ammonium? How does fall X2 affect the distribution, concentration, and effects of other contaminants? How does fall X2 affect the frequency of occurrence and distribution of acute and chronic toxicity of ambient water to delta smelt and their food organisms?

Hypothesis: High X2 increases losses to agricultural diversions. Questions: Does high X2 shift delta smelt distribution to an area with a higher risk of agricultural entrainment? How do agricultural operations in the western delta change in response to higher X2? How do agricultural losses of delta smelt vary with X2?

Hypothesis: High X2 increases losses to power plants. Questions: Does high X2 shift delta smelt distribution to an area with a higher risk of power plant entrainment in the Sept-Nov period? How do power plant losses of delta smelt vary with X2? Does power plant entrainment present a substantial risk of mortality?

Hypothesis: High X2 increases losses to SWP and CVP export facilities. Questions: How does the probability of fish entrainment during winter upstream migration vary with fall X2?

Interactions with abiotic habitat components in other seasons

In analyzing the importance of fall X2 variability and the effects of RPA 3 we must look for evidence of sporadic, non-linear, or interactive effects of flows in the fall with other drivers and in other seasons. Most of the hypotheses and questions about these types of interactions follow from the hypotheses and questions about the effects of individual drivers, and in several cases the questions included under the individual drivers above already address various interactions.

Hypothesis: Conditions in the spring affect flow effects on delta smelt in the fall. Questions: How does distribution of delta smelt in the spring and summer affect their distribution and growth in the fall? How do delta smelt "find" suitable fall habitat? How do pesticide exposure and toxicity to delta smelt in the fall vary with flows? How do pesticide exposure and toxicity in the spring affect the delta smelt population in the fall? What is the fate of contaminants mobilized in wet springs under different fall flow conditions? Do summer Microcystis blooms affect delta smelt distribution in the fall? How do flows affect this interaction? How do agricultural use patterns in the Delta or energy demands on power plants in Suisun Bay change with springtime conditions, and does this amplify the impacts on delta smelt by higher X2 in the following fall?

Biotic Habitat components:

A 4: Plankton Analyses and Modeling

Hypothesis: Low flow results in reduced transport of *Pseudodiaptomus* copepods from the freshwater Delta into the LSZ. Questions: What is the quantitative change in transport and in the subsidy to the copepod populations in the LSZ as flow changes? How is this affected by the greater distance between the LSZ and the central delta when flows are higher?
Approach:

Hypothesis: Low flow results in reduced transport of dissolved and particulate organic materials (detritus, phytoplankton, bacteria, and microzooplankton) from the freshwater Delta into the LSZ. Questions: How does the transport rate of these

materials to the LSZ change at the level of flows proposed for the fall? What is the relative importance of transport and turnover rates of these materials in the LSZ? How does food quantity and quality for copepods change as flow increases in the fall?
Hypothesis: High X2 exposes foodweb organisms, including phytoplankton, microzooplankton, and copepods (esp. *Pseudodiaptomus*) to pumping losses, with the result being lower copepod abundance in the LSZ.
Questions: How does the fractional daily loss of chlorophyll and labile organic matter change with X2 and export pumping rate? What fraction of the *Pseudodiaptomus* population is lost to export pumping? How do these losses affect conditions in the LSZ?

Hypothesis: Production or abundance of *Microcystis* increases with high X2. *Microcystis* may interfere with the LSZ foodweb through various mechanisms including toxic effect, nutritional deficiency, and interference with feeding by copepods. Questions: How does X2 affect the abundance, distribution, or effects of *Microcystis*? What are the trophic dynamics by which *Microcystis* changes the zooplankton community composition? What is the population-level impact of *Microcystis* on copepods such as *Pseudodiaptomus*? How do pelagic foodwebs change when *Microcystis* blooms? How do *Microcystis* bloom dynamics change with X2?

Hypothesis: Lower outflows result in higher concentration of ammonium, suppressing phytoplankton growth and therefore biomass accumulation.
Questions: How important is ammonium suppression of diatom growth in the freshwater and in the low salinity regions of the estuary, compared with the suppression of biomass by clam grazing, and suppression of growth by high turbidity? How do the relative magnitudes of these limits on phytoplankton change as X2 changes?

Hypothesis: Changes in the shape or size of the LSZ cause a reduction in production when X2 is high. Questions: Using refined models, how does the size and shape of the LSZ change as X2 changes? How does the change in depth (or fraction of the area shallow enough for net phytoplankton production) translate to changes in phytoplankton productivity or impact of benthic grazers on all foodweb components?

Hypothesis: Overlap between *Pseudodiaptomus* and *Limnoithona* increases with a landward X2, intensifying competition for food between these apparent competitors. Questions: What is the nature and magnitude of competition for food between the copepods in the upper estuary? How does this change with X2?

Hypothesis: Overlap between *Pseudodiaptomus* and *Acartiella* increases with a landward X2, intensifying predation by *Acartiella* on early stages of

Pseudodiaptomus. Questions: What is the predation rate of *Acartiella* on different life stages of *Pseudodiaptomus*, and is it an important source of mortality? How does mortality and predation rate change with X2?

Hypothesis: Recruitment of gelatinous plankton to the LSZ is higher when X2 is high; this increases predation on zooplankton which in turn causes reduction in abundance of food for delta smelt. Questions: Are jellyfish important components of the plankton in terms of their consumption rates? Does jellyfish abundance in the LSZ vary with X2?

Hypothesis: Low flow favors nutritionally inferior phytoplankton and zooplankton species. Questions: To what extent does low flow (high X2) affect the community composition and nutritional quality of phytoplankton and zooplankton in the LSZ?

A 5: Benthic Macroinvertebrate Analyses and Modeling

Hypothesis: A persistently high X2 results in recruitment of *Corbula* and, in turn, reduction in biomass of phytoplankton, bacteria, microzooplankton, and mesozooplankton. Questions: What is the response of *Corbula* to changing salinity/variable X2? For example, how does recruitment vary with salinity? What conditions promote large recruitment events? What conditions limit recruitment or limit successful growth of *Corbula* into juveniles?

Hypothesis: Movement of X2 causes a mismatch between the location of *Corbula* populations and the LSZ, reducing consumption of phytoplankton and zooplankton by clams; conversely, a stable X2 (particularly during clam recruitment periods) allows for these locations to match over a period of time, maximizing consumption by clams. Questions: Does tidal and longer-term movement of X2 result in mismatch of clam, phytoplankton, and copepod populations? How much difference does that mismatch make to overall consumption? What is the magnitude of consumption of phytoplankton, microzooplankton, and mesozooplankton? What is the resulting effect on calanoid copepods in the LSZ?

A 6: Delta smelt responses:

Hypothesis: High fall X2 results in lower abundance of delta smelt. Questions: How does delta smelt adult abundance vary with fall X2? How does production of juvenile smelt vary with fall X2?

Hypothesis: High fall X2 affects life history. Questions: How do fall conditions affect population structure or life history characteristics of delta smelt?

Hypothesis: High fall X2 reduces delta smelt growth rates. Questions: How does delta smelt growth vary with X2 in the fall?

Hypothesis: High fall X2 results in lower fecundity of delta smelt. Questions: How does delta smelt fecundity vary with fall X2? How does egg quality vary with fall X2?

Hypothesis: High fall X2 reduces condition of delta smelt. Questions: How does delta smelt condition vary with fall X2?

Hypothesis: High fall X2 reduces health of delta smelt. Question: How does delta smelt health vary with fall X2?

Hypothesis: Delta smelt are food limited in the fall. Questions: To what extent are individual delta smelt limited by food supply in terms of their ingestion rate, growth rate, development, or survival? How does subsequent fecundity of delta smelt in late winter-early spring respond to feeding conditions in the fall?

Additional environmental studies, characterizations, and analyses that will help inform and provide context for the above-outlined study efforts:

- USFWS (Newman et al.) state-space modeling project to address uncertainty in estimating delta smelt abundance estimates
- Rivercourse Engineering (MacWilliams et al.) 3-dimensional modeling project for hydrology, salinity, and turbidity
- UC Berkeley (Stacey and Wagner) hindcasting study and Delta Science Program (Enright and Culberson) study detailing temperature and heat transfer processes in the Estuary
- DWR and USGS (Thompson et al.) GRTS-related benthic analysis for foodweb underpinnings
- DWR water quality profile analyses with improved spatial resolution to show process-based effects on salinity, turbidity, chlorophyll a, dissolved oxygen, and temperature
- SFSU (Kimmerer et al.) sampling to understand zooplankton transport into the low salinity zone

ITERATIVE ELEMENT: ASSESSING OUTCOMES FOR DECISION SUPPORT

Assessing outcomes is closely tied to modeling and will be laborious and technically difficult. It will also be very dependent on the final form of the models we are developing. For reasons outlined below, we plan to jointly staff assessment with modeling and to allow one or more skilled analysts time on a year-round basis to develop results and work with policymakers and stakeholders to formulate decision support information.

The process model assumptions articulated earlier establish four linked levels of expected effects, including: 1) flow and X2 on physical conditions (salinity, temperature, turbidity, area of potential habitat), 2) physical conditions on zooplankton density and distribution, delta smelt survival, and transport of food from production to consumption areas, 3) food and habitat quality on growth, health, condition and survival rates, and 4) size, health and condition on fecundity and egg size or quality, and hence recruitment. At each level, the assessment requires both measurements or estimates of the outcomes and an evaluation of the uncertainty propagated to each outcome. Providing these is the major objective of the integrative quantitative modeling discussed earlier.

In general, outcome assessment is based on the degree of difference between observed outcomes and the predictions. Setting aside the simple cases (all predictions borne out; all predictions contradicted; all predictions unresolved), there are other permutations that may pose more interesting interpretive challenges. Outcome patterns that uniformly enhance or diminish the role of model links have obvious interpretation. On the other hand, internally contradictory results (for example, independent lines of evidence that at once say that zooplankton density is increasing and decreasing) imply that we are measuring something incorrectly or that the underlying dynamics are more complicated than envisioned in our process model. Sorting these issues out is very situation-specific.

Because some internal variables, for example those measuring delta smelt health, have no history on which to base quantitative predictions, evaluation of outcomes will initially be a matter of judgment. As the monitoring data voids are filled, assessments will become better formalized.

As the decision analysis becomes clearer, we intend to consider the use of multicriteria decision analysis (Linkov et al. 2006a,b) and other tools to make the adaptive management process more efficient. We also propose to require publication or public release of annual assessment reports and key scientific results bearing on important management decisions, recognizing the public interest in this process.

ITERATIVE ELEMENT: DECISIONS AND COORDINATION

As we described above, Reclamation's plan places a high value on learning about the efficacy of the fall outflow action, and on generating the information needed to adjust or change the action should understanding so require. For this reason, we proposed initially examining a strongly contrasting pair of alternatives: implement the targets of the 2008 RPA or implement a reduced-outflow alternative supported by the USFWS. The choice of which alternative to implement in a given "wet" or "above normal" year implicates the first type of annual decision agency managers face: what should the management alternatives be?

This type of decision fundamentally belongs to the three agencies engaged in the operations consultation under Section 7: USFWS, Reclamation, and DWR. Because of the potential for a fall outflow action to interact with Shasta carryover storage, there is also a nexus with NOAA Fisheries Service. We anticipate that the choice of alternatives would be reviewed by these agencies annually after the technical review of the previous year's activities and findings is completed, and would be the last management decision made in each annual cycle.

The second category of decision includes those decisions required to implement the action or elements of the monitoring and evaluation program. The strictly technical implementation decisions would be taken by the agencies responsible for funding and/or carrying out the relevant work. Implementation decisions that potentially affect ESA obligations would entail additional consultation involving the .

Potential affects of fall outflow augmentation on Shasta carryover storage is a special case. NOAA Fisheries Service included a prescription in its 2009 RPA to deal with this, as follows (NOAA 2009, p. 593).

> **Action I.2.2.A Implementation Procedures for EOS Storage at 2.4 MAF and Above**
> If the EOS storage is at 2.4 MAF or above, by October 15, Reclamation shall convene a group including NMFS, USFWS, and CDFG, through B2IT or other comparable process, to consider a range of fall actions. A written monthly average Keswick release schedule shall be developed and submitted to NMFS by November 1 of each year, based on the criteria below. The monthly release schedule shall be tracked through the work group. If there is any disagreement in the group, including NMFS technical staff, the issue/action shall be elevated to the WOMT for resolution per standard procedures.
>
> The workgroup shall consider and the following criteria in developing a Keswick release schedule:
>
> 1. Need for flood control space: A maximum 3.25 MAF end-of-November storage is necessary to maintain space in Shasta Reservoir for flood control.
>
> 2. Need for stable Sacramento River level/stage to increase habitat for optimal spring-run and fall-run redds/egg incubation and minimization of redd dewatering and juvenile stranding.
>
> 3. Need/recommendation to implement USFWS' Delta smelt Fall X2 action as determined by the Habitat Study Group formed in accordance with the 2008 Delta smelt Opinion. NMFS will continue to participate in the Habitat Study Group (HSG) chartered through the 2008 Delta smelt biological opinion. If, through the HSG, a fall flow action is recommended that draws down fall storage significantly

from historical patterns, then NMFS and USFWS will confer and recommend to Reclamation an optimal storage and fall flow pattern to address multiple species' needs.

This plan assumes that the approach described here would be used to address carryover storage issues arising through implementation of fall outflow adaptive management.

The third category of annual decision is scientific: what has been learned, and what are the next investigative steps? We envision an annual management and science conference and report on findings to date, with the report used to inform a standing review panel and the agencies that are parties to the operations consultation.

ITERATIVE ELEMENT: OUTSIDE EXPERT REVIEW

Independent expert review of this plan is critical. It is also critical that there be ongoing independent review of the results of management and other scientific activities to support management review of the effectiveness of the conservation action and learning program. After discussion with the Delta Stewardship Council's Delta Science Program leadership, we have concluded that the most effective approach to satisfying both of these needs is to establish a permanent panel for the purpose.

As currently envisioned, the panel would convene to review Reclamation's draft adaptive management plan before implementation in order to ensure that it is of sufficient robustness and scientific quality to serve the intended purposes. Results of the review would be implemented in the draft plan before the plan is made final. The same panel of experts would then be retained to conduct an annual review of progress and findings and would provide a report to Reclamation and the Service detailing each panel member's findings. This report, along with other information available at the time, would be used to inform management decisions pertaining to adaptive management of Fall outflow.

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APPENDIX I: Study Descriptions

Descriptions of each study are provided below; the delta sediment measurements element is not part of the HSG package but is included for completeness. As noted in the preceding section, Reclamation is also working with others to develop UnTRIM/SEDIMORPH-based tools to carry out physical modeling tasks required to carry out this plan.

Hydrodynamic and particle tracking modeling of delta smelt habitat and prey

Wim Kimmerer (SFSU) and Lenny Grimaldo (USBR)

This study is using existing modeling tools and laboratory and field data to accomplish two broad goals. The first goal is to better understand the variability of physical habitat with variation in X2 for key fish species including delta smelt. The second goal is to better understand the population dynamics of calanoid copepods, the most important food for delta smelt in summer and fall. These two goals are closely linked in that the same hydrodynamic simulations can be used to achieve both goals. This study seeks to answer three research questions: (i) How can existing or new monitoring data, modeling, or other methods be applied to better define and monitor smelt habitat; (ii) How do abiotic or biotic conditions during spring and summer influence how flow affects smelt habitat and ecological processes important to smelt during fall; and (iii) How much food is available for delta smelt in the LSZ, what is its quality and how are they affected by flow variability? The study is using the UnTRIM 3-dimensional hydrodynamic model to quantify flow-habitat relationships for delta smelt and other fish by simulating seven steady Delta outflow conditions over a wide range of X2 values. It will also perform sensitivity analyses to determine the effect of modified export flows on model outcomes at low Delta outflows. The study is also using the UnTRIM model in combination with the Flexible Integration of Staggered-grid Hydrodynamics Particle Tracking Model (FISH-PTM) to simulate the vertical migration, retention and transport of the calanoid copepod *Pseudodiaptomus forbesi.* The goal is to construct a four-box model of the Delta-LSZ to simulate the population dynamics of *P forbesi* and to link the boxes using advective and dispersive terms estimated from the hydrodynamic and particle tracking Model with an adjustment to reduce seaward movement as indicated by the retention analysis for the life stages that migrate (copepodites and adults). This work will culminated with the development of an Individual-Based Model (IBM) of *P. forbesi* that will be linked to the FISH-PTM.

Delta sediment measurements to support numerical modeling of turbidity

Scott Wright (USGS) and Dave Schoellhamer (USGS)

The purpose of this 3-year study is to collect data that will support the development, calibration,and validation of numerical models of sediment transport and turbidity in the Sacramento-SanJoaquin Delta. One component of the study focuses on the measurement of suspended sediment fluxes into and through the Delta by continuously monitoring turbidity at a dozen locations and calibrating turbidity measurements against velocity-weighted mean concentrations of suspended sediment. These data will address the following questions. How much sediment is entering the Delta from the various river sources, and how much is transported from the Delta downstream to San Francisco Bay? What are the concentrations and particle size distributions of suspended sediment in the Delta, and how do these properties vary spatially and temporally? What are the relationships between turbidity, suspended sediment concentration, and particle size? How do pulses of suspended sediment that are delivered by the upstream watersheds move throughout the Delta, i.e. what are the transport pathways and how are these pathways linked with Delta hydrodynamics? Another component of the study focuses on the estimation of suspended and bed sediment parameters for incorporation into numerical models. Questions addressed include the following. What are the erodibility and critical shear stresses for erosion of Delta sediments? How much flocculation of sediment particles occurs in the Delta, and what are the settling velocities of the flocs? How do erosion and settling properties vary spatially and temporally in the Delta? What are the particle size distributions of the bed sediment in the Delta? What are the spatial patterns in size distributions and how do these patterns change temporally? Are there "hotspots" of deposition and erosion cycles within the Delta?

<u>Delta smelt feeding and food web interactions</u>

Wim Kimmerer (SFSU) and Larry Brown (USGS)

The purpose of this study is to investigate the food supply for delta smelt, how it is affected by predators and competitors, and how these interactions depend on delta outflow. This study seeks to answer two questions: (i) To what extent is growth or survival of delta smelt food limited; and (ii) What limits the availability of food for delta smelt? The study will determine ingestion rate and oxygen consumption rate of larval and juvenile delta smelt incubated under a range of copepod densities. It will also determine the response of delta smelt to changes in turbidity and the presence of predator stimuli under controlled laboratory conditions. The study will conduct feeding experiments using naturally-occurring food to link ambient food quantity and quality with copepod reproduction and development rates and to assess the overlap in feeding between *P. forbesi* and *L. tetraspina*. The study will also measure the abundance and distribution of gelatinous predators throughout the upper regions of the San Francisco Estuary and conduct incubation experiments to quantify predation rates on crustacean zooplankton and larval fish.

POD fish diet and condition

Steven Slater and Randall Baxter (DFG)

The purpose of this study is to examine the diet, feeding incidence, stomach fullness and body condition of delta smelt and some of the other POD fishes to determine if these assessments provide evidence of food limitation, either seasonal or spatial. This study has and continues to examine delta smelt diet regionally and seasonally, and has derived estimates of maximum stomach fullness and mean body condition at length to act as references when assessing the well being of delta smelt. To date, unpublished study information suggests there are potential spring transition and fall periods when food might be limited, and a regional gradient, from western Suisun Bay through the lower rivers just above the confluence, of increasing stomach fullness and body condition during summer and early fall. This study is ongoing and will process delta smelt not otherwise directed to other projects (see

Monitoring inter-annual variability in delta smelt population contingents and growth

James Hobbs (UCD)

The primary goal of this research is to gain a better understanding of the mechanisms (e.g. climate variability, hydrology) responsible for apparent success of different life history contingents and how entrainment as indexed by salvage at CVP and SWP could alter life history diversity. Archived samples from 1999 – 2008 monitoring surveys, already prepared for otolith microstructure and microchemistry studies, will be assayed with a laser line from the core to the edge to reconstruct the entire life history. Sub-adult and adult sampled collected by the IEP in 2010/2011 will be examined for microchemistry and growth rates will be quantified by otolith microstructure analysis. The primary research questions are:

1. Can life-history and growth of fish salvaged at CVP and SWP be compared to fish that survive the TNS to determine the effects of entrainment and salvage? What are the habitat effects on delta smelt population dynamics?

2. Do life-history contingents vary inter-annually, in association with growth, freshwater outflow, water temperature, abundance?

3. Does growth rate increase with increased fall outflow?

This work will be continued into the fall-winter of 2011/2012 to focus on examining the issues of variable fall growth and salinity history between putative resident delta smelt in Cache Slough and the Sacramento Deep Water Ship Channel region and those in the Suisun Bay and river confluence region. These analyses should provide evidence for (or against) upstream residence in the Cache Slough and the Sacramento Deep Water Ship Channel region, and provide a general contrast in fall growth exhibited in Suisun Bay responding to increased fall flows and the Cache Slough Region, which should be less influenced by any fall flows.

Health of threatened fish: role of contaminants, disease and nutrition

Swee Teh (UCD)

In collaboration with IEP fish monitoring surveys and studies, this project proposes to determine the biological effects of contaminants, pathogens/diseases, and nutritional status of striped bass, threadfin shad, splittail and tule perch from three regions in the upper estuary, Cache Slough complex, Suisun Marsh and the lower San Joaquin River. Dr. Teh has agreed to incorporate delta smelt from IEP monitoring surveys into his study design. The study's main goal is to establish a conceptual framework that proposes and investigates relationships among stressor effects, ecosystem variables, and the health indices of the fish (see objectives below).

Study objectives include the following;
1) Detecting differences in physiological and morphological health of fish based on body condition factor and organo-somatic indices (e.g., hepato-somatic index);
2) Employing biomarkers capable of selectively recognizing specific types of contaminants (e.g. P450 induction from PCB exposure, vitellogenin or choriogenin induction in males from endocrine disruptor exposure) and biomarkers specific for both exposure and deleterious effects (e.g. endocrine disruption and histopathology);
3) Identify the presence and severity of pathogens/disease as a significant health indicator and relate to both other stressors discussed above and below and to environmental variables; and
4) Determine the nutritional status of fish through measures of lipid and fatty acid content and protein composition.

Much of the information collected will be used to establish baselines for various health indices (e.g., body condition, hepatosomatic indices, etc.), The proposed suite of measures, if they can be made on sufficient numbers of each fish species, should provide an important assessment of whether contaminants and pathogens/disease affects are present and related to the nutritional status of the fish, including delta smelt.

Metabolic responses to variable salinity environments in field-acclimatized *Corbula amurensis*

Jonathon Stillman (SFSU) and Jan Thompson (USGS)

This study seeks to characterize the metabolic physiology of *Corbula amurensis* in locations representing the extremes of their salinity distribution ranges in the northern San Francisco estuary. The overarching questions addressed by this research are the following. How does *Corbula amurensis* affect the food web supporting delta smelt, how is *Corbula* physiology affected by flow variability, and what are the seasonal carry-overs between fall flow and physiology of clams in the spring? More specifically, this research asks:

(i) How much metabolic variation exists in *Corbula* acclimatized to different salinities across sites (low to high salinity variability) and seasons?

(ii) How are *Corbula* acclimatized to different salinity regimens partitioning energy into different physiological categories (e.g., osmotic content, growth, reproduction, storage, metabolic pathways)?

(iii) How much of the variation in *Corbula* metabolic physiology in specimens collected at different sites or time of year is due to variation in water chemistry and variation in the planktonic assemblage?

The study requires a year-round monthly sampling regime to collect clams at 9 stations along a salinity gradient. At each monthly sampling, water samples are collected and filtered to determine water quality (e.g., water temperature, pH, specific conductance and turbidity) and the size distribution of plankton (as measured by size-fractionated chlorophyll, total organic carbon and total nitrogen measurements). *In vivo* physiological performance assays include filtration and metabolic rate measurements. Biochemical assays to determine osmotic content, growth, reproductive output potential, energy storage and biochemical indicators of metabolic state of clams are also performed using field-frozen specimens. Statistical analyses will be performed to determine how water quality variation affects *Corbula* physiological performance.

<u>Distribution, concentration and fate of ammonium in the Sacramento River and the low salinity zone</u>

Richard Dugdale (SFSU) and Carol Kendall (USGS)

The goal of this study is to determine the distribution, concentration, and fate of ammonium ($NH4^+$) in the Sacramento River and low salinity zone (LSZ) of the San Francisco Estuary/Delta. Specifically, this research will quantify two key biological processes influencing $NH4^+$ distribution: bacterial nitrification ($NH4^+$ oxidation) and phytoplankton uptake. The first year of this 3-year effort will focus on developing a protocol for measuring water column nitrification using 15N-labeled $NH4^+$ as a tracer. The subsequent two years will focus on determining how river flow affects these processes. This task addresses the following questions:

(i) Can pelagic nitrification rates be measured (and validated) in SF Bay using 15N labeling, the NH4 micro-diffusion technique and mass spectrometry;

(ii) What is the distribution of $NH4^{+}$downstream from Sacramento to Suisun Bay in spring, summer and fall;

(iii) What are the rates of a) bacterial/archaeal nitrification and b) phytoplankton $NH4^{+}$ uptake downstream from Sacramento to Suisun Bay in spring, summer and fall; and

(iv) Does the fate of $NH4^{+}$ (i.e. uptake and nitrification) change with season, salinity and flow? To address these questions will require the following sub-tasks.

<u>Influence of elevated ammonium (NH4) on phytoplankton physiology in the Sacramento-San Joaquin Delta during fall</u>

Alex Parker (SFSU) and Larry Brown (USGS)

The goal of this study how nutrients affect the food web supporting delta smelt in the low salinity zone and how nutrients in turn are affected by flow variability. More specifically, the questions addressed by this study include: (i) What are the rates of primary production and phytoplankton NO3 and NH4 uptake in the Sacramento and San Joaquin Rivers during the fall period and how do they compare between the two rivers; (ii) What role does dissolved inorganic nitrogen (DIN) composition and concentration play in modulating these rates; (iii) What role does DIN composition play in shaping the phytoplankton community; (iv) Are there differences in phytoplankton taxa between the Sacramento and San Joaquin Rivers; (v) If so, can these differences be attributed to differences in DIN composition; and (vi) How does river flow affect nutrient distribution and phytoplankton rates. Additional questions addressed by the study include the following: (i) How do primary production and phytoplankton N uptake rates vary in response to irradiance in the Sacramento and San Joaquin Rivers during the fall; (ii) What are the nitrate uptake-irradiance relationships for the SFE; (iii) Are there differences in the irradiance response for phytoplankton using NH4 and NO3; and (iv) Does the conceptual model of NH4 suppression of phytoplankton NO3 uptake and primary production hold under low light conditions?

Appendix II: Quantitative models

In the previous section we erected a set of assumptions capturing what is currently known or believed to be known about the effects of fall outflow on delta smelt habitat and subsequent abundance. This section develops a novel integrative analysis based on these assumptions that will incorporate existing historic data and new kinds of data yet to be collected. Note that the expression 'quantitative models' is used here to refer to statistical models. We also rely on hydrodynamic models for certain purposes, but our uses are not novel.

Because the approach described here has not previously been implemented and is of high importance, its development is a key priority of this plan. The modeling will be tightly integrated with the life-history modeling effort led by Ken Newman at USFWS, in which Reclamation and USGS scientists and several academics are active participants. Models will be used to make quantitative predictions that serve as benchmarks to assess the performance of management actions. Bayesian state-space models are used because they offer a great deal of flexibility and are designed to integrate data obtained from different sources and levels of temporal and spatial resolution.

Models will be used to address key questions, some of which are expected to require additional supporting laboratory and/or field studies. Supporting studies will focus on elucidating mechanisms and estimating parameters that would be difficult to study with an observational approach where explanatory factors naturally covary, leading to ambiguous or highly variable parameter estimates. For example, the functional response linking zooplankton abundance, turbidity and fish sized to rate of intake of net energy can only be determined in the lab. Key questions are:

1. What amount and quality of LSZ delta smelt habitat could be expected for what duration by varying the Fall outflow prescription?
2. What is the effect of habitat area and distribution on delta smelt distribution?
3. How does fish condition/health vary across a gradient of habitat quality?
4. How will delta smelt growth rates be affected if food density, composition, or distribution is changed during fall?
5. Does fish health/condition affect over-winter survival?
6. How does fecundity and egg quality change as a function of fish size, condition, and health?
7. What is the effect of outflow-driven changes in ammonium and N:P ratio on the composition and productivity of plankton?
8. What are the most important mechanisms linking Fall outflow to survival and fecundity?

Learning will be optimized by using the models to forecast multivariate effects of the action. The nature of the multivariate difference between predicted and observed system states will be analyzed to guide future management actions and to improve the models. Posterior distributions of state and parameter estimates can be used to optimize additional measurements to reduce uncertainty.

In the following sections, the modeling approach is illustrated by listing the variables that characterize the system, proposing equations for a few key processes and establishing relationships between state variables (e.g., delta smelt abundance) and observed quantities (e.g., catch).

The estuary is viewed as a series of regions as depicted in Figure 5 above. The late summer, fall and winter seasons are divided into a series of two-week periods, more or less consistent with the intervals between fish sampling events. Each region is characterized each time step by the spatiotemporal averages of a series of variables listed below. Sampling events and observation methods yield observed values that are modeled as functions of the true values of state variables.

Variables

System state at any give time (t) and region (r) is characterized by the following variables:

1. Number of delta smelt (DS)
2. Delta smelt size (FL)
3. Abundance of zooplankton (Zoop)
4. Abundance of phytoplankton (Phy)
5. Water turbidity (Secchi)
6. Bottom salinity (Sal)
7. Water temperature (Temp)
8. NH4 concentration (Ammo)
9. N:P ratio (NP)
10. P concentration (Phos)
11. Abundance of silversides (SSide)
12. Abundance of striped bass (Sbass)
13. Abundance of interspecific competitors (Comp)
14. Abundance of predators (Pred)
15. Abundance of *Corbula amurensis* and similar clams (Corb)
16. Abundance of other clams
17. Average X2 (X2)
18. Flow rate (Flow)

19. Wind speed (Wind)
20. Microcystis bloom or abundance (Micro)
21. Volume of water in marsh habitat (Vmarsh)
22. Volume of water in shallow water habitat (Vshall)
23. Volume of water in river channel habitat (Vchan)

Modeling approach

A Bayesian state-space approach is promising because of several characteristics of the problem. First, the system is large and heterogeneous. Its state must be described by multiple variables in many places and times. Second, the true state of the system is not directly observable, but we can observe proxies of state, uncontrolled inputs, and auxiliary variables. For example, the population of delta smelt is so low that it challenges the ability of current methods to detect it with acceptable certainty. Both the observation and the biological processes need to be modeled as outlined below. Third, bay-delta state variables are connected by a complex network of relationships that need to be taken into account in an integrated fashion, but data available come from diverse sources with different spatial and temporal resolutions. Finally, effects of unpredictable uncontrolled inputs such as precipitation, contamination events, invasions and *Microcystis* blooms are incorporated into system state and cause deviations from the goal. The fact that process noise is incorporated into system state makes adaptive management indispensable, because even if management is optimized, system state will deviate from expectations and corrections will be necessary.

According to the state-space approach, we formulate both process and observation equations. Note that the state variables defined above represent the actual state of the system and are not the same as the observations. Following the state-space approach, we consider that observed values result from sampling and measurement processes that introduce errors about the true system state.

Sources of uncertainty

There are four main sources of uncertainty made explicit in adaptive management: environmental, control, process and observation. Environmental uncertainty is due to the fact that there are important factors that affect the system (delta smelt) whose values are not known in advance. A management action (for instance, the 2008 RPA Fall outflow element) prescribes either outflow magnitudes or positions for X2 for specific durations. The results of applying this management depend on the sequence of water years into the future. An ex-ante prediction of action effects must incorporate the uncertainty due to not knowing what the precipitation will be in the future. Ex-post predictions remove environmental uncertainty from the model and allow identification of deviations due to other sources of uncertainty. Environmental uncertainty is incorporated into system state.

Control uncertainty refers to the fact that the controllable factors (decision variables, in this case X2) are not perfectly controllable. The actual average X2 obtained in a month may differ from the goal. This uncertainty may be difficult to assess quantitatively if it depends on rare events or complex institutional and/or legal processes. Control "errors" are incorporated into system state and propagate into the future.

Process uncertainty or error is due to the lack of complete agreement between the model and the actual biophysical process modeled. The difference between model and system state becomes part of the true state and it propagates forward with the process. Thus, process uncertainty is also incorporated into system state. Process uncertainty is a major component of our current ability to manage the system, particularly because the knowledge about the various processes has not been integrated into tools that can yield quantitative predictions. Such an integrative modeling is a key component of the present adaptive management plan.

Observation error is the difference between the actual system state and estimates based on samples. More generally, observation error results from the complex sampling, observation and measurement process that generates data. The most common source of observation error is sampling error. Observation errors are not incorporated or propagated forward in the system.

Latent variables can be useful to consider the observation error in covariates. For example, the model states that food availability affects delta smelt growth. However, the "true" availability experienced by an individual fish is not measurable and is represented by a latent variable that is related to the measureable zooplankton density.

Delta smelt process equations

The purpose of these equations is to provide a framework for the modeling process. Equations will have to be improved or modified on the basis of a more detailed study of data available and importance of processes and covariates. The selection of temporal and spatial resolutions will have to be refined and adjusted to the data and inherent scale of processes modeled.

Three main delta smelt population processes are modeled, growth, survival, and movement of delta smelt. The season of interest does not involve reproduction, and the regions modeled span the whole range of the species. Time is treated as discrete with steps of two weeks, and space is represented as a series of regions as in Newman (2008) and Feyrer et al., (2007).

For computation purposes, a specific order of processes is assumed. Growth takes place first. Second, death and survival are calculated. Movement is the third and last step.

Growth

$$E\{FL^*_{rt}\} = FL_{rt-1} + E\{\Delta FL_{rt-1}\} \quad (1)$$

$$g(E\{\Delta FL_{rt-1}\}) = \Sigma f_k(\mathbf{X}_{FL}) \quad (2)$$

$$FL^*_{rt} \sim \text{Lognormal}(E\{FL^*_{rt}\}, \sigma_{FL}) \quad (3)$$

where g( ) is a link function, E{ } indicates expectation, sumation if over k from 1 to p functions, and $f_k(X_{FL})$ are smoothing functions of the vector of covariate values X_{FL}.; i.e., growth is described with a generalized additive model (GAM). Elements of X_{FL} are Zoop, Secchi, Sal, Comp, DS, Temp, Sbass, Sside, Age, FL_{rt-1}, Micro, Vmarsh, Vshall, Vchan and Pred.

Growth (ΔFL_{rt-1}) could be modeled more parsimoniously with, for example, a mechanistic bioenergetic approach such as the one presented in Fujiwara et al., (2005). The mechanistic approach could combine (1) an equation for net energy intake derived from food abundance, competitor abundance, temperature, salinity and Secchi, (2) an equation for energy cost of gains derived from age and size and net energy intake, and (3) an equation to relate mass and length changes as a function of age and length. These relationships and the necessary parameters can be derived experimentally and independently of the field data, thus increasing the power and precision of the main model.

Because growth may be different in different regions, movement will result in a mixing of sizes. It is assumed that the average size of fish that migrate is the same as the average for the area prior to movement. Thus, fork length after movement is a weighted average of sizes calculated as

$$FL_{rt} = \Sigma\, DS_{r\leftarrow j}\, FL^*_{jt}/DS_{rt} \quad (3)$$

where the subscript $r\leftarrow j$ indicates the movement from region j to region r.

Survival

Expected proportion of fish surviving from time t-1 to t can be modeled as a GAM or a logistic function of covariates. We describe the logistic approach with a binomial distribution.

$$DS^*_{rt} = s_{rt}\, DS_{rt-1} \quad (4)$$

$$\text{Logit}(E\{s_t\}) = \mathbf{X'}_s\, \boldsymbol{\beta}_s \quad (5)$$

$$s_t \sim \text{Binomial}(DS_{t-1}, E\{s_t\}) \quad (6)$$

The vector of covariates $\mathbf{X}_s$ includes Sbass, Pred, FL_t, Age, Sside, Micro, Temp and Sal. Equation 6 may need to be modified to incorporate the lack of independence of mortality events resulting from groups of fish being exposed to predation or physiologically stressful conditions. Rate of survival could be modeled more mechanistically by developing equations for the different sources of mortality such as predation, chemical pollution, physiological stress, and depleted energy reserves.

Further refinement of the survival model may consider the distribution of FL and other covariates within regions. Instead of being a set of at identical individuals, as implied in equations 4-6, each fish could have its own expected survival rate based on its FL, Age, and most likely set of conditions experienced within the region.

Movement

Modeling movement can require many parameters, and it is particularly difficult because there are no direct observations movement of individual delta smelt. Our practical approach is to assume that most fish move among first and second order neighboring regions during the period from t-1 to t. Delta smelt movement is promoted by differences in covariate values between regions (gradients), and hindered by distance between regions.

The redistribution of fish among all regions is calculated as

$$\mathbf{DS}_t = \mathbf{M}_t\,\mathbf{DS}^*_t \tag{7}$$

$$E\{m_{ijt}\} = \exp(\mathbf{X'}_{mijt}\,\beta_{mij})/[1 + \Sigma_i \exp(\mathbf{X'}_{mijt}\,\beta_{mij})] \quad \text{when } i \neq j \tag{8}$$

$$E\{m_{ijt}\} = 1/[1 + \Sigma_i \exp(\mathbf{X'}_{mijt}\,\beta_{mij})] \quad \text{when } i = j$$

$$\mathbf{m}_{.jt} \sim \text{Multinomial}\{DS^*_{jt};\ E\{m_{ijt}\},\ i \in N_j\} \tag{9}$$

where $\mathbf{DS}_t$ is the vector of fish abundances in all regions at time t after movement, $\mathbf{DS}^*_t$ is fish abundance prior ot movement, $\mathbf{M}_t$ is a matrix with elements m_{ijt} representing the expected proportion of delta smelt moving from region j to region i. The vector $\mathbf{m}_{.jt}$ is column j of $\mathbf{M}_t$ which results from a multinomial process. The vector $\mathbf{X'}_{mijt}$ contains values for Zoop, Temp, Sal, Secchi, Pred, Comp, Sside, Sbass, volume of water in each type of habitat (marsh, shallow and channel) and DS both at the origin and destination of movement. It also includes values for the distance between i and j, net particle movement between i and j, PT_{ijt}, as determined, for example, by the particle tracking model PTM of DSM2, (Kimmerer and Nobriga, 2008) and net linear stream velocity. The vector β_{mij} contains the corresponding parameters.

The sum of elements in each column of $\mathbf{M}_t$ equals one, which ensures conservation of population size. Each column of $\mathbf{M}_t$ is a multinomial logistic function with probabilities that increase as gradients and flows increase and distances decrease. These equations are stated in very general terms, which requires many parameters. Number of parameters could be greatly reduced by assuming that habitat selection depends on the relative differences of covariates between source and destination. Further experimentation to determine habitat selection and movement behavior or delta smelt will be crucial to develop more mechanistic and parsimonious equations for the movement process.

Table 1. Symbols and variables

FL^*_{rt}	Average fork length before movement
FL_{rt}	Average fork length after movement
ΔFL_{rt-1}	Growth in fork length from t-1 to t in region r
$f_k(\mathbf{X}_{FL})$	Smoothing function of covariates for fork length
$\mathbf{X}_{FL}$	Vector of covariates that affect fork length growth
$DS_{r\leftarrow j}$	Number of delta smelt that move from region j to r
DS^*_{rt}	Delta smelt abundance in region r after death and before movement
DS_{rt}	Delta smelt abundance in region r after death and before movement
$\sim$	Symbol to indicate "is distributed as"
$\mathbf{X}'_s$	Vector of covariates that affect survival
β_s	Vector of parameters to calculate survival
$\mathbf{DS}_t$	Vector of delta smelt abundances in each region
$\mathbf{M}_t$	Matrix of movement probabilities.
$E\{m_{ijt}\}$	Expected proportion of fish that will move from region j to i at time t
$\mathbf{X}'_{mijt}$	Vector of covariate values in source and destination regions
β_{mij}	Vector of parameters for the multinomial logistic movement equation
$\mathbf{m}_{.jt}$	Column j of redistribution matrix $\mathbf{M}_t$
R	Number of regions
N_j	Set of region numbers that are 1st or 2nd order neighbors of j.
PT_{ijt}	Net particle movement from j to i
V_{rt}	Volume of water in region r at time t
n_{rt}	Number of delta smelt in the volume swept by the gear

Because we are not focusing on processes outside fall, we can model FL and DS between summer and fall or even between falls as empirical structural models with potentially nonlinear trends.

Other biotic processes

The main biotic processes to be considered are zooplankton dynamics, *Microcystis* blooms, and growth, movement and mortality of predators and competitors.

Movement and mortality of other fish

Movement and mortality of predators and competitors can be modeled using the same equations above, perhaps simplified to eliminate the growth process.

Zooplankton abundance

Statistical process models for, phytoplankton, zooplankton and *Microcystis* models will be developed on the basis of existing mechanistic models (e.g., Lucas and Cloern

2002) Meanwhile, zooplankton can be modeled with GAMs where the vector of covariates includes $Zoop_{t-1}$, $Corb_t$, $Temp_t$, $Secchi_t$, density of zooplankton consumers, transport of zooplankton to and from neighbors, light intensity, volume of water in each habitat type, and water flows.

Physical processes

Physical modeling is needed to simulate the physical dynamics of the LSZ, and for particle tracking simulations. Key physical dynamics needed for this application include water motion, salinity, and suspended sediment (as a conservative substitute for turbidity). Particle tracking applications include fish, plankton, and point-source solute movement. Historically (e.g. USBR 2008), we have used DSM2 and DSM2 PT for these purposes. However, because of the well-known limitations of DSM2, we are moving toward the use of UNTRIM as the platform for Delta hydrodynamic modeling, including work needed for fall outflow. In addition to the obvious advantages, UNTRIM has been coupled with the fractioned sediment transport model SEDIMORPH, enabling the joint simulation of hydrodynamics and turbidity dynamics. We hope to build on UNTRIM/SEDIMORPH development for Delta applications that has already been done for the Army Corps of Engineers, and are currently supporting work by Wright and Schoellhamer at USGS to develop empirical data with which to calibrate SEDIMORPH in this application.

In general terms, the physical processes relevant to the present application can be incorporated directly by looking up data from physical model runs, or meta-modeled with "empirical" equations that capture most of the behavior elicited by the physical models.

Observation equation

Catch

The observation model for catch has to describe the sampling distribution of number of fish caught and their sizes as a function of the average abundance and size of fish in each region at each time step. One of the major challenges here is to model the gear selectivity (Newman 2008) or probability that a fish of length FL within the volume of water to be swept ends up being caught (p(FL)). Different sampling equipment such as the summer townet and the fall midwater trawl result in potentially different relationships between p(FL) and FL. The probability of being caught can be included as a parameter in the model. The Department of Fish and Game has generated data from several side-by-side sampling with different equipment. Those data can be used to model p(FL) for fall midwater trawl directly to provide empirical prior distributions for p(FL), or they could be incorporated as part of the overall likelihood component of the model.

Assuming that fish have a Poisson distribution in the water volume, the number present in the volume swept by the net is

$$n_{rts} \sim \text{ziNegativeBinomial}(p_0, DS_{rt}/V_{rt}, k) \quad (10)$$

where p_0 is the probability that no delta smelt are in the volume sampled, and the other two parameters describe the mean and overdispersion of the negative binomial distribution.

Each sample (say, trawl) results in a collection of delta smelt fork lengths fl_{rts}, where the subscript refers to region, time and sample (tow, trawl, etc). This vector is the result of size-specific catch probabilities (Newman 2008) applied to the vector FL_{rts} of actual lengths of all fishes present in the volume sampled. FL_{rts} and fl_{rts} are vectors of fork lengths. Each element in FL_{rts} has a probability $p(FL_{rtsi})$ of being present in fl_{rts}, which could be described by a logistic function of FL.

$$\text{Logit}[p(FL\ rtsi)] = \exp(\mathbf{X'}_p\ \boldsymbol{\beta}_p) \quad (11)$$

Where $\mathbf{X'}_p$ contains a column of1's and one with the fork lengths in the sampled volume, and $\boldsymbol{\beta}_p$is the corresponding set of parameters.

Other observation equations for variables that are more directly observed without bias or selectivity can be specified as the distributions of the deviations about the mean, for example, for water temperature:

$Temp_{rt} \sim \text{Normal}(E\{Temp_{rt}\}, \text{observation variance})$

CLIMATE CHANGE SCENARIOS AND SEA LEVEL RISE ESTIMATES FOR THE CALIFORNIA 2009 CLIMATE CHANGE SCENARIOS ASSESSMENT

A Paper From:
California Climate Change Center

Prepared By:
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FINAL PAPER

Arnold Schwarzenegger, *Governor*

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California's electricity and natural gas ratepayers. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts focus on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

In 2003, the California Energy Commission's PIER Program established the **California Climate Change Center** to document climate change research relevant to the states. This center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions. Priority research areas defined in PIER's five-year Climate Change Research Plan are: monitoring, analysis, and modeling of climate; analysis of options to reduce greenhouse gas emissions; assessment of physical impacts and of adaptation strategies; and analysis of the economic consequences of both climate change impacts and the efforts designed to reduce emissions.

The California Climate Change Center Report Series details ongoing center-sponsored research. As interim project results, the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the center seeks to inform the public and expand dissemination of climate change information, thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

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Abstract

For the 2008 California Climate Change Assessment, to further investigate possible future climate changes in California, a set of 12 climate change model simulations was selected and evaluated. From the Intergovernmental Panel on Climate Change Fourth Assessment activities projections, simulations of twenty-first century climates under a B1 (low emissions) and an A2 (a medium-high emissions) emissions scenarios were evaluated. Six climate models were chosen. These emission scenarios and climate simulations are not "predictions," but rather are possible scenarios of plausible climate sequences that might affect California in the next century. Temperatures over California warm significantly during the twenty-first century in each simulation. Also the rise in global sea level, and by extension the rise of sea level along the California coast, increases. Along with this, there are marked increases in the frequency, magnitude, and duration of heat waves and sea level rise extremes. There is quite a strong inclination for higher warming in summer than winter and greater warming inland than along the coast. In several of the simulations there is a tendency for drier conditions to develop during mid-and late-twenty-first century in Central and Southern California, and along with this, a decline in winter wave energy along the California coast.

Keywords: Regional climate change, California, hydroclimate adaptation, sea level rise, waves, runup

1.0 Introduction

This is a contribution to the second California Climate Change Scenarios Assessment. The assessment process has its origin in an Executive Order S-3-05, which, in addition to setting greenhouse gas emission targets, charges the Secretary of the California Environmental Protection Agency to "report to the Governor and the State Legislature by January 2006 and biannually thereafter on the impacts to California of global warming."

This work is motivated by recent examinations of observed climate in California and the western United States that have demonstrated that recent warming and associated hydrological changes are unlikely to have been caused entirely by natural climate fluctuations (Bonfils et al. 2007; Maurer et al. 2007). Furthermore, subsequent studies (Barnett et al. 2008; Pierce et al. 2008; Bonfils et al. 2008) demonstrated that it is very likely that major parts of these changes were caused by greenhouse gas loading of the atmosphere by humans. The present study builds upon previous climate model-based studies of possible climate change impacts on various sectors in the California region, including a broad assessment of possible ecological impacts by Field et al. (1999); an assessment of a range of potential climate changes on ecosystems, health, and economy in California described by Wilson et al. (2003); a study of how a "business-as-usual emissions scenario simulated by a low sensitivity climate model would affect water resources in the western United States, overviewed by Barnett et al. (2004); a multisectoral assessment of the difference in impacts arising from high versus low greenhouse gas (GHG) emissions in Hayhoe et al. (2004); and the initial 2006 California climate change scenarios assessments (e.g., Franco et al. 2008; Cayan et al. 2008a; Cayan et al. 2008b).

2.0 Climate Scenarios

In view of the uncertainty in the climate responses by greenhouse gases and other forcings and the variability amongst models in representing and calculating key processes, it is important to consider results from several climate models rather than to rely on just a few. For the 2008 California Climate Change Scenarios Assessment, the set of global climate models (GCMs) evaluated has been expanded to GCMs that contributed to the recent Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment (IPCC 2007) using *Special Report on Emissions Scenarios* (SRES) A2 and B1 emission scenarios were employed to assess climate changes and their impacts.

The following models were selected for the assessment: the National Center for Atmospheric Research (NCAR) Parallel Climate Model (PCM); the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluids Dynamics Laboratory (GFDL) model, version 2.1; the NCAR Community Climate System Model (CCSM); the Max Plank Institute ECHAM5/MPI-OM; the MIROC 3.2 medium-resolution model from the Center for Climate System Research of the University of Tokyo and collaborators; and the French Centre National de Recherches Météorologiques (CNRM) models.

These models, only a subset of those included in the IPCC Fourth Assessment, were selected on the basis of providing a set of relevant monthly, and in some cases daily, data. Another rationale was that the models provided a reasonable representation, from their historical simulation, of the following elements: seasonal precipitation and temperature (Figure 1), the variability of annual precipitation, and El Niño/Southern Oscillation (ENSO). It should be noted though, that the historical skill criteria is probably not very well founded, since it has been shown that model historical skill is not well related to model climate change performance (Coquard et al. 2004; Brekke et al. 2008). The emission scenarios considered are among the same ones that were used for the 2006 California climate change scenarios Assessment (Cayan et al. 2008). The A2 emissions scenario represents a differentiated world in which economic growth is uneven and the income gap remains large between now-industrialized and developing parts of the world, and people, ideas, and capital are less mobile so that technology diffuses more slowly. The B1 emissions scenario presents a future with a high level of environmental and social consciousness, combined with a globally coherent approach to a more sustainable development (Figure 2). To put the A2 and B1 scenarios into perspective, however, it is worth noting that the estimated emissions growth for 2000–2007 was above even the most fossil fuel intensive scenario of the Intergovernmental Panel on Climate Change (SRES-IPCC) (Science Daily 2008).

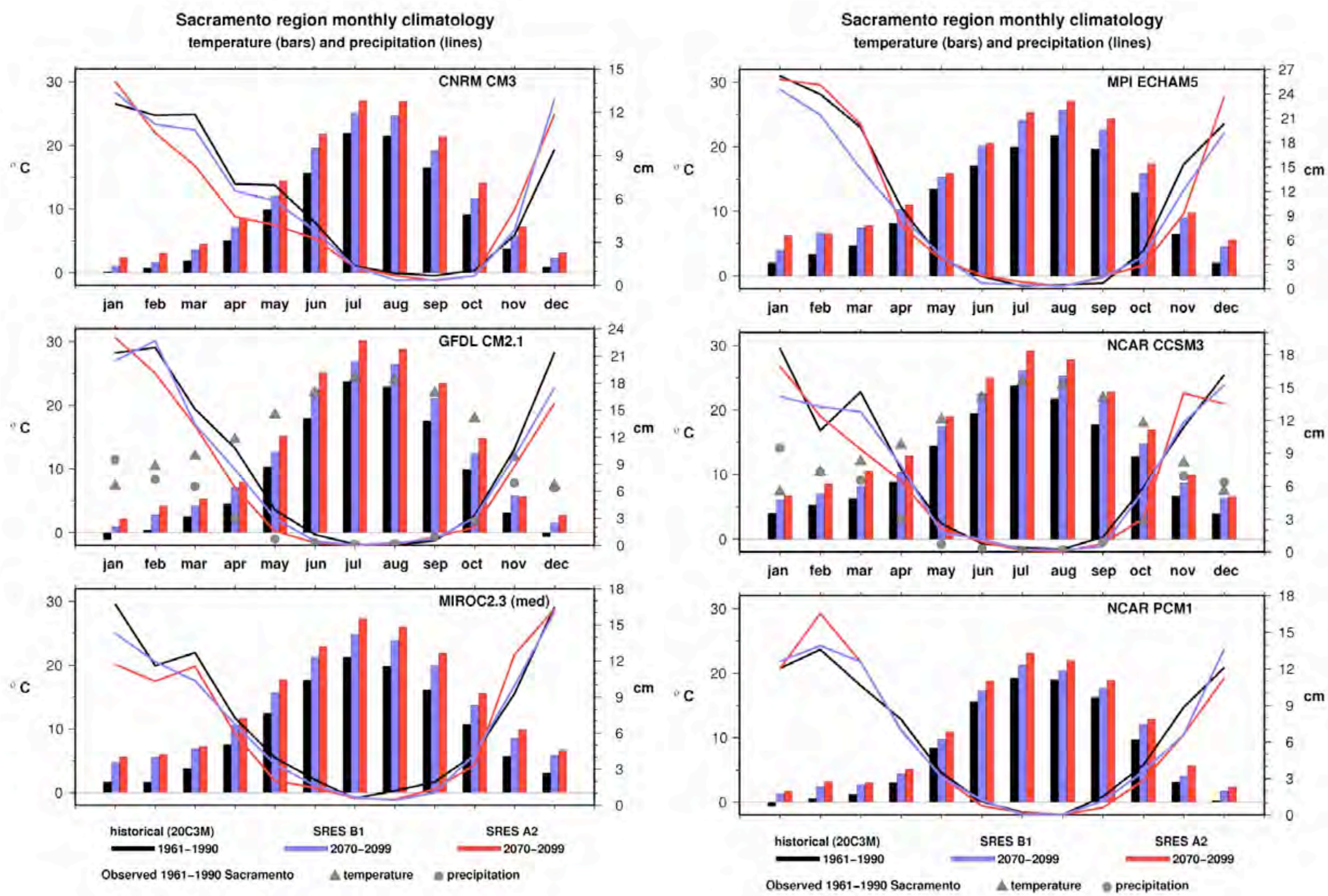


Figure 1. California would retain its strong Mediterranean temperature and precipitation, as indicated by six GCMs, run under A2 (red) and B1 (blue) emission scenarios, along with historical simulated temperature and precipitation (black). Observed temperature and precipitation averages (1961–1990) from Sacramento are shown by gray symbols on the GFDL CM2.1 plot (middle). A2 temperature warming does not rise much above that of B1 by 2050.

Temperature and precipitation have been taken directly from each GCM, no downscaling, from the grid point closest to Sacramento.

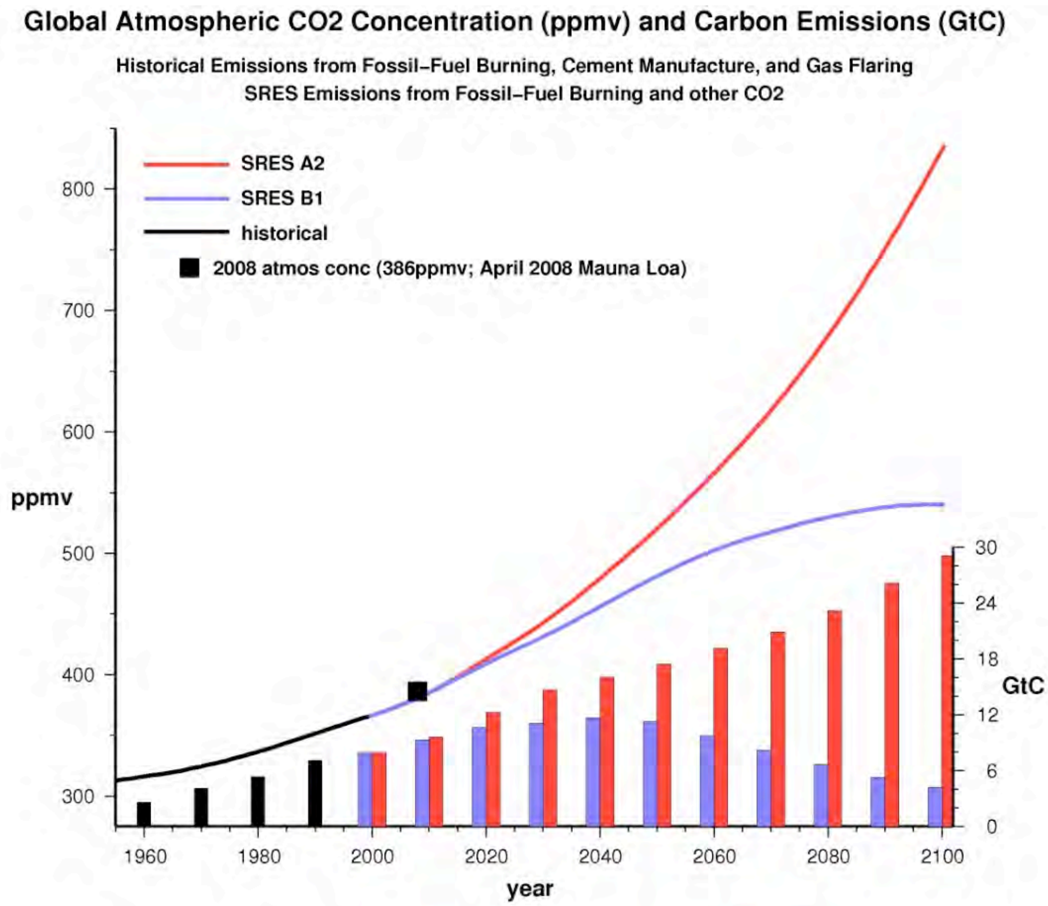


Figure 2. The global carbon emissions (gigatonnes of carbon, GtC) are shown by bars. The atmospheric CO_2 concentration (parts per million, volume, or ppmv) is shown by lines. The bars represent the historical period (black) and SRES B1 (blue) and SRES A2 (red) emissions scenarios. The black square represents the present day (2008) atmospheric concentration (386 ppmv).

Because there is considerable uncertainty in future greenhouse gas emissions, it is not possible to assign odds to either of the two emissions scenarios. Also, each GCM differs, to some extent, in its representation of various physical processes from other GCMs, and so the different models contain different levels of warming, different patterns and changes of precipitation, and so on. The result is a set of model simulations having different climate characteristics, even when the models are driven by the same GHG emissions scenario. Consequently, the climate projections should be viewed as a set of possible outcomes, each having an unspecified degree of uncertainty. In short, these models results provide a rather coarse set of scenarios from which to view the future; but they are not detailed predictions.

As has been emphasized in the IPCC results and in prior California climate change assessments, results of different mitigation strategies, as expressed by the two GHG emission scenarios (A2 medium-high emissions and B1 moderately low emissions) do not become very clear until after the middle of the twenty-first century—they are much more distinctly evident in the following decades (IPCC 2007; Hayhoe et al. 2004; Cayan et al. 2008).

3.0 Downscaling

The two downscaling methods employed in the 2009 California Assessment are (1) constructed analogues (CA), and (2) bias correction and spatial downscaling (BCSD). Maurer and Hidalgo (2008) compare the two methods and find that they both perform reasonably well, but they do contain some noteworthy differences. Both methods have been shown to be skillful in different settings, and BCSD (Wood et al. 2004) has been used extensively in hydrologic impact analysis. Both methods use the coarse scale Reanalysis fields of precipitation and temperature as predictors of the corresponding fine scale fields. The CA (Hidalgo et al. 2008) method downscales daily large-scale data directly, and BCSD downscales monthly data, with a random resampling technique to generate daily values. The methods produce generally comparable skill in producing downscaled, gridded fields of precipitation and temperatures at a monthly and seasonal level. For daily precipitation, both methods exhibit limited skill in reproducing both observed wet and dry extremes, and the difference between the methods is not significant, reflecting the general low skill in daily precipitation variability in the reanalysis data. For low temperature extremes, the CA method produces greater downscaling skill than BCSD for fall and winter seasons. For high temperature extremes, CA demonstrates higher skill than BCSD in summer. The most appropriate downscaling technique depends on the variables, seasons, and regions of interest; on the availability of daily data; and whether the day-to-day correspondence of weather from the GCM needs to be reproduced for some applications. The ability to produce skillful downscaled daily data depends primarily on the ability of the climate model to show daily skill. In the selected examples shown here, we employ results using either the BCSD or the CA method. Most of the cases which we have compared have yielded comparable results, but the degree of similarity varies depending on the topic, with cases that feature rarer individual events having the greatest likelihood for substantial difference between the two.

4.0 Warming

From observed climate and hydrologic records and from the model historical simulations, it is seen that the model simulations begin to warm more substantially in the 1970s; this is likely a response to effects of GHG increases, which began to increase significantly during this time period (Bonfils et al. 2007; Barnett et al. 2008).

All of the climate model simulations exhibit warming, globally and regionally over California (Figure 1 and Figure 3). In the early part of the twenty-first century, the amount of warming produced by the A2 scenario is not too much greater than that of B1, but becomes increasing larger through the middle and especially the latter part of the century (Figure 3 and Figure 4). Overall, the six models' warming projections in mid-century range from about 1°C to 3°C (1.8°F to 5.4°F), rising by end-of-twenty-first century, from about 2°C to 5°C (3.6°F to 9°F). The upper part of this range is a considerably greater warming rate than the historical rates estimated from observed temperature records in California (Bonfils et al. 2008).

There is considerable variability between the six GCMs, but the lower sensitivity model (the PCM) contains the lowest temperature rise in both cool and warm seasons. The models do contain decade-to-decade variability, but this decadal component is not too large, and overall there is a steady, rather linear increase over the 2000–2100 period (Figure 3). All of the model runs result in a loss of spring snowpack in California, as has been previously discussed (e.g., Hayhoe et al. 2004; Cayan et al. 2008b). The models produce substantial warming during the hydrologically sensitive spring period (Figure 5). Along with the increasing occurrence of very warm spring temperatures, a sensitive index of the spring snow loss is the increasingly frequent incidence of tenth percentile snow years, illustrated for the CNRM A2 model run in Figure 6.

There is considerable asymmetry, both seasonally and spatially, in the amount of warming (Figure 4). Winter (January–March) temperature changes range from 1°C–4°C (1.8°F–7.2°F) in the six GCMs, under A2 and B1 GHG emissions scenarios, averaged over 30 years at the end of the twenty-first century relative to the 1961–1990 climatology. Importantly, there is greater warming in summer than in winter. Summer (July–September) temperature changes range from 1.5°C–6°C (2.7°F–10.8°F) over the six GCMs, under A2 and B1 GHG emissions scenarios. During summer, the models suggest that climate warming of land surface temperatures is amplified in the interior of the California as shown by the temperature change along a coast-interior transect through the San Francisco Bay region (Figure 7). A distinct Pacific Ocean influence occurs, wherein warming is more moderate in the zone of about 50 kilometers (km) from the coast, but rises considerably, as much as 4°C (7.2°F) higher, in the interior landward areas as compared to the warming that occurs right along the coast.

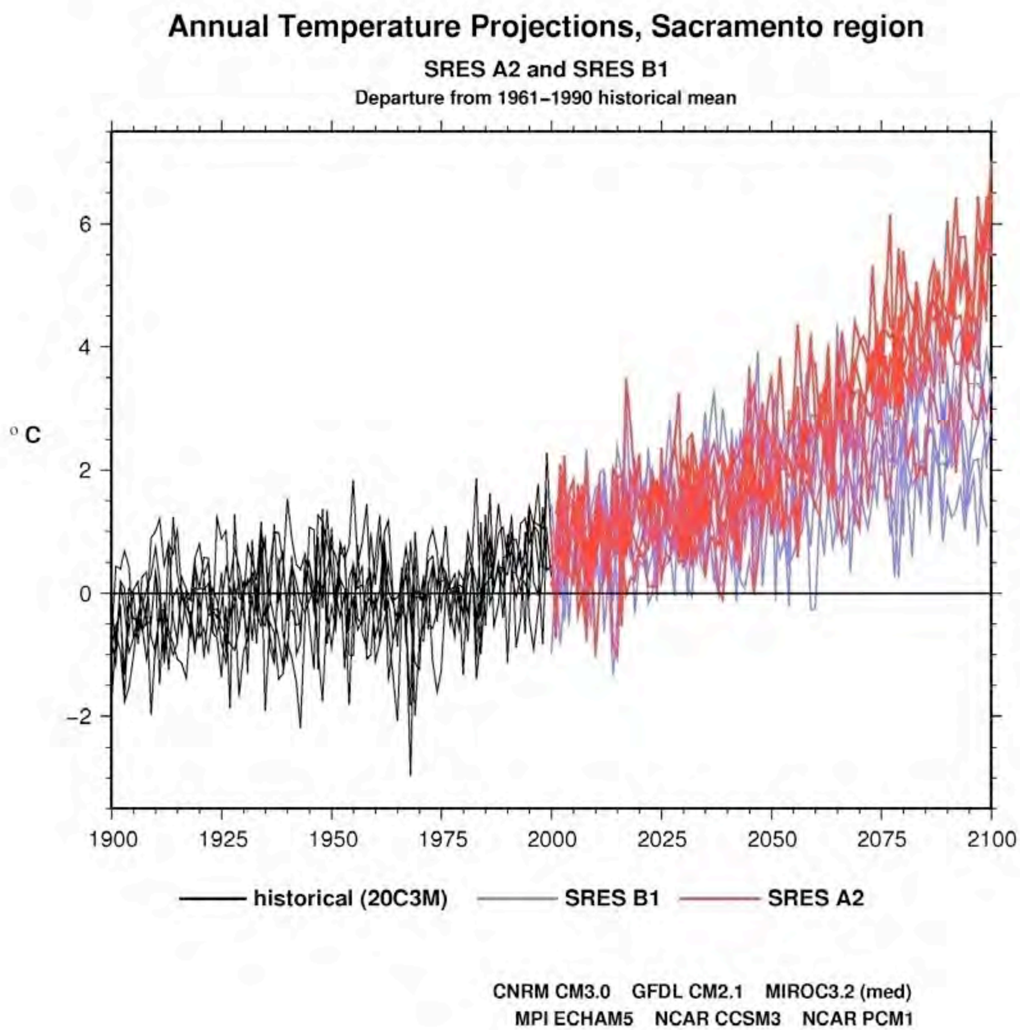


Figure 3. Annual temperatures near Sacramento, for the six GCMs for 203CM simulations of the historical period (black) and for the projected 2000–2100 periods under the A2 (red) and B1 (blue) GHG emissions scenarios. In this case, the values plotted are taken directly from the GCMs from the grid point nearest to Sacramento.

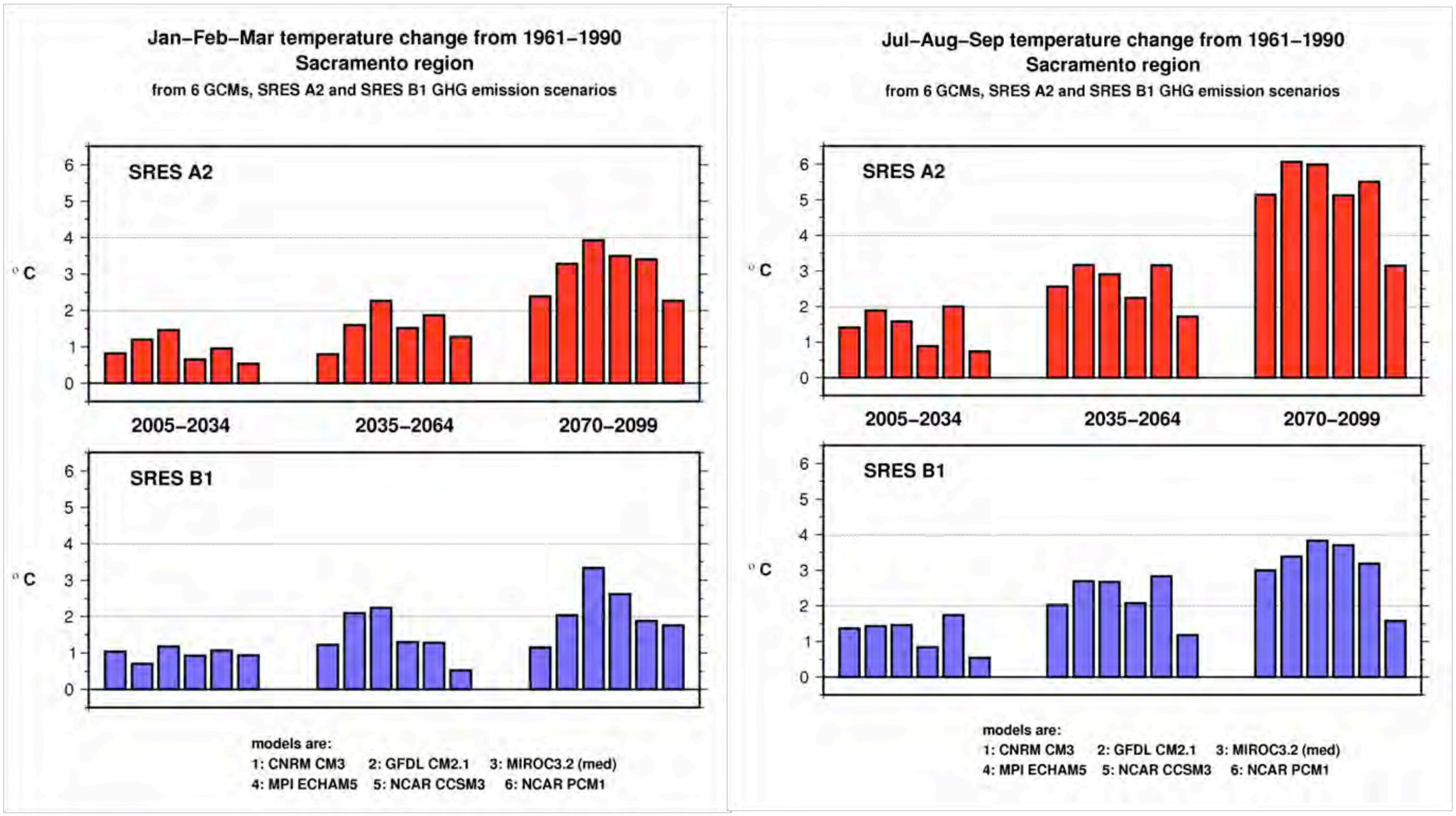
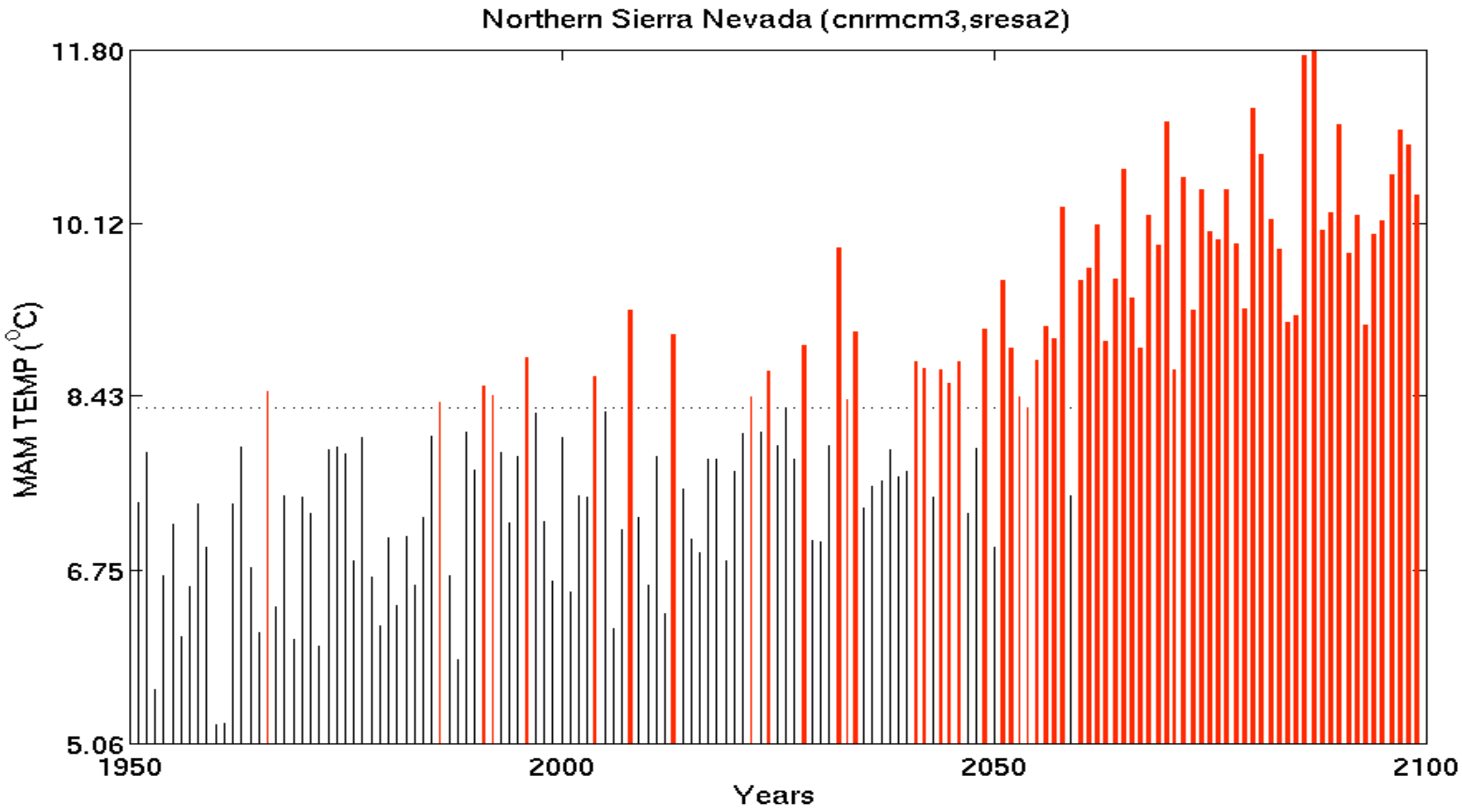
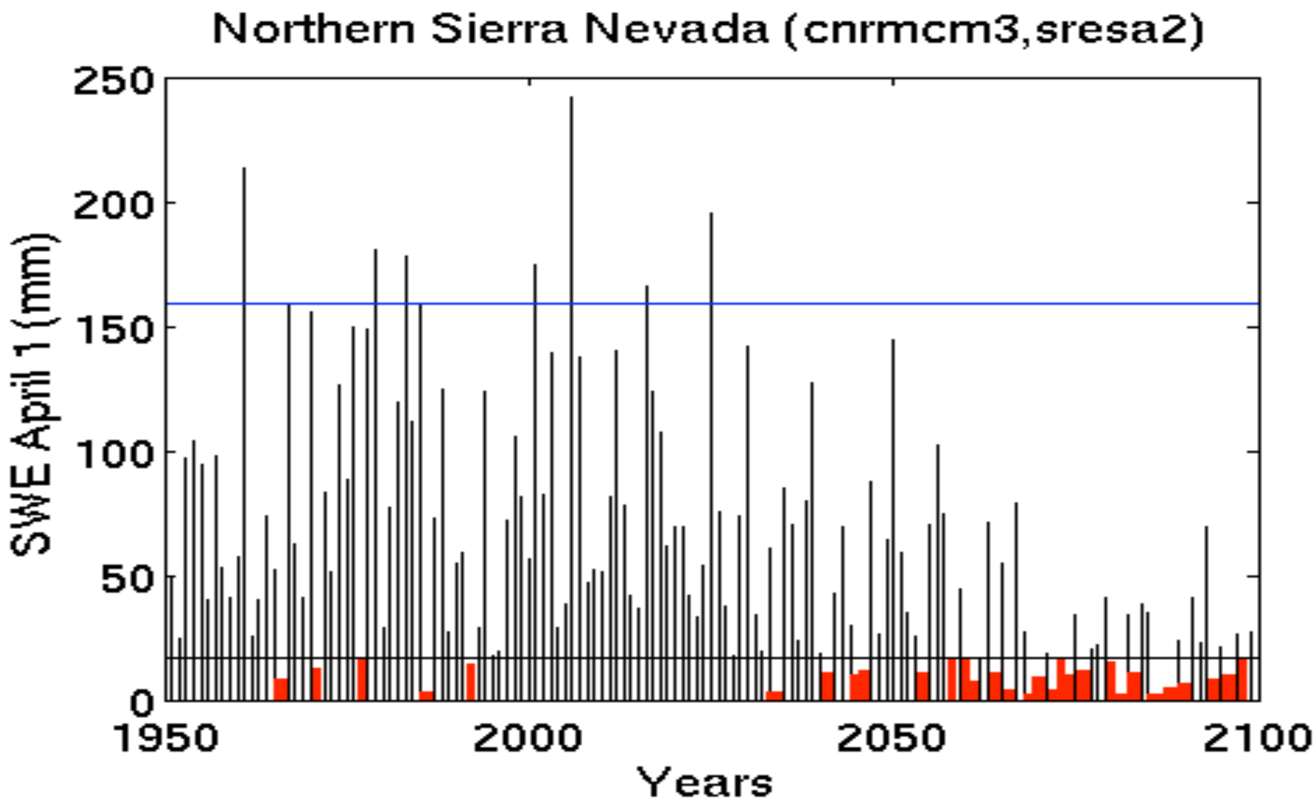


Figure 4. Winter (January, February, March average, left) and summer (July, August, September average, right) surface air temperature changes for the Sacramento region, relative to each model's 1961–1990 average, for each of the six GCMs under the A2 (upper; red) and B1 (lower; blue) GHG emission scenarios. Sacramento region temperatures are extracted directly from each GCM from the grid point closest to Sacramento.



Northern California spring temperature CNRM A2

Figure 5. Spring temperature (°C) from the CNRM A2 simulation, for the historical and twenty-first century climate change periods. Years exceeding historical 90th percentile level (1961–1990) are shown in red. Temperature is for the Sacramento watershed, from Constructed Analogues downscaled CNRM data.



Snow Accumulation (April 1) CNRM

Figure 6. April 1 snow accumulation (snow water equivalent, SWE) from the CNRM A2 simulation. Years with less SWE than its historical 10th percentile (1961–1990) are shown in red. The 90th percentile and 10th percentile SWE levels are indicated by blue and black horizontal lines, respectively. SWE has been produced from Variable Infiltration Capacity (VIC) hydrological model driven by Constructed Analogues downscaled precipitation and temperature.

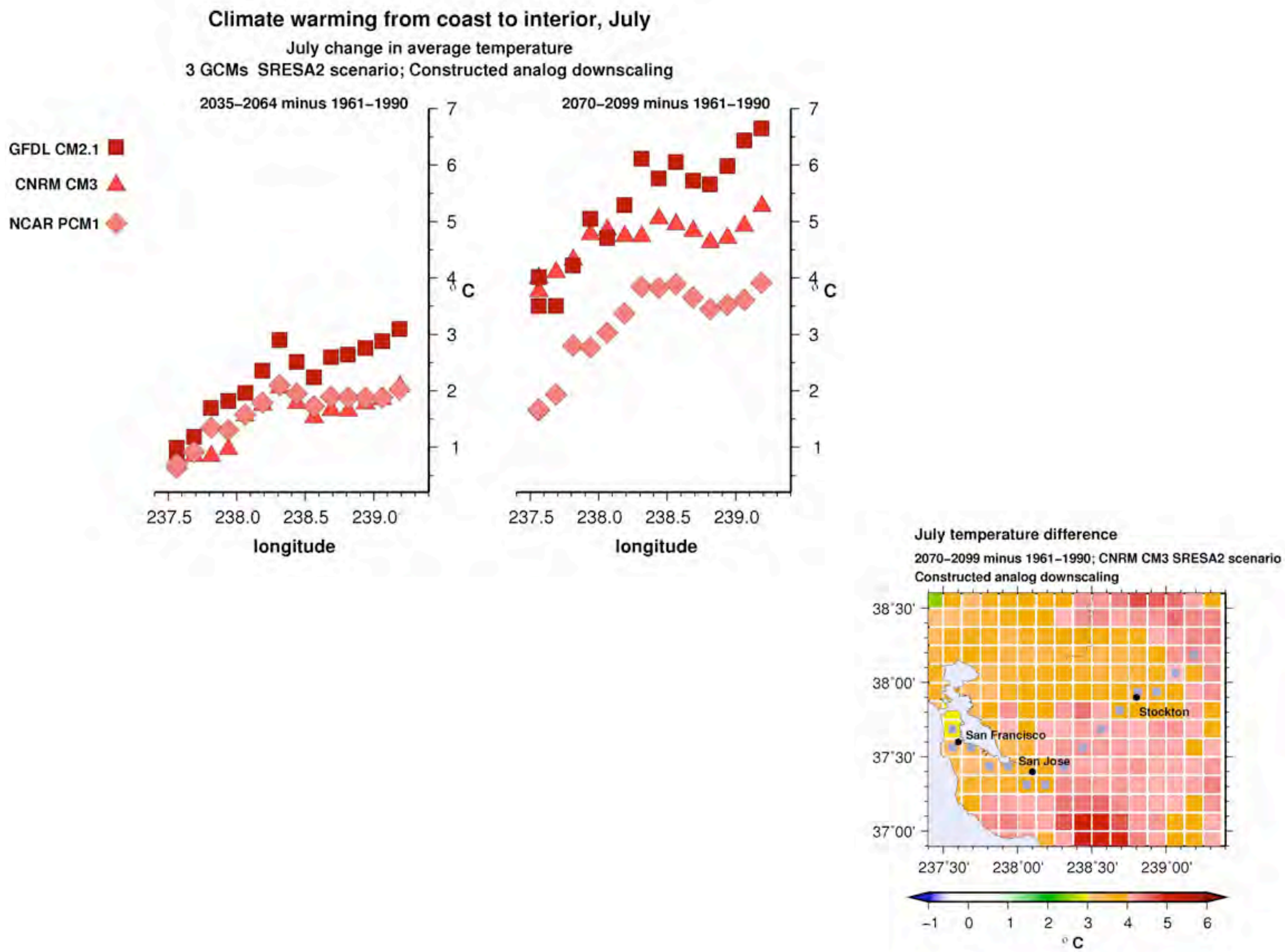


Figure 7. Amount of warming in July, (2045–2054 minus 1961–1990) and (2090–2099 minus 1961–1990) along a coast-to-interior transect for three GCMs under A2 simulation downscaled via Constructed Analogues to the region from San Francisco through the interior region of Central California. The transect is shown in the map at the lower right, which illustrates the amount of warming for July for the CNRM CM3 A2 simulation.

5.0 Heat Waves

Historically, extreme warm temperatures in the California region have mostly occurred in July and August (Gershunov and Cayan 2008), but as climate warming takes hold, the occurrences of these events will increase in frequency and magnitude (Hayhoe et al. 2004; Gershunov and Douville 2008; Miller et al. 2008) and likely will begin in June and could continue to be found in September. All simulations indicate that hot daytime and nighttime temperatures (heat waves) increase in frequency, magnitude, and duration from the historical period and during the projected period through the first half of the twenty-first century (Table 1). Several model simulations for a location near Sacramento contain a more-than-threefold increase in frequency and a decided increase in intensity of hot days. Within a given heat wave, there is an increasing tendency for multiple hot days in succession, and the spatial footprint of heat waves is more and more likely to encompass multiple population centers in California. Figure 8 depicts the number of hot days that occur concurrently at successively larger spatial scales within California, as represented by collectives of key stations as defined by the California Energy Commission. Also, as cataloged in Table 1, the duration of heat waves tends to grow longer through the twenty-first century as "average" conditions warm. Especially important is the occurrence of events having durations of five days or longer, which become much more prevalent—20 times or more frequent in several of the simulations—by the last 30 years of the twenty-first century.

6.0 Precipitation

Precipitation in most of California is characterized by a strong Mediterranean pattern wherein most of the annual precipitation falls in the cooler part of the year between November and March. The climate change simulations from these GCMs indicate that California will retain its Mediterranean climate with relatively cool and wet winters and hot dry summers (Figure 1). Another important aspect of the precipitation climatology is the large amount of variability, not only from month to month but from year to year and decade to decade (Figure 9). This variability stands out when mapped across the North Pacific and western North America complex, and it is quite well represented by models in comparison to the observed level of variability from global atmospheric data, via the NOAA National Centers for Environmental Prediction (NCEP) Reanalysis. The climate model-projected simulations indicate that the high degree of variability of annual precipitation will also prevail during the next century (Figure 10), which would suggest that the region will remain vulnerable to drought. The examples presented here, oriented on Sacramento, do not capture the magnitude of precipitation in the heaviest key watersheds in California. However, because winter precipitation in Sacramento is well correlated to that in the Sierra Nevada, these measures are representative of precipitation variability in the watersheds of the central Sierra Nevada and coast regions.

But in addition to the interannual-decadal variability contained within the simulations, there is a decided drying tendency (Figures 9 and 11). By mid- and late-twenty-first century, all but one of the simulations has declined relative to its historical (1961–1990) average. For the B1 simulation in mid-twenty-first century, two of the six simulations have a 30-year mean precipitation in Sacramento that is more than 5% drier than its historical average, and by late-twenty-first century, three of the six have 30-year averages that decline to more than 10% below their historical average. By the late twenty-first century, the differences of 30-year mean precipitation from its historical average in three of the B1 simulations and four of the A2 simulations reaches a magnitude exceeding the 95% confidence level, as gauged from a Monte Carlo exercise that establishes the distribution of a historical sample, shown in Table 2. By the mid- and late-twenty-first century, only one of the simulations has 30-year mean precipitation that is wetter (slightly) than the historical annual average. Also shown in Table 2, the 30-year mean precipitation changes are similar in the southern part of the state, in the Los Angeles region, but not as consistent in the far northern part of the state, in the Shasta region. Consideration of the projected sequence of daily precipitation events indicates that the drying of annual precipitation in three of the models is associated with both a decline in the *frequency* of precipitation events but not a clear cut change in precipitation *intensity.* These changes are indicated (Table 3) by three of the models having downward trends in the number of 3 millimeter (mm) and greater daily precipitation events (e.g., the frequency of most of the precipitation events that occur) in each of the Shasta, Sacramento, and Los Angeles regions. Changes in frequency of days with heavier (15 mm and greater, and 25 mm and greater) precipitation events was not as consistent as the changes in broader category of 3 mm and greater days, indicating that the rarer, heavy events may be dictated by processes that do not necessarily mimic the more general trends.

Even for a simulation whose mean precipitation is essentially unchanged, in this case the CNRM A2 run, the warming alone would not only deplete the spring snowpack but accentuate the summer dryness, as determined by Variable Infiltration Capacity (VIC) hydrological model calculations of soil moisture in the Central California region (Figure 12).

Table 1. Heat waves, Sacramento area. Number of events in which daily maximum temperature (Tmax) exceeds historical (1961–1990) 95th percentile Tmax of May–September days. Events are counted separately for 1, 2, 3, 4, and 5 or more days in succession; these are mutually exclusive, e.g., a 1-day event does not include any 2, 3, 4, or 5 day events. Data used has been downscaled via Bias Corrected Spatial Downscaling.

GCM/simulation	30-yr period	1 day	2 days	3 days	4 days	5 or more days	Total days (of 4590)
CNRM CM3 SRESA2	1961–1990	37	20	23	16	3	232
	2005–2034	44	15	37	30	13	384
	2035–2064	56	33	36	30	23	495
	2070–2099	104	48	56	24	66	975
SRESB1	1961–1990	29	25	23	18	2	233
	2005–2034	45	27	28	32	11	378
	2035–2064	54	24	29	37	17	445
	2070–2099	70	25	36	33	30	550
GFDL CM2.1 SRESA2	1961–1990	40	24	28	7	5	231
	2005–2034	91	45	37	34	23	588
	2035–2064	149	60	46	42	46	941
	2070–2099	91	76	39	36	132	1747
SRESB1	1961–1990	29	26	25	17	1	231
	2005–2034	62	29	26	42	12	445
	2035–2064	71	30	37	28	35	583
	2070–2099	94	56	40	26	48	748
MIROC3.2 (med) SRESA2	1961–1990	39	22	29	14	1	231
	2005–2034	52	26	41	30	16	461
	2035–2064	75	26	49	27	49	723
	2070–2099	84	64	50	49	83	1352
SRESB1	1961–1990	40	27	25	14	2	233
	2005–2034	47	27	28	34	15	413
	2035–2064	80	38	35	28	34	606
	2070–2099	113	55	41	18	62	835

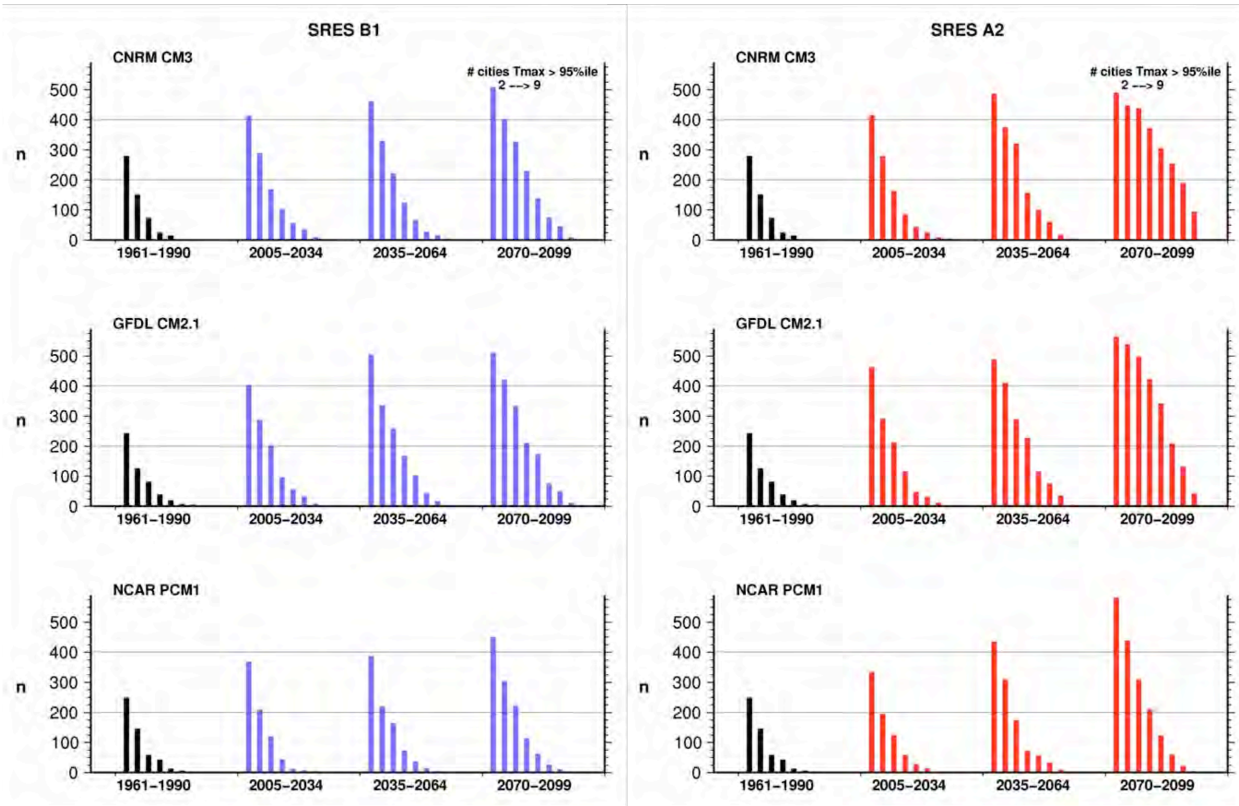


Figure 8. Number of days with simultaneous hot days (exceeding 95th percentile historical value) at nine key California locations, as projected by three GCMs, under B1 (left; blue) and A2 (right; red) GHG emission scenarios, using constructed analogues downscaling. Number of hot days from historical simulation shown by black bars.

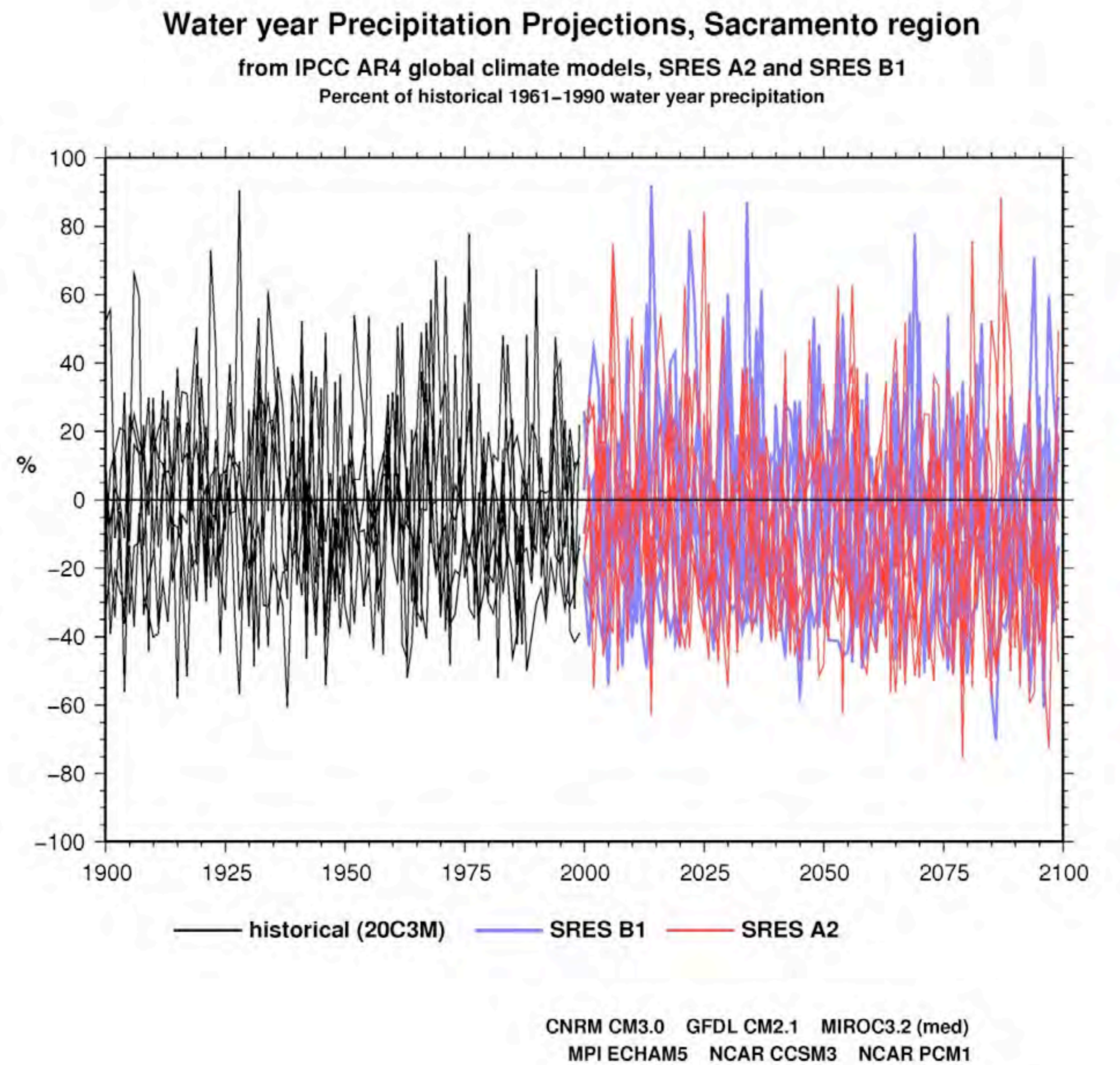


Figure 9. Precipitation, by water year, 1901–1999 historical period (black) and 2000–2100 climate change period for SRES B1 (blue) and SRES A2 (red) GHG emission scenarios from six GCMs. The values plotted are taken directly from the GCMs from the grid point nearest to Sacramento.

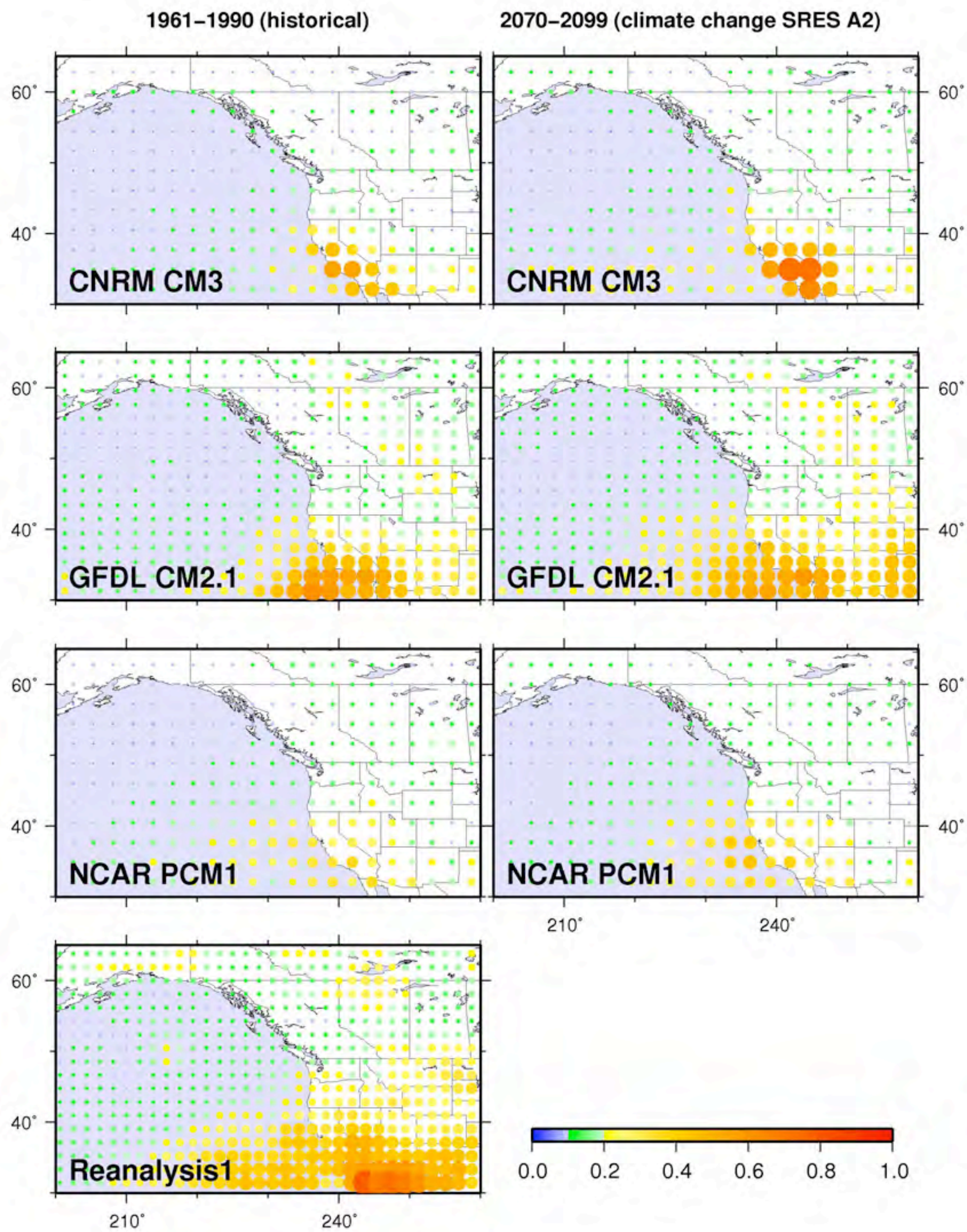


Figure 10. Magnitude of year-to-year precipitation variability is very large in Southern California, as indicated by the ratio of the standard deviation to the mean precipitation (sigma/mean) for the water year. Historical and A2 simulations for three models are shown, along with estimated observed precipitation from NCEP Reanalysis 1. Magnitude of sigma/mean is indicated by dot size, and also by color assignment, shown by color key. The values plotted are taken directly from the GCMs.

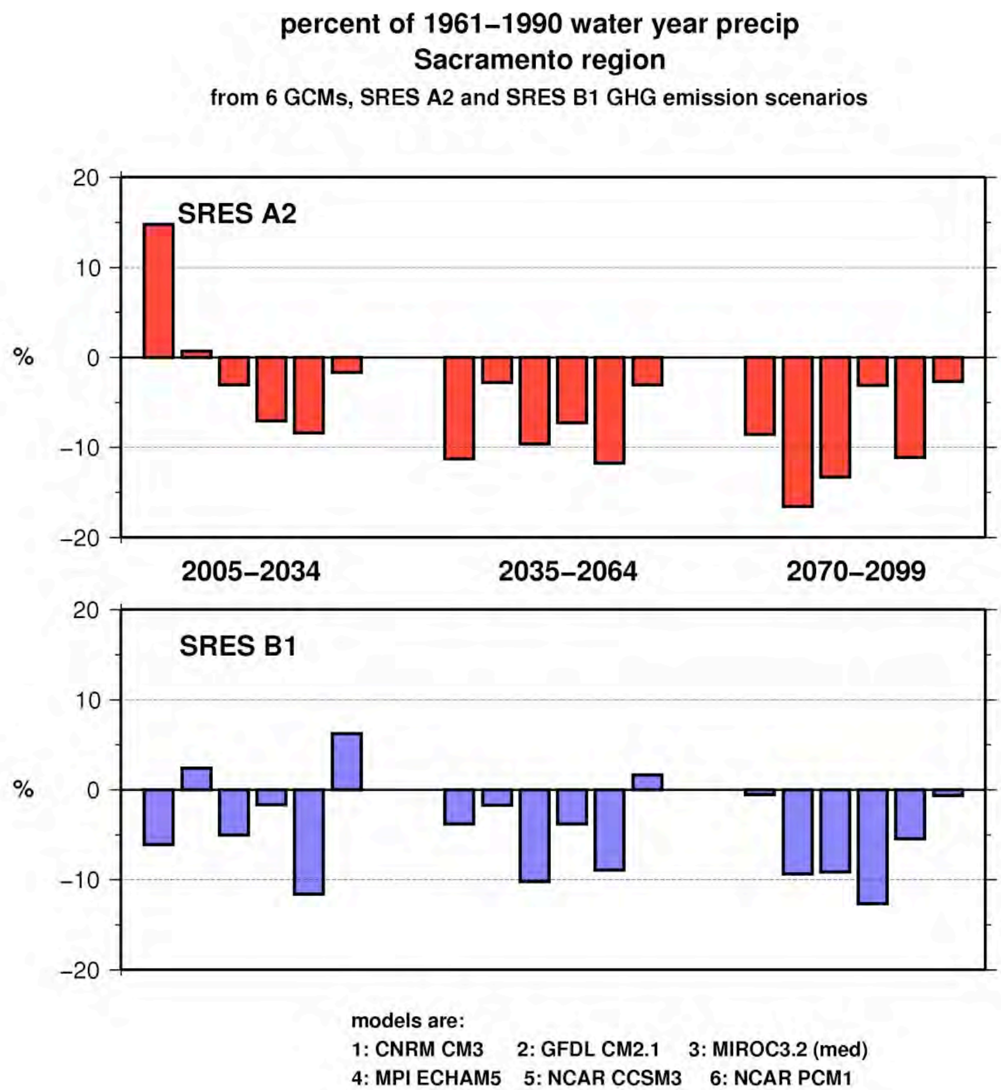


Figure 11. Differences in 30-year mean annual total precipitation of early (2005–2034), middle (2035–2064), and late (2070–2099) twenty-first century relative to 1961–1990 climatology for each of six GCMs, for SRES B1 (lower; blue) and SRES A2 (upper; red). Precipitation is taken directly from the GCMs from the grid point nearest to Sacramento.

Table 2. Evaluation of significance of differences in the SRES B1 (top) and SRES A2 (bottom) for the Shasta, Sacramento, and Los Angeles regions' 30-year mean precipitation from historical (1961–1900) average as a percent of historical annual average precipitation. Percentile ranks were obtained from placing 30-year average precipitation from each of the simulations within a distribution from a set of 1000 Monte Carlo sequences of the model historical precipitation. Values that are significant at the 95% confidence level are highlighted with bold type. Precipitation is taken directly from the GCMs from the grid point nearest Shasta, Sacramento, and Los Angeles, respectively.

Shasta SRES B1

Model	2005–2034	Rank (%)	2035–2064	Rank (%)	2070–2099	Rank (%)
CNRM CM3	+0.03	34	+4.41	89	**+7.45**	**99**
GFDL CM2.1	+2.83	45	+0.19	16	**-3.73**	**1**
MIROC3.2 (med)	-0.32	26	-2.07	11	+0.69	38
MPI ECHAM5	-2.13	18	-0.74	32	**-5.91**	**1**
NCAR CCSM3	**-10.35**	**1**	**-7.91**	**4**	-6.94	7
NCAR PCM1	+4.06	85	+4.27	87	+1.76	62

Sacramento SRES B1

Model	2005–2034	Rank (%)	2035–2064	Rank (%)	2070–2099	Rank (%)
CNRM CM3	-6.07	8	-3.77	17	-0.53	39
GFDL CM2.1	+2.42	51	-1.72	17	**-9.32**	**0.3**
MIROC3.2 (med)	-5.01	12	**-10.17**	**0.2**	**-9.11**	**0.4**
MPI ECHAM5	-1.64	31	-3.79	14	**-12.65**	**0.1**
NCAR CCSM3	**-11.60**	**1**	**-8.89**	**4**	-5.43	20
NCAR PCM1	+6.22	89	+1.65	52	-0.65	28

Los Angeles SRES B1

Model	2005–2034	Rank (%)	2035–2064	Rank (%)	2070–2099	Rank (%)
CNRM CM3	**-14.96**	**4**	**-24.76**	**0.1**	**-23.15**	**0.1**
GFDL CM2.1	-2.14	31	**-11.62**	**3**	**-22.59**	**0.1**
MIROC3.2 (med)	-18.40	11	**-24.64**	**0.3**	**-35.93**	**0.1**
MPI ECHAM5	-3.84	54	-4.00	54	**-16.35**	**1**
NCAR CCSM3	**-8.07**	**0.4**	+12.54	77	-1.13	8
NCAR PCM1	+16.96	94	**-2.81**	**3**	+7.18	45

Table 2. (continued)

Shasta SRES A2

Model	2005–2034	Rank (%)	2035–2064	Rank (%)	2070–2099	Rank (%)
CNRM CM3	**+9.75**	**99**	+0.03	34	+1.90	60
GFDL CM2.1	-0.57	11	**-5.23**	**0.3**	**-13.12**	**0.1**
MIROC3.2 (med)	+1.02	43	-1.07	18	-0.70	21
MPI ECHAM5	-3.42	9	-0.99	29	-1.09	27
NCAR CCSM3	**-20.81**	**0.1**	**-23.35**	**0.1**	**-23.3**	**0.1**
NCAR PCM1	+0.04	41	+1.53	59	-3.36	8

Sacramento SRES A2

Model	2005–2034	Rank (%)	2035–2064	Rank (%)	2070–2099	Rank (%)
CNRM CM3	**+14.79**	**99**	**-11.24**	**0.6**	**-8.51**	**2**
GFDL CM2.1	+0.68	35	-2.78	12	**-16.56**	**0.1**
MIROC3.2 (med)	-3.02	24	**-9.61**	**0.3**	**-13.28**	**0.1**
MPI ECHAM5	-7.05	**2**	**-7.27**	**1**	-3.07	19
NCAR CCSM3	-8.37	6	**-11.73**	**1**	**-11.09**	**1**
NCAR PCM1	-1.68	20	-3.06	12	-2.69	13

Los Angeles SRES A2

Model	2005–2034	Rank (%)	2035–2064	Rank (%)	2070–2099	Rank (%)
CNRM CM3	**+21.23**	**98**	**-41.10**	**0.1**	**-22.96**	**0.1**
GFDL CM2.1	-6.38	12	-2.48	29	**-25.77**	**0.1**
MIROC3.2 (med)	-19.48	7	**-30.09**	**0.1**	**-36.11**	**0.1**
MPI ECHAM5	-11.21	10	-10.81	12	-1.48	73
NCAR CCSM3	+1.52	15	-0.56	9	**-11.65**	**0.1**
NCAR PCM1	+6.35	38	+4.88	30	+6.44	39

Table 3. Trends 2000–2100 in the number of days when precipitation exceeds 3 mm (top), 15 mm (middle), and 25 mm (bottom) over the Shasta, Sacramento, and Los Angeles regions from SRES A2 simulations for CNRM, GFDL, and PCM GCMs, from grid points nearest these locations. Significance determined from Monte Carlo exercise generating distribution of 1000 possible historical trends. Values that are significant at the 95% confidence level are highlighted with bold type.

Days when precipitation is > 3 mm

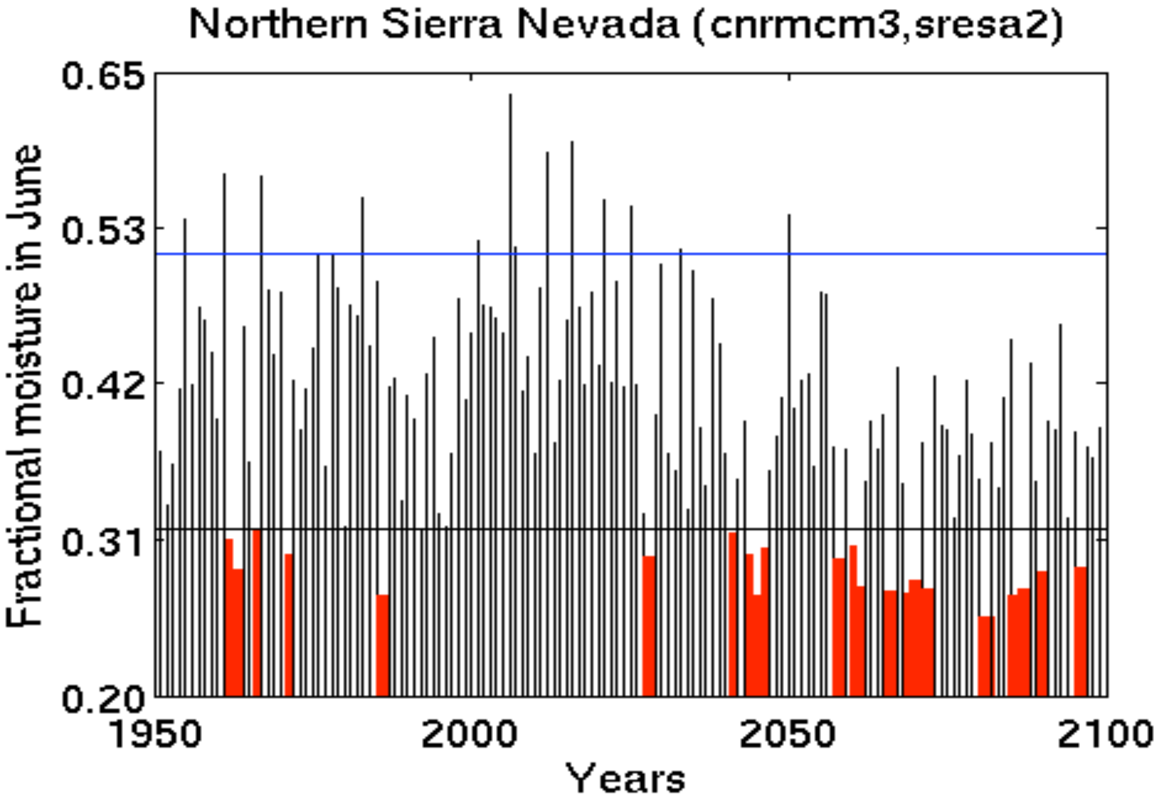
	Shasta		**Sacramento**		**Los Angeles**	
Model	2001 – 2100 trend	Rank (%)	2001 – 2100 trend	Rank (%)	2001 – 2100 trend	Rank (%)
CNRM CM3	**-30.37**	**0.1**	**-34.20**	**0.1**	**-9.10**	**0.1**
GFDL CM2.1	**-28.16**	**0.1**	**-23.42**	**0.1**	**-13.54**	**0.1**
NCAR PCM1	**-11.10**	**0.3**	**-12.98**	**0.1**	-5.56	7

Days when precipitation is > 15 mm

	Shasta		**Sacramento**		**Los Angeles**	
Model	2001 – 2100 trend	Rank (%)	2001 – 2100 trend	Rank (%)	2001 – 2100 trend	Rank (%)
CNRM CM3	**+2.85**	**96**	**-2.66**	**1**	**-1.12**	**3**
GFDL CM2.1	**-2.59**	**7**	**-6.04**	**1**	-0.86	29
NCAR PCM1	-0.17	58	+1.53	83	-1.00	16

Days when precipitation is > 25 mm

	Shasta		**Sacramento**		**Los Angeles**	
Model	2001 – 2100 trend	Rank (%)	2001 – 2100 trend	Rank (%)	2001 – 2100 trend	Rank (%)
CNRM CM3	**+1.04**	**99**	-0.50	17	-0.28	6
GFDL CM2.1	-0.57	23	-1.47	17	+0.09	58
NCAR PCM1	+0.60	94	**+0.91**	**95**	+0.43	70



Soil Moisture (June) CNRM A2

Figure 12. June soil moisture from the Variable Infiltration Capacity (VIC) hydrological model driven by the CNRM A2 simulation downscaled using the Constructed Analogues method. Years with soil moisture being less than historical 10th percentile level are shown in red. The 90th percentile and 10th percentile June soil moisture levels are indicated by blue and black horizontal lines, respectively.

The trend toward drier conditions in California in some of these models is a response to changes in the atmospheric circulation along the eastern North Pacific and western United States margin. Although there does not appear to be much change in the wintertime (November through March) central North Pacific Aleutian low complex (Table 4), changes toward fewer storms do appear farther east along the coast of Northern California and Oregon. Regional winter season atmospheric circulation changes consistent with these changes can be seen in Figure 13 and Table 5, showing a tendency for winter (December through February) and spring (March through May) sea level pressure, in the area offshore centered at 40°N, 130°W that is most strongly linked to precipitation in the central and northern part of the state, previously named the California sea level pressure pattern (Cayan and Peterson 1989).

Table 4. North Pacific sea level pressure index (after Trenberth and Hurrell 1995), formed from average of November through March sea level pressure, 30N–65N, 160E–140W. Units are in hectopascals (hPa).

NDJFM			CNRM CM3	GFDL CM2.1	MIROC3.2 (med res)	MPI ECHAM5	NCAR CCSM3	NCAR PCM1
20C3M	1961–1990	mean	1012.57	1009.61	1006.97	1010.72	1006.74	1011.58
		sigma	2.44	3.30	2.14	2.82	3.08	3.11
SRESA2 (change from historical)	2005–2034		-0.28	-1.42	1.06	-0.45	-0.96	0.42
	2035–2064		0.97	-0.26	1.39	-0.56	-0.56	-0.27
	2070–2099		0.78	-0.83	2.62	-1,95	-0.30	-0.97
SRESB1 (change from historical)	2005–2034		0.46	-0.76	0.33	-0.54	-1.06	0.18
	2035–2064		-0.97	-1.55	0.70	-0.45	-0.62	-0.31
	2070–2099		0.17	-0.48	-0.19	-1.28	-0.99	-1.46

Consistent with the overall tendency toward somewhat drier conditions, the occurrence of significant storms, as indicated by the number of days per year when sea level pressure in the neighborhood of the San Francisco region equals or falls below 1005 millibar (mb) declines, at least marginally, in three of the models (Figure 14). Shown in Table 6, the decline in storms is stronger in the A2 simulations, in which all three simulations exhibit a decreasing trend over the 2000–2099 period that are less than the tenth percentile, according to a Monte Carlo exercise where a series of annual storm counts was randomly shuffled 1000 times to produce a distribution of 1000 such trends. The negative trends found in the San Francisco region are reinforced by the occurrence of equally or even more significant negative trends in this storm count measure in the Crescent City region. Interestingly, the storm count results are not so consistent at the La Jolla region, where only one of the six simulations reaches the 5 percentile threshold. In Figure 14, the observed occurrence of this storm measure near San Francisco from NCAR/NCEP Reanalysis is shown for comparison. In addition, the occurrence of high daily precipitation events, as indicated by daily precipitation of 25 millimeters (mm) or more, varies from year to year, but generally remains about the same level in the projected 2000–2100 climate as it was during the simulated historical period from each of the six models (Figure 15). Not surprisingly, the number of storms (using the 1005 mb threshold index) is positively correlated with the number of heavy precipitation events and also with the annual total precipitation, although these correlations are only modest (about 0.3 level). The continued occurrence of significant storms within the model simulations would suggest that future decades would continue to be occasionally affected by floods in the California region (Neiman et al. 2008).

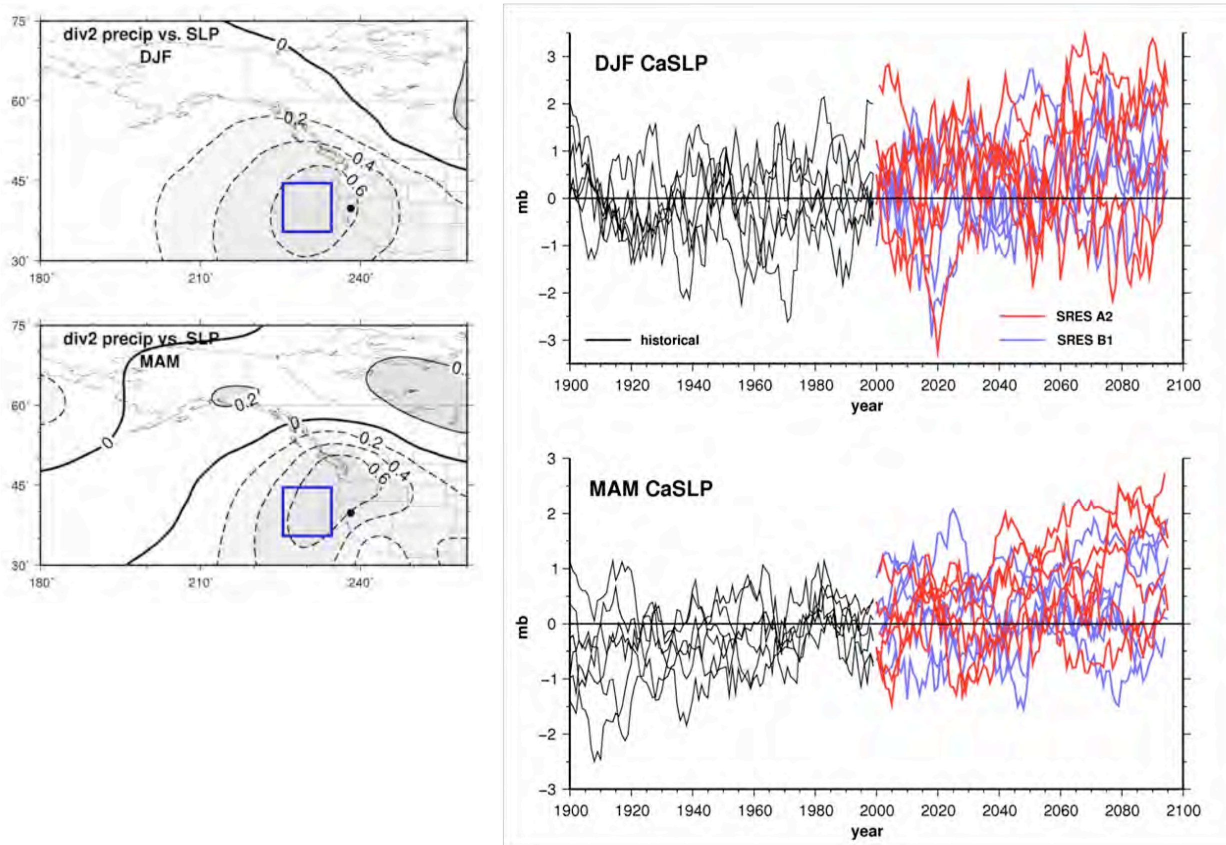


Figure 13. Simulated variability, in California sea level pressure index (CaSLP) (Cayan and Peterson 1989) for winter (upper) and spring (lower), shown in two right-hand side plots of 6 GCMs for 203CM historical simulations (black) and for B1 (blue) and A2 (red) emission scenario simulations. Maps on the left side show correlations of historical observed precipitation with NCEP Reanalysis sea level pressure, as indicated by contour lines, along with delineation of the 35-40°N, 125-135°W CaSLP "box."

Table 5. California sea level pressure index, (after Cayan and Peterson 1989) formed from average of sea level pressure centered at 40N, 130W. Units are hPa.

SON			CNRM CM3	GFDL CM2.1	MIROC3.2 (med res)	MPI ECHAM5	NCAR CCSM3	NCAR PCM1
20C3M	1961–1990	mean	1021.90	1019.70	1019.97	1020.77	1021.60	1021.35
		sigma	0.89	1.55	1.60	1.50	1.56	1.36
SRESA2 (change from historical)	2005–2034		0.00	-0.06	0.27	0.21	0.40	0.40
	2035–2064		0.27	0.66	0.16	0.18	0.75	0.17
	2070–2099		-0.12	0.21	-0.50	0.32	0.15	0.44
SRESB1 (change from historical)	2005–2034		-0.03	0.23	-0.26	0.45	0.36	0.50
	2035–2064		0.16	0.07	-0.44	0.25	0.29	0.27
	2070–2099		-0.28	0.13	-0.56	-0.32	-0.06	0.51

DJF			CNRM CM3	GFDL CM2.1	MIROC3.2 (med res)	MPI ECHAM5	NCAR CCSM3	NCAR PCM1
20C3M	1961–1990	mean	1020.69	1017.68	1019.59	1017.98	1019.53	1021.17
		sigma	2.66	3.49	2.49	3.03	2.58	4.20
SRESA2 (change from historical)	2005–2034		-1.30	-0.08	0.68	0.51	0.26	0.67
	2035–2064		1.41	0.11	1.35	0.27	0.43	0.35
	2070–2099		1.82	1.94	2.54	-0.25	1.01	-0.19
SRESB1 (change from historical)	2005–2034		0.23	-0.35	0.64	0.25	0.97	-0.93
	2035–2064		-0.50	0.06	1.59	0.00	0.31	0.59
	2070–2099		1.56	1.24	0.82	0.87	0.06	0.21

MAM			CNRM CM3	GFDL CM2.1	MIROC3.2 (med res)	MPI ECHAM5	NCAR CCSM3	NCAR PCM1
20C3M	1961–1990	mean	1021.86	1019.59	1019.50	1020.74	1021.89	1023.50
		sigma	1.39	2.83	1.90	1.36	1.62	2.67
SRESA2 (change from historical)	2005–2034		0.51	-0,15	0.25	0.11	0.19	-0.32
	2035–2064		1.51	0.61	1.03	-0.17	0.63	0.06
	2070–2099		2.28	1.70	1.44	0.12	1.00	-0.12
SRESB1 (change from historical)	2005–2034		0.53	1.25	0.64	-0.86	-0.29	0.28
	2035–2064		0.95	0.15	0.42	-0.38	0.16	-0.16
	2070–2099		1.58	0.99	1.04	-0.00	-0.00	-0.38

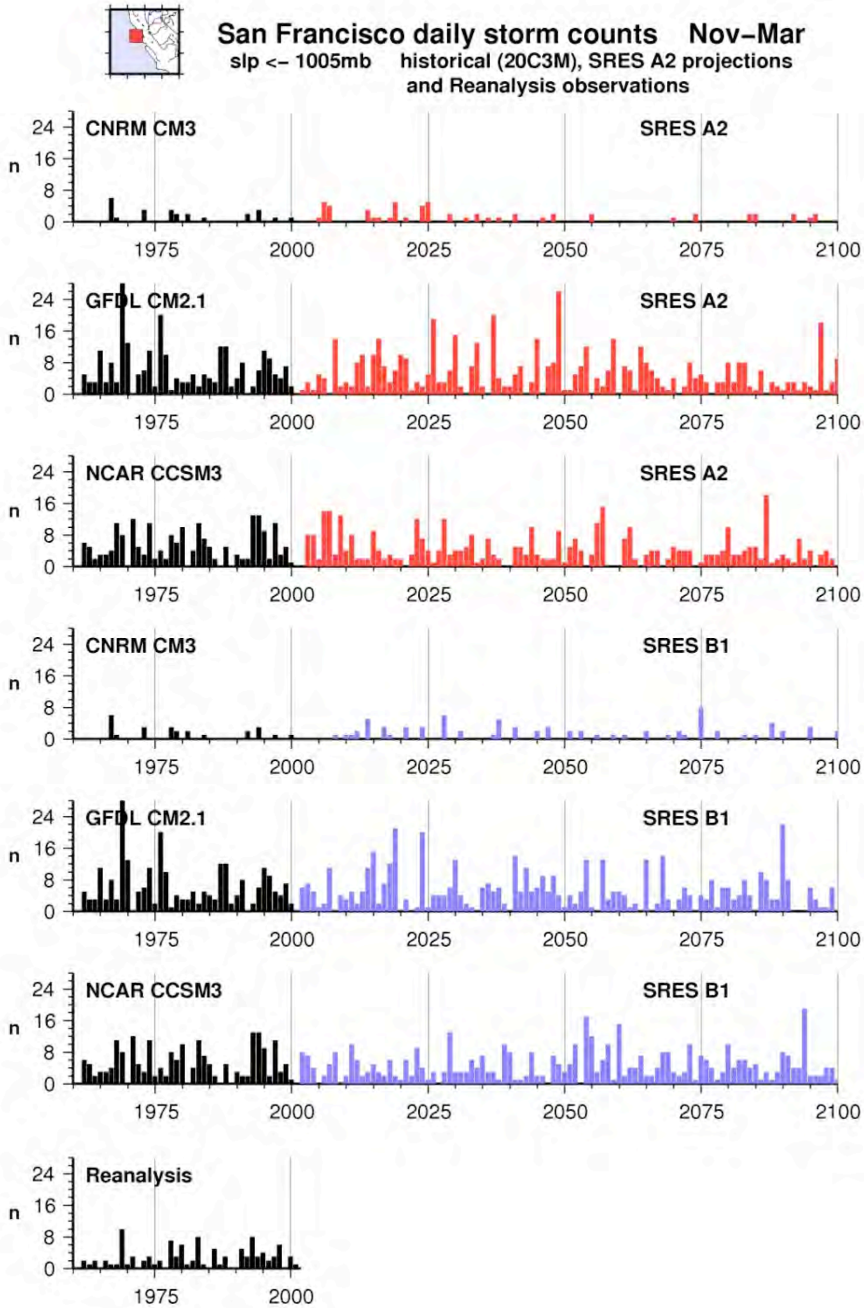


Figure 14. Number of "storms" per year as indicated by days when average daily sea level pressure (SLP) is 1005 mb or less for historical (1950–2000) (black) and projected (2001–2100) periods of the three GCMs for the B1 (below; blue) and A2 (above; red) emissions scenarios. SLP is taken directly from GCMs for the grid point nearest San Francisco.

Table 6. Trends in number of storms in the neighborhood of three regions: Crescent City, San Francisco, and La Jolla. *Storms* are defined as days having mean daily sea level pressure (SLP) less than 1005 mb in the neighborhood of Crescent City, San Francisco, or Shasta from the GCM (CNRM, GFDL, or CCSM). Percentile level of trend is indicated, as evaluated using a Monte Carlo sampling exercise. Values reaching the 90% level of significance are shown in boldface.

	Model	Scenario	Trend 2098/99 minus 2000/01	Percentile, from Monte Carlo Run
Crescent City	CNRM CM3	SRES A2	**-4.99**	**1**
	GFDL CM2.1	SRES A2	**-2.59**	**7**
	NCAR CCSM3	SRES A2	**-2.31**	**8**
	CNRM CM3	SRES B1	**-4.69**	**0.6**
	GFDL CM2.1	SRES B1	**-2.88**	**7**
	NCAR CCSM3	SRES B1	+0.57	73
San Francisco	CNRM CM3	SRES A2	**-1.01**	**0.3**
	GFDL CM2.1	SRES A2	**-2.16**	**8**
	NCAR CCSM3	SRES A2	**-2.47**	**2**
	CNRM CM3	SRES B1	-0.12	33
	GFDL CM2.1	SRES B1	**-2.00**	**9**
	NCAR CCSM3	SRES B1	+0.79	76
La Jolla	CNRM CM3	SRES A2	+0.08	78
	GFDL CM2.1	SRES A2	-0.83	13
	NCAR CCSM3	SRES A2	**-1.20**	**0.2**
	CNRM CM3	SRES B1	**+0.14**	**91**
	GFDL CM2.1	SRES B1	+0.83	87
	NCAR CCSM3	SRES B1	-0.17	35

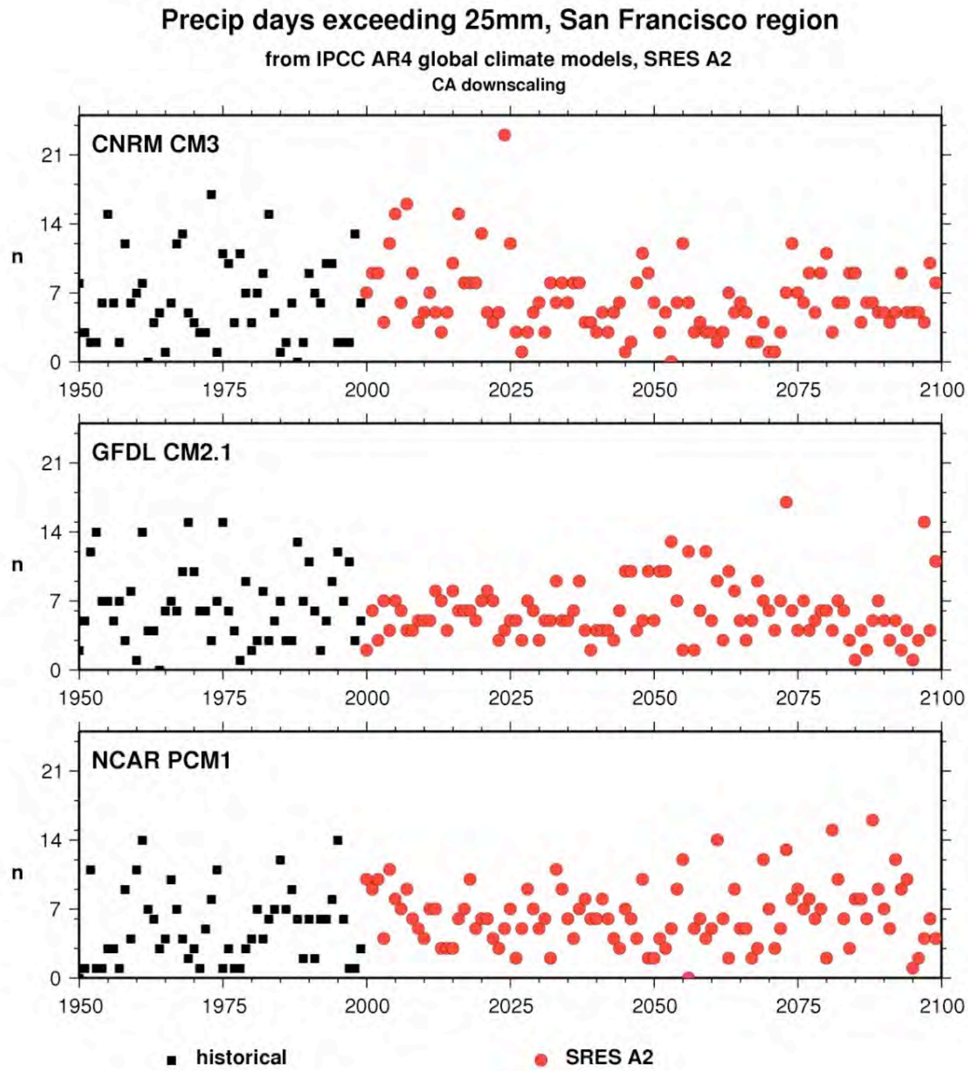


Figure 15. Number of days per year when precipitation at San Francisco equals or exceeds 25 mm. From constructed analogues downscaling of CNRM CM3, GFDL CM2.1, and NCAR PCM1 GCMs; result from BCSD downscaling (not shown) is very similar. Historical period and A2 2000–2100 projection indicated by black and red symbols, respectively. Precipitation is taken from BCSD downscaling.

7.0 El Niño/Southern Oscillation

Historically, El Niño/Southern Oscillation (ENSO) has been an important influence on weather conditions in California. The reliability of linear correlations between ENSO and precipitation is strongest in Southern California and diminishes northward. Each of the climate models contain ENSO within their historical simulations (Figure 16). Although there is no evidence for an increase in the frequency or the intensity of ENSO, each of the simulations exhibits continued ENSO activity within the twenty-first century. As displayed by observations (Redmond and Koch 1991; Gershunov et al. 2000; Cayan et al. 1999), and also during the historical GCM simulations, there is a modest tendency for the Southern California region to experience higher than normal precipitation during El Niño winters and lower than normal precipitation during La Niña winters. To a limited degree, this pattern is also found during the climate change projections.

8.0 Sea Level Rise

Over the past several decades, sea level measured at tide gages along the California coast has risen at a rate of about 17–20 centimeters (cm) per century, a rate that is nearly the same as that from global sea level rise estimates (Church and White 2006). A paper authored by Rahmstorf (2007) demonstrated that over the last century observed global sea level rise can be linked to global mean surface air temperature. This provides a methodology to estimate global sea level using the surface air temperature projected by the global climate model simulations, and it leads to larger rates of sea level rise than those produced by other recent estimates (Cayan et al. 2008). The present estimates include those of Rahmstorf's method, assuming that sea level rise along the Southern California coast will be the same as the global estimates. Also, the projections here include a second set of estimates that are a modification of Rahmstorf's method that attempts to account for the global growth of dams and reservoirs, which have artificially changed surface runoff into the oceans (Chao et al. 2008), in addition to the effects of climate change. Using the global surface air temperature from the GCMs included in this assessment, the resulting estimates in Figures 17 and 18 indicate that potential sea level rise over the next century will increase over its historical rate by a considerable amount. Each model has a different rendition of global surface air temperature within the historical period within its "20C3M" historical simulation,[1] so that simulated historical sea levels vary between models. But in the experiments run here, the sea level estimates were adjusted so that for year 2000 their value was constrained to the same, zero value—this allows for comparison across the simulations of the amount of projected sea level rise over the twenty-first century. By 2050, sea level rise, relative to the 2000 level, ranges from 30 cm to 45 cm. As sea level rises, there will be an increased rate of extreme high sea level events (Figure 19 and Table 7), which occur during high tides, often when accompanied by winter storms and sometimes exacerbated by El Niño occurrences (Cayan et al. 2008c). Importantly, as decades proceed, these simulations also contain an increasing tendency for heightened sea level events to persist for more hours, which would seem to imply a greater threat of coastal erosion and other damage. Virtually all of the increase in frequency and magnitude of sea level exceedances can be ascribed to the underlying secular increase in mean sea level. The increase in exceedances cannot be attributed to a change in weather activity, as demonstrated by running the sea level model with weather-forcing only, as summarized in Table 8. This steady behavior in weather is consistent with the relative lack of major changes in the Aleutian Low system (not shown).

[1] For example, see www.ccsm.ucar.edu/working_groups/Change/CCSM3_IPCC_AR4/20C3M.html.

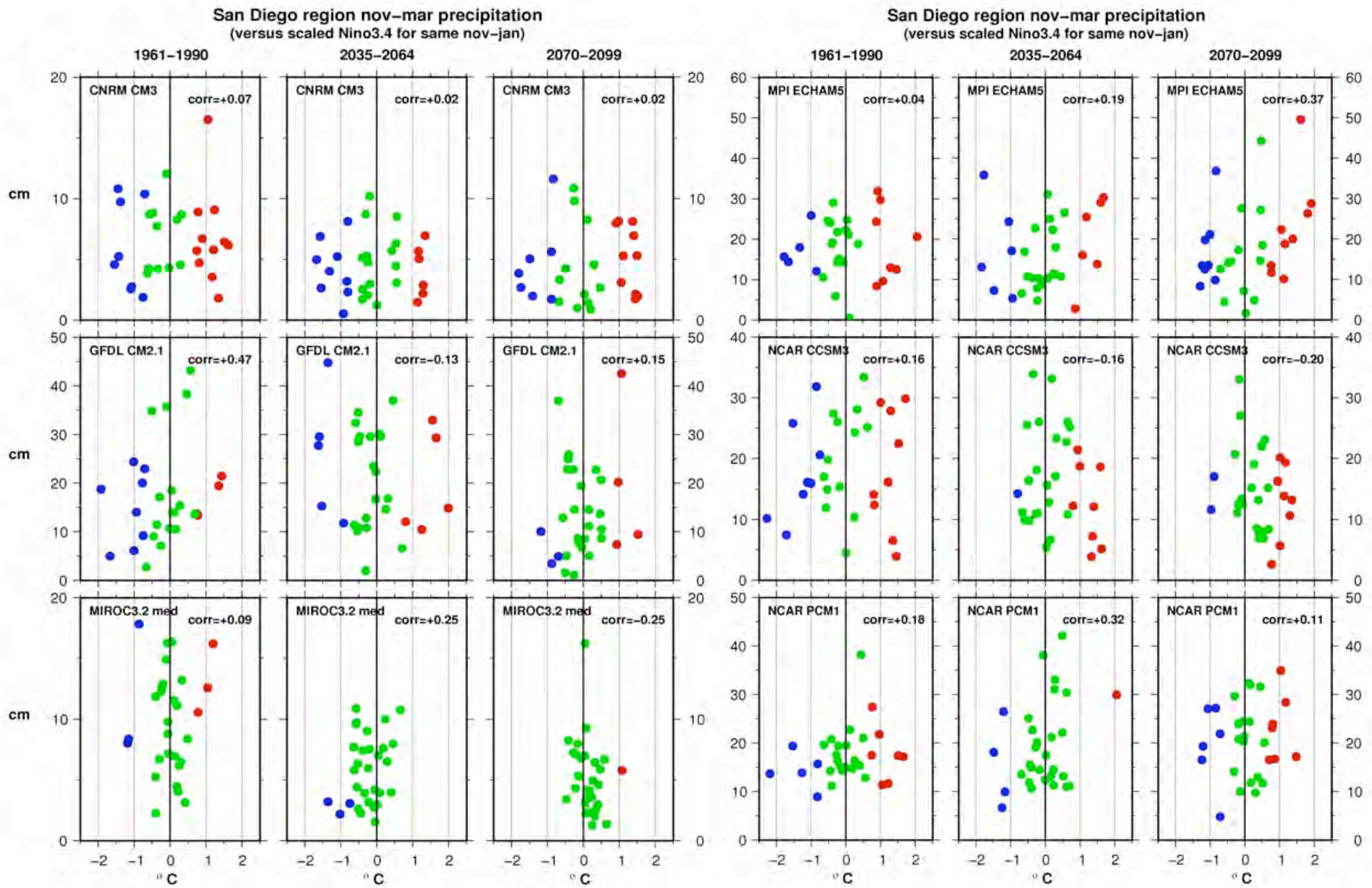


Figure 16. Association of precipitation in San Diego region to ENSO, as indicated by the El Niño 3.4 sea surface temperature (SST) index, which is the area average sea surface temperature departure from the historical average in the central equatorial Pacific Ocean. Projected Niño 3.4 SST series have been adjusted by removing the linear trend to better discern interannual fluctuations. Precipitation values during cool, neutral, and warm Niño 3.4 SST

years indicated by blue, green, and red dots respectively. San Diego region precipitation extracted directly from each of the GCMs, from the grid point nearest to San Diego.

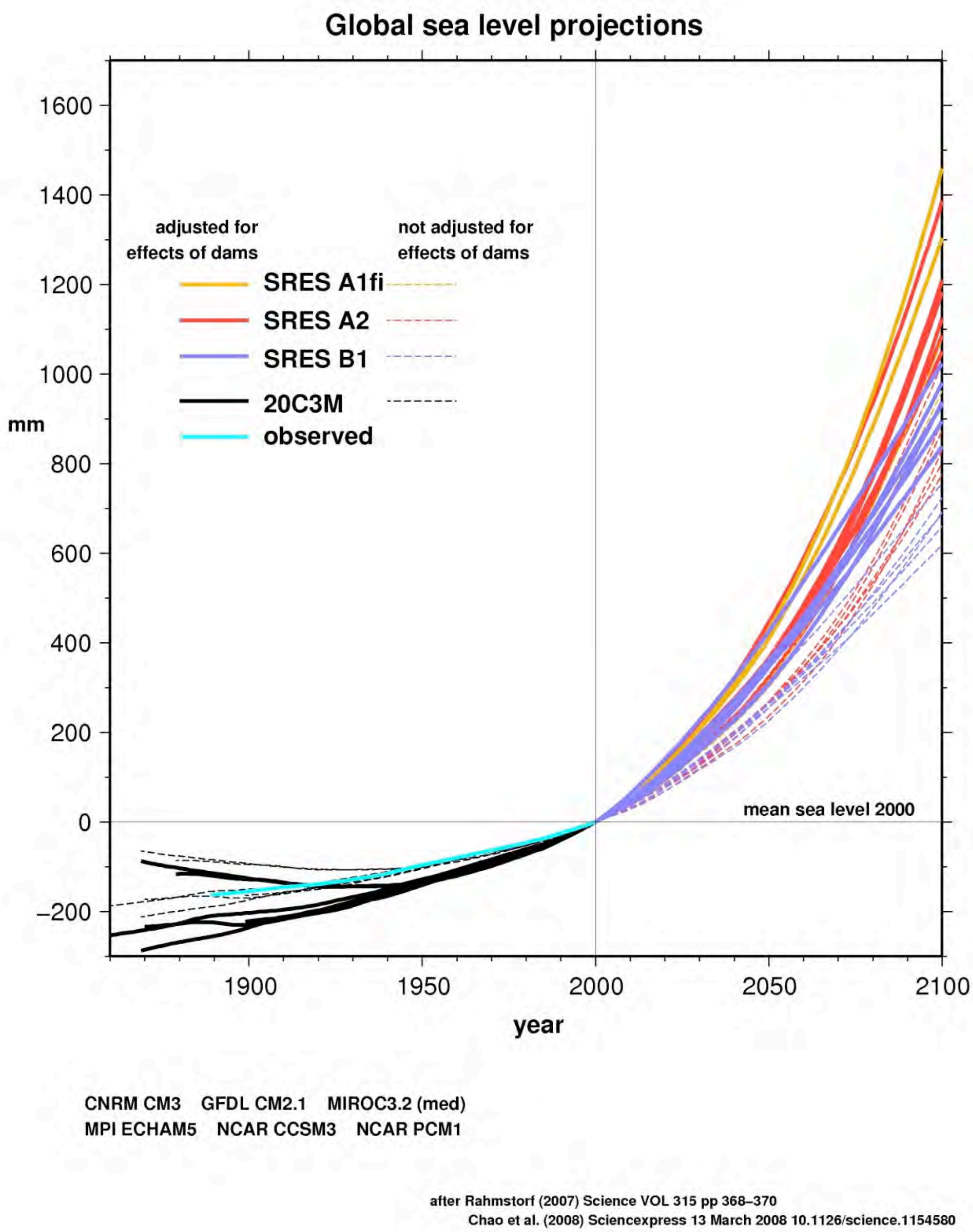


Figure 17. Projected global sea level using the Rahmstorf (2007) scheme from each of the six models (set to zero at 2000). Climate change simulations for the SRES A1fi, A2 and B1 emission scenarios are shown for both the original Rahmstorf (dashed curves) and a version adjusted for the affect of reservoirs and dams (solid). Historical (black) and projected B1 simulations (blue), A2 simulations (red), A1fi (gold) are shown along with observed global sea level (aqua).

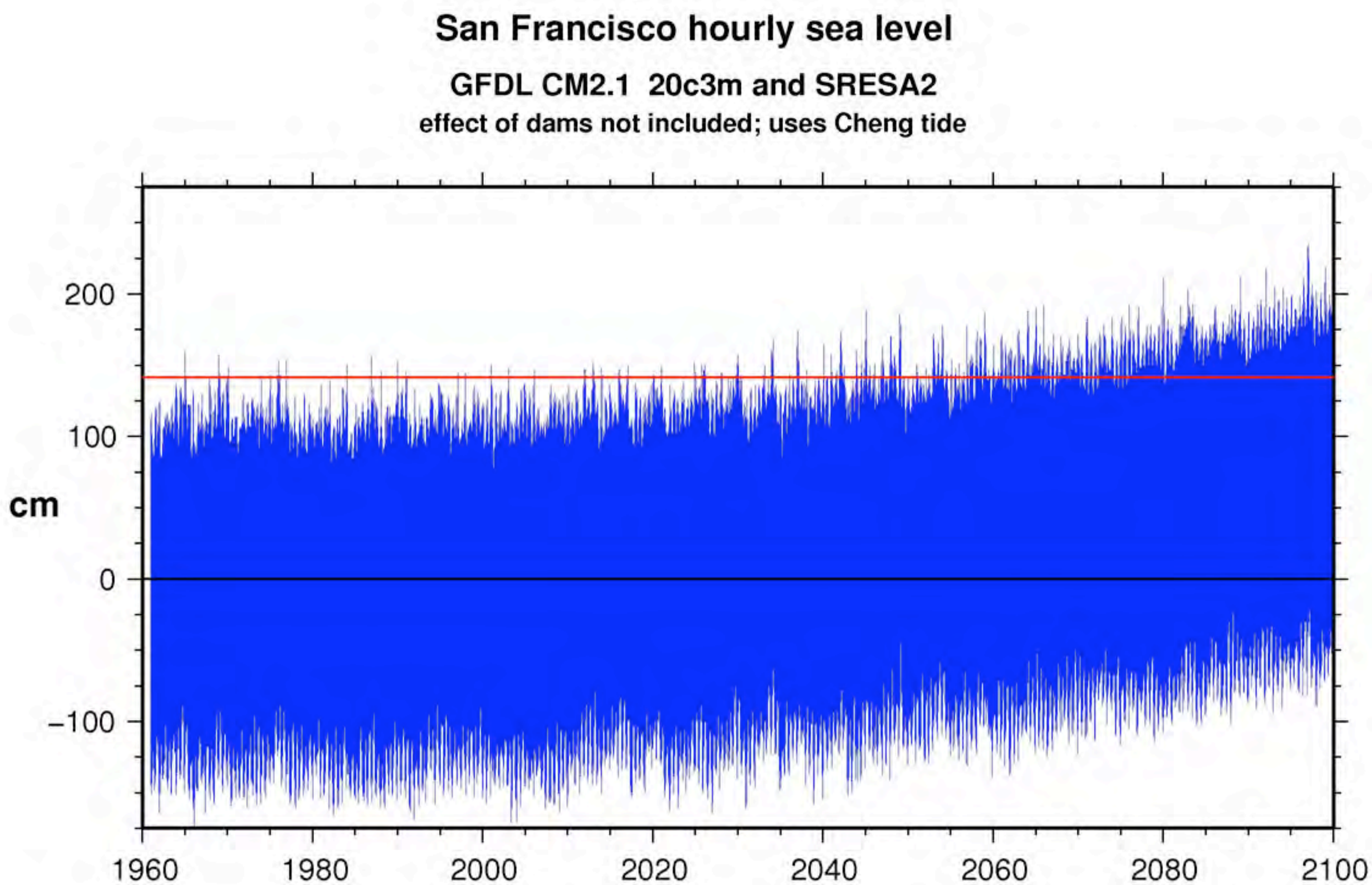


Figure 18. Hourly sea level simulated for San Francisco (Fort Point) location, using secular change estimated using the Rahmstorf (2007) scheme. Hourly sea level model from Cayan et al. 2008c includes this secular rise and superimposes predicted astronomical tides, barometric pressures winds, and ENSO from GFDL A2 simulation. Sea level values are referenced to the long-term mean historical average.

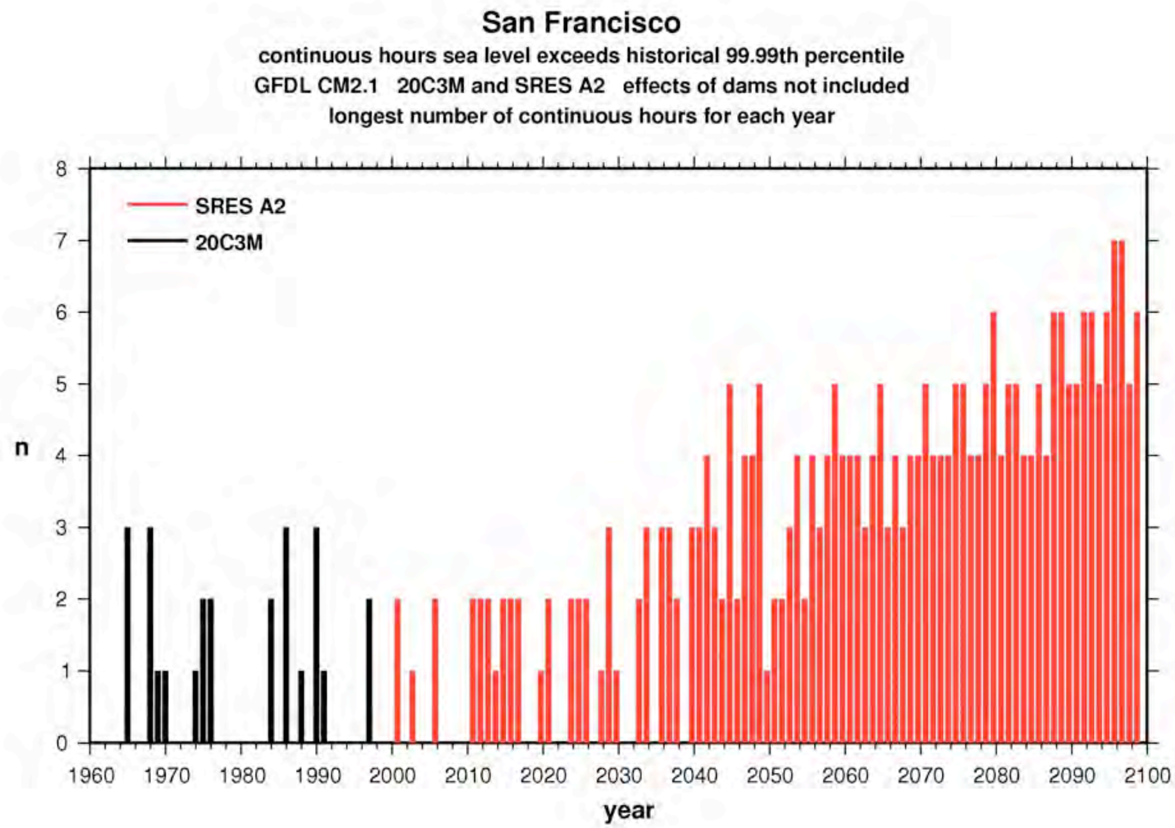


Figure 19. Maximum duration (hours) that San Francisco sea level, as depicted in Figure 18, exceeds the 99.99th percentile level (140 cm above mean sea level), as modeled from the GFDL historical (20C3M) simulation (black) and the GFDL climate change (SRESA2) simulation (red) using the Rahmstorf sea level scheme without adjustment for effect of dams

Table 7. Hourly Sea Level Exceedances, San Francisco. Number of hours and percent of total hours sea level exceeds the 99.99th historical (1960–1978) percentile for each 30 year period. The 99.99th historical percentile is 141 cm.

Model	Scenario	2005–2034	2035–2064	2070–2099
CNRM CM3	SRESB1	64 (0.02%)	810 (0.31%)	10428 (3.97%)
	SRESA2	32 (0.01%)	627 (0.24%)	19225 (7.32%)
GFDL CM2.1	SRESB1	161 (0.06%)	1112 (0.42%)	9304 (3.54%)
	SRESA2	108 (0.04%)	1206 (0.46%)	15447 (5.88%)
NCAR CCSM3	SRESB1	217 (0.08%)	2108 (0.80%)	16768 (6.38%)
	SRESA2	171 (0.07%)	2480 (0.94%)	34736 (13.22%)

(2008 sea level model; Rahmstorf scheme, no adjustment for dams)

Table 8. Standard deviation of hourly sea level (cm) from the weather component of the sea level model

		La Jolla			San Francisco			Crescent City		
		CNRM CM3	GFDL CM2.1	NCAR CCSM3	CNRM CM3	GFDL CM2.1	NCAR CCSM3	CNRM CM3	GFDL CM2.1	NCAR CCSM3
20C3M	1961–1990	2.93	4.47	4.11	5.56	8.41	8.90	9.15	11.35	12.19
SRESA2	2005–2034	3.00	4.53	4.22	5.87	8.03	9.04	9.74	11.18	12.53
	2035–2064	2.83	4.58	3.96	5.33	8.41	8.88	9.22	11.61	12.33
	2070–2099	2.92	4.35	3.90	5.71	7.77	8.65	9.88	10.90	11.98
SRESB1	1961–1990	3.02	4.42	4.07	5.82	8.36	8.83	9.51	11.36	12.23
	2035–2064	2.88	4.42	4.06	5.62	8.26	9.06	9.38	11.21	12.24
	2070–2099	2.92	4.38	4.09	5.61	7.95	9.01	9.37	10.86	12.24

9.0 North Pacific Wind Waves along the California Coast

Wind wave modeling was conducted over the North Pacific, with emphasis on the waves that impinge upon the California coast. The model used is the Wavewatch III v1.18 wave model (Tolman 1998), configured at a resolution of 1.0 x 1.5 degrees latitude / longitude using 20 frequency bands covering the range of periods 27.2 to 4.4 seconds and using a directional resolution of 5 degrees. The spatial domain covers the entire North Pacific Ocean from 20N to the coasts of Asia, the Aleutian Islands, and North America. The ocean is treated as flat bottomed, 1000 meters deep (i.e., there is no refraction); there are no currents or sea ice included.

Six simulations were conducted:

- RA – NCEP Reanalysis nominal "10 meter (m) mean sea level (MSL)" winds, 1948–1999, native resolution about 1.8 degrees latitude / longitude.
- CCSM-20C – NCAR CCSM using the IPCC SRES twentieth-century emissions scenario, native resolution about 1.4 degrees latitude and longitude. Time covered is 1941–1999; winds are from the lowest model level at approximately 60 m MSL.
- CCSM-A1B – NCAR CCSM using the IPCC SRES A1B emissions scenario, native resolution about 1.4 degrees latitude and longitude. Time covered is 2000–2099; winds are from the lowest model level at approximately 60 m MSL.
- CCSM-A2 – NCAR CCSM using the IPCC SRES A2 emissions scenario, native resolution about 1.4 degrees latitude and longitude. Time covered is 2000–2099; winds are from the lowest model level at approximately 60 m MSL.
- CNRM-20C – CNRM GCM using the IPCC SRES twentieth-century emissions scenario, native resolution about 1.8 degrees latitude and longitude. Time covered is 1970–1999; winds are nominally from 10 m MSL.
- CNRM-A2 – CNRM GCM using the IPCC SRES A2 century emissions scenario, native resolution about 1.8 degrees latitude and longitude. Time covered is 2000–2099; winds are nominally from 10 m MSL.

All simulations used the available six-hourly wind data. The wave model used a nominal one-hour time step, with a sub-step adaptive time step depending on the generation characteristics.

Tuning (spatially and temporally fixed) was conducted to bring the wave climatologies from the CCSM-20C and CNRM-20C simulations into approximate congruence with the NCEP Reanalysis simulation. The latter was tuned in earlier simulations using the NCEP Reanalysis winds to give good agreement for larger wave events at buoys in the eastern North Pacific. There is some low bias for waves driven by near-coastal winds along the California coast. This is due primarily to wind speed bias in the NCEP Reanalysis wind data near the coast, a result of the rather coarse atmospheric general circulation model resolution and the importance of coastal effects in the wind climatology of this region. This bias has very little effect on the results here. Comparison of the NCEP Reanalysis results with buoy data for larger wave events is quite good; with correlations for many years of three-hourly data in winter of about 0.9 (Graham 2005).

The North Pacific near-surface wind climatology of the CCSM model is quite good (not shown). The tuning used a relatively simple boundary layer model, similar to Liu et al. 1979, to adjust the raw CCSM winds to near-surface winds. After a series of trial simulations the tuning resulted in a wave climatology for the California coast that is essentially indistinguishable from the NCEP Reanalysis results for the period 1978–1999. The CNRM near-surface wind climatology over the North Pacific is less realistic than for the CCSM model, but after several trial simulations satisfactory overall winter wave climatology was obtained with a modest low bias (about 0.4 m) along the California coast.

The CCSM-A1B, CCSM-A2, and CNRM-A2 simulations were examined for 2000–2001 to 2098–2099. The annual November–March (NDJFM) fiftieth and ninety-ninth percentile climatologies for approximately the year 2000 are shown (the 2001–2099 climatology less half the trend over that period) along with the trends in NDJFM fiftieth and ninety-ninth percentile significant wave heights (Hs50 and Hs99, respectively) expressed as meters per century and as percentages of the climatologies described above. The CCSM trends are statistically significant and negative for Hs50 south a line roughly following the typical storm track from about 35N along the coast of Asia to near 60N and the North American coastline. Near the coast of California these trends are typically 5%–10% (declines) of the year 2000 climatology. For Hs99 the trends are generally not statistically significant except off the coast of Asia. The lack of significance is probably due to the "noisier" nature of ninety-ninth percentile statistics and would likely appear qualitatively much like the Hs50 results if the many ensemble simulations were performed.

For the CCSM-A2 simulation the trends are significant for both Hs50 and Hs99 and follow the same pattern as the CCSM-A1B fiftieth percentile results and show significant negative trends amounting to 5%–10% (declines) of the year 2000 climatology for Hs50 with slightly smaller magnitudes for Hs99.

For the CNRM-A2 results the pattern of trends is similar to those described for the CCSM-driven results with mostly negative trends in the southern part of the domain and mostly positive trend farther north and the largest negative trends off the coast of Japan. Trends along the California coast are only marginally statistically significant and are about 3%–5% declines for Hs50 and 5%–10% declines for Hs99.

Overall, the model results are quite satisfactory in providing information about likely scenarios of winter wave height changes along the California coast. The pattern of negative trends to the south with a tendency toward positive trends to the north reflects a decrease of winter storm wind forcing. This is produced as the mean cyclone track tends to move north as the climate warms, a robust feature of greenhouse climate change simulations reflecting in part the warming of the higher land masses and oceans (and declining sea ice coverage) and the expansion of the subtropical high pressure regions. The lower waves of California is thought to be largely due to this northward migration of the storm track (this shift is clear, but rather small—on the order of 1 degree (latitude)—and may also reflect some decrease in cyclone intensity. The consistency of the wave modeling results is heartening with the suggestion of slight negative trends in wave heights, with larger negative and more significant trends with higher greenhouse gas concentrations. It should be noted that the trends along the California coast, shown in Figure 20 for the Northern California coast and in Figure 21 for Point Conception, are generally marginally significant. The simulations clearly suggest that interannual (not shown) and inter-decadal fluctuations in larger wave episodes (as indexed by Hs99) will continue to dominate wave climate impacts as they have in the past. A final point is that these results indicate that the positive trends in eastern North Pacific winter wave heights noted over the latter half of the twentieth-century are very likely due to natural climate variability rather than anthropogenic warming.

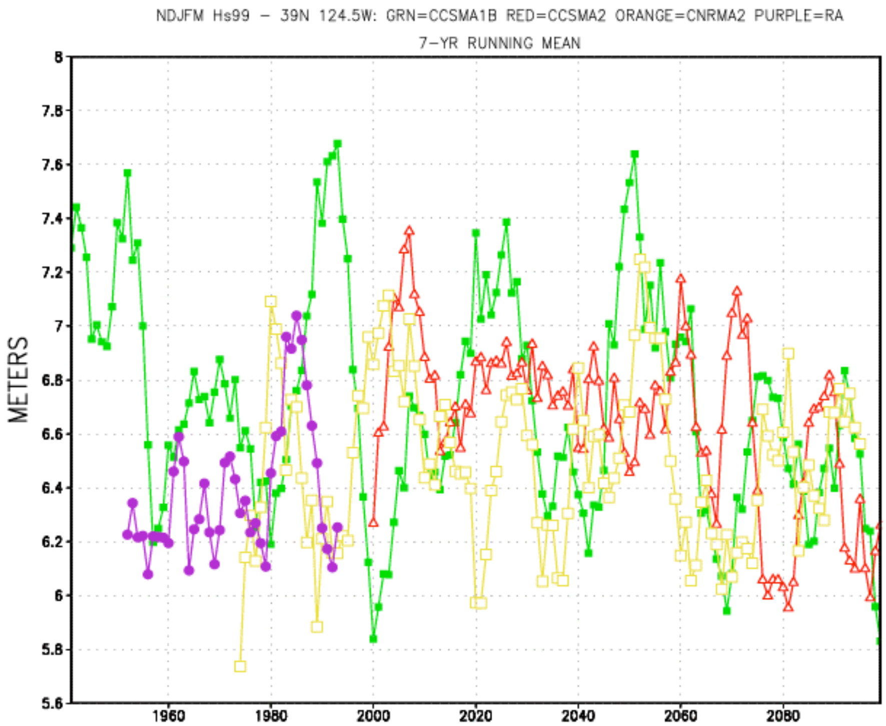


Figure 20. The 99th percentile significant wave heights (Hs99), November through March for Reanalysis (purple), and CCSM A1 (green), CCSM A2 (red), and CNRM A2 climate simulations for Northern California coast offshore from San Francisco. Series have been smoothed with a 7-year running mean.

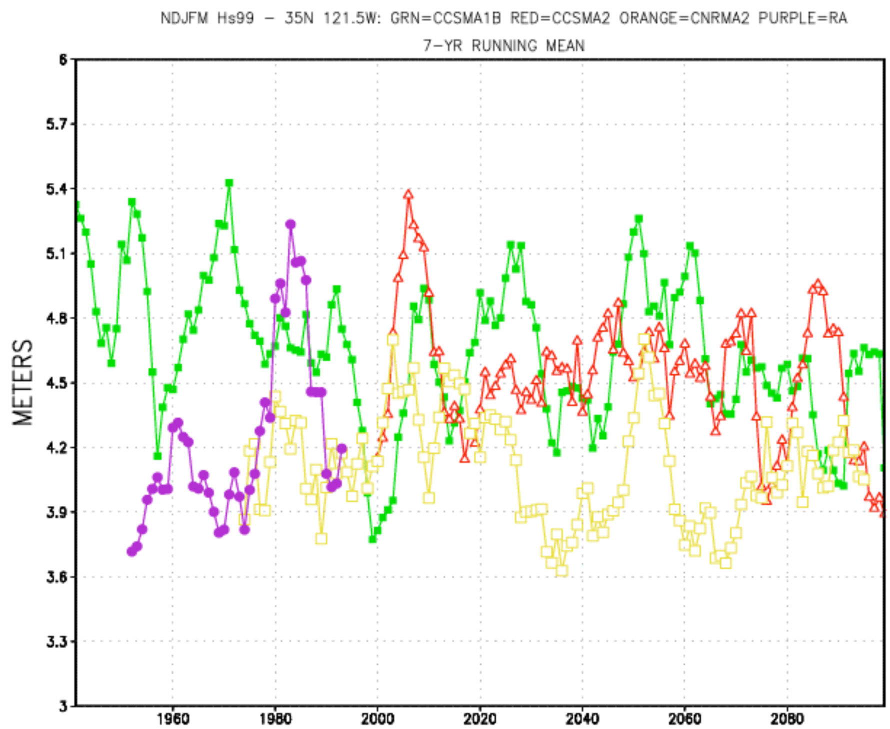


Figure 21. The 99th percentile significant wave heights (Hs99), November through March for Reanalysis (purple), and CCSM A1 (green), CCSM A2 (red), and CNRM A2 climate simulations for location offshore from Point Conception. Series have been smoothed with a 7-year running mean.

10.0 Shore Zone Wave Runup Variability

Rising sea level in response to climate change allows more wave energy to reach farther shoreward, increasing the potential for greater coastal impacts. Mean sea level is the base level on which shorter duration fluctuations (such as El Niño-related increases, tides, storm surge, and waves) are superimposed. Coincident occurrence of extremes in these short-term fluctuations results in the greatest coastal impacts. Rising sea level augments extreme sea level fluctuations, causing increased coastal erosion potential from wave activity. This is investigated using a model of the runup of waves onto an idealized Central California beach.

Beach erosion, exacerbated by rising sea levels, can potentially have a serious impact on the economy of Southern California. Depending upon the rate that sea level rises during the twenty-first century, many beaches will shrink in width, and some beaches may disappear entirely.

Waves provide nearly all the energy that drives physical processes along coasts, and the occurrence of high waves coincident with sea level and tidal extremes is of critical importance.

Projections of wave height and directional wave spectral estimates offshore California were generated for winter months (November–March, when the highest waves occur along the California coast) over the twenty-first century using the WAVEWATCH III (WWIII; Tolman 2002) wave model with forcing by NCAR CCSM3 global climate model winds for the high greenhouse gas A2 emissions scenario.

Previous work has shown that winds from this GCM generate waves that compare reasonably well statistically with coincident observations from buoys along the coast (Graham and Diaz 2001). Wave heights decrease from north-to-south (Table 9), reflecting the dominant pattern observed in historical NOAA buoy data (Bromirski et al. 2005). The winter ninety-eighth percentile significant wave height (*Hs*, the average of the highest one-third of the waves) at three locations that span the California coast have downward trends (Figure 22), likely associated with either decreased model winds or a northward shift in storm track in response to climate change. This projected tendency for decreased extreme waves could partially compensate for the expected significant rise in sea level (Figure 17), somewhat reducing the projected coastal erosion potential. It should be noted that these model wave heights result from model winds from one realization of a single GCM, and it is uncertain how closely these projections will match future observations.

The largest or fastest beach and shoreline changes can generally be associated with the maximum wave runup—the height of discrete water-level maxima at the shore. To investigate potential changes due to the combination of wave variability and sea level rise, runup projections using the directional wave and sea level projections were determined. Because beach-face slopes vary both spatially and temporally, three low-to-moderate fixed beach slopes were selected. Runup depends on the nearshore deep-water wave height, H_0, and its associated wavelength, L_0, and the beach slope, β, as well as geology (e.g., headlands, bedrock outcrops) and exposure (local coastline configuration and bathymetry).

There is considerable uncertainty in the variability of the near-coastal wave climate and the associated erosion response of beaches to wave activity, as well as the reliability of model projections of wave and sea level extremes. Wave direction can vary significantly between storms during winters. Interannual and seasonal changes in nearshore bathymetry can greatly affect the amount of wave energy reaching the shore at specific locations. The current understanding of coastal wave processes and beach response is not sufficient to model the long-term beach evolution in response to changes in wave and sea level extremes. Furthermore, observationally based runup models incorporate empirically determined coefficients (Stockdon et al. 2006), which may have significant site dependence not accounted for. Because of these and runup model uncertainties, the empirical runup formulation of Stockdon et al. (2006, eqn. [19]) provides adequate runup estimates for projected model wave spectra and sea levels for non-specific beach configurations, and it was used to obtain the runup estimates presented here.

The non-wave instantaneous relative sea level projection represents the “still water level” (SWL), i.e., the base water level from which wave-induced runup estimates are projected shoreward. The SWL estimate at the time of each model directional wave spectrum estimate processed was obtained from the hourly sea level projections.

Wave conditions at the coast depend both on the wave conditions offshore and, critically, on their transformation as they travel over the continental shelf and into the nearshore zone. The projected wave energy (frequency-directional wave spectra) from near-coastal deep-water sites associated with the top 10% of the model *Hs* estimates in each winter (about 120) were transformed to near-shore locations using the linear refraction model of O'Reilly (1991). This gives a sufficiently large sample size to obtain a stable estimate of extreme winter runup variability. The transformed wave spectra provide the input parameters for coastal runup modeling. The peak in the transformed wave spectrum gives the peak wave period, and its associated wavelength L_0 is used in the runup model computation.

The transformed nearshore wave spectra were used to generate wavetrains of three-hour duration having randomized phase. This wavetrain time series length was selected to ensure an adequate statistical sampling of 20 s period waves, the maximum wave period generally expected to be observed. Individual waves (successive peak-to-trough heights) within each wavetrain were ranked according to amplitude, with the ninety-eighth and fiftieth percentiles identified. These percentiles served as the wave height estimate H_0 in the runup model.

Wave heights vary in concert along the California coast. That is, when high waves are observed along the north coast, they are generally observed along most of the coast to the south, and vice versa (Bromirski et al. 2005). Wave conditions in the San Francisco region are representative of most of the California coast, so generalized runup estimates in that region are also likely representative. To assess potential trends and long-term variability, runup projections were made for directional wave spectra offshore Central California at 38°N 124.5°W, transformed to 15 m water depth at San Francisco's Ocean Beach (37.733°N 122.606°W).

Winter averages of runup give an indication of trends and long-term variability (Figure 23) using the A2 model waves for both A2 and B1 sea level projections (the sea level projections used include the future dam-construction correction factor). The greatest differences between A2 and B1 mean winter runup levels for the ninety-eighth percentile H_0 estimates occur during the latter half of the twenty-first century, dominated by the acceleration in projected sea level (Figure 17). Comparison of Figures 22 and 23 indicates, as would be expected, that high mean winter runup appears to be associated with peaks in extreme winter wave heights, although the upward trends must be dominated by rising sea level.

Because of the multiple uncertainties associated with absolute runup projections, percentage changes associated with changing wave and sea level conditions likely have the most significance. The percentage increases in runup are greatest for lower foreshore beach slopes, suggesting that these beaches will be most vulnerable under rising sea levels. Percentage increases for the fiftieth percentile wave heights (not shown) are substantially greater (~50%) than for the ninety-eighth percentile waves for all foreshore beach slopes, suggesting that moderate waves will have a greater impact on beach erosion processes under higher sea levels in the future.

An upward trend in wave energy has been observed in the eastern North Pacific during recent decades (Bromirski et al. 2005). If this pattern should continue, or at least maintain its recent climatological level, the downward trend in projections of wave model extremes will not be realized, and given the projected sea level rise, the coastal erosion potential would increase even more than in the present scenarios.

Table 9. Projected WWIII model significant wave height, *Hs*, percentile levels at Crescent City (CRE), San Francisco (SFO), and San Miguel Island (SML) over all 2000–2099 winters (November–March)

Percentile	25	50	75	90	99
CRE	1.90	2.84	4.04	5.37	8.10
SFO	1.71	2.46	3.38	4.43	6.68
SML	1.36	1.96	2.67	3.46	5.23

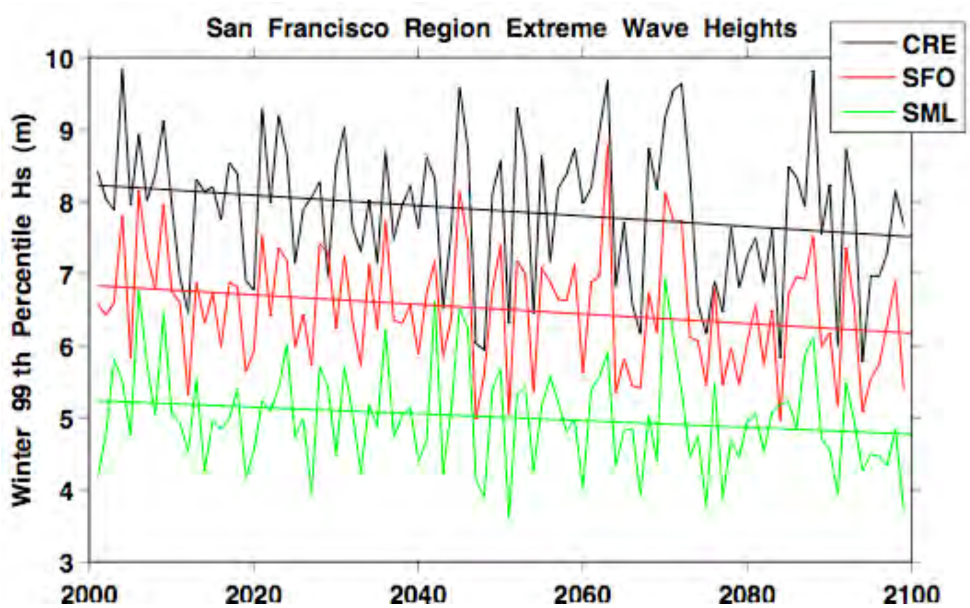


Figure 22. Winter (Nov.–Mar.) 99th percentiles of the WAVEWATCH III model significant wave height, *Hs*, projections forced by NCAR CCSM3 model winds. Offshore locations at northern California near Crescent City (CRE, 42°N 126°W; black), Central California near San Francisco (SFO, 38°N 124.5°W; red), and Southern California near San Miguel Island (SML, 34°N 121.5°W; green) are shown. Downward least squares trends steepen slightly going northward. These downward trends represent about a 9% decrease.

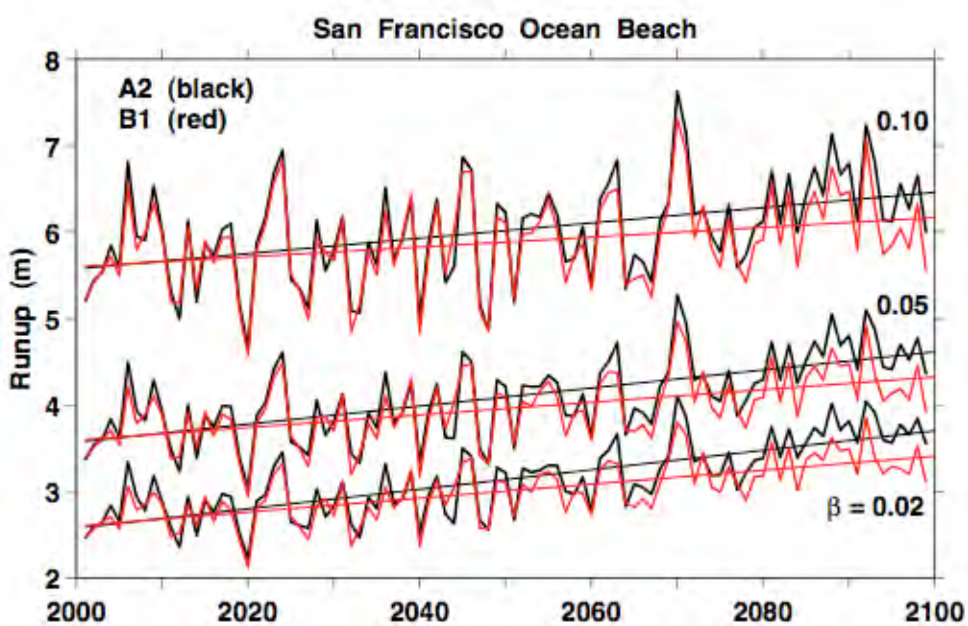


Figure 23. Projected mean winter (Nov.-Mar.) runup for the 98th percentile wave H_0 amplitudes for both low, B1 (red) and high, A2 (black) GHG emission scenario sea level projections. Low to moderate foreshore beach slopes, β, have upward trends with associated changes of 43%, 29%, and 16% for A2 and 31%, 20%, and 10% for B1 for β = 0.02, 0.05, 0.10, respectively.

11.0 Discussion

A set of simulations of possible twenty-first century climate in California were investigated. They are being used as drivers of impacts in a variety of sectors in the state, so it is important to understand the structure and changes that are contained in these simulations. The first-order surface climate variables, temperature, and precipitation—and some immediate implications for snowpacks and runoff in California—were the focus of the present study. The projections analyzed were based upon simulations by global climate models and associated statistically downscaled counterparts. Although regional models will be needed to distribute climate over the complex landscape of California, the first-order climate changes tend to derive from the large, indeed global, scale responses to increasing GHGs, even when considered at the California scale. These projections were based upon six global climate models forced by the SRES B1 and SRES A2 greenhouse gas emission scenarios. These projections are not "predictions," but are, based upon current understanding, plausible scenarios of climates that may occur in the twenty-first century.

Physical aspects of the climate scenarios in the present investigation are consistent with those described in previous studies and, in particular, those described in the previous 2005–2006 California climate scenarios assessment. This latest version reinforces, and in certain respects amplifies, the previous results, introducing climate simulations from four additional global climate models (GCMs).

Some clear results emerge from these simulations—these reiterate findings from many previous studies. Rising temperatures and rising sea levels are found in all of the projections, although the amount of change is still uncertain. The simulations also contain variability time scales from synoptic to multidecadal, but their general tendency is to rise quite steadily and rather linearly over the twenty-first century. As the differences in greenhouse gases accumulate from the higher (A2) versus the lower (B1) scenarios, the differences in warming mount, and the difference in global and regional (California) temperature also grows. From a method described by Rahmstorf (2007) using global air temperature to determine sea level rise, the simulations with higher warming result in greater rates of sea level rise. The range of sea level rise from the beginning to the end of the twenty-first century, as derived by the present analysis, range from about 0.5 meters (m) to 1.4 m, which is significantly larger than the estimates reported by a somewhat different methodology in the previous California Climate Change Scenarios study (Cayan et al. 2008). It is notable that until about the middle of the twenty-first century, different emissions scenarios do not too produce much difference in temperature, but thereafter the warming of the A2 scenario becomes increasingly distinct, and larger than that in the B1 scenario. As temperatures rise, so does sea level and so does wave runup along California beaches and the loss in spring snowpack in the Sierra Nevada. The incidence of years with very low spring snowpack and associated low soil moisture in late spring and early summer occur much more frequently. Also, as temperatures rise, there is a substantial increase in the occurrence, magnitude, and duration of certain kinds of extremes, such as heat waves and high sea level events. These short period events will have great impacts on California's natural and societal systems.

Other results from the simulations are more variable across models and across simulations using the same model, but contain some noteworthy tendencies that also have serious implications. Asymmetries in warming (warmer in summer than winter, and warmer in the interior than along the coast) that occur in some of the models would have important impacts for California's climate. The magnitude of these asymmetries can be fairly large, which underscores the importance of investigating climate changes in more detail than from simply investigating mean annual temperature and other average measures. The set of models' precipitation changes do not present the equivalent uniformity nor the relentless increases throughout the twenty-first century as do those for temperature, but there is a disquieting preponderance of simulations that become significantly drier during the twenty-first century. This drying appears to be linked to a rise in sea level pressure in the key storm track and wind wave and precipitation generating regions across the North Pacific and along Northern California and Oregon's Pacific coast. Seven of these simulations contain mid- and late-twenty-first century 30-year averages with precipitation deficits within -5% to -15% of our 1961–1990 climatology. It is useful to put these levels into historical perspective. Using the National Climatic Data Center Sacramento drainage divisional precipitation division record beginning 1895, a running tally of 30-year averages finds a high of +14.6% to a low of -2.7%, or if we change the standard climatology to a different 30-year period, a range of about -8.6% to +8.6%. Thus, the drying changes that are projected are rivaling or exceeding the largest observed multi-decadal deficits within the modern California historical experience. Should these drying trends materialize, they would present a challenge to sustaining many of California's societal structures and its ecosystems.

Consistent with the decline in precipitation described above, in some of the simulations the incidence of large coastal storms and the level of wind wave energy reaching much of the California coast decreases, at least marginally, over the twenty-first century. Thus, in addition to our future research to understand future impacts of warming, sea level rise, and drought, it is important to study event-scale process such as coastal erosion and flood events.

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13.0 Glossary

BCSD	bias correction and spatial downscaling
CA	constructed analogues
CaSLP	California sea level pressure index
CCSM	Community Climate System Model
CNRM	Centre National de Recherches Météorologiques
DJF	December, January, February
ENSO	El Niño/Southern Oscillation
GCM	global climate models
GFDL	Geophysical Fluids Dynamics Laboratory
GHG	greenhouse gas
GtC	gigatonnes of carbon
hPa	hectopascal
Hs	significant wave height
IPCC	Intergovernmental Panel on Climate Change
MAM	March, April, May
MSL	mean sea level
NDJFM	November–March
NCAR	National Center for Atmospheric Research

NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
PCM	Parallel Climate Model
ppmv	parts per million, volume
SLP	sea level pressure
SON	September, October, November
SRES	Special Report on Emissions Scenarios
SST	sea surface temperature
SWE	snow water equivalent
SWL	still water level
Tmax	maximum temperature
VIC	Variable Infiltration Capacity hydrological model

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

ASSUMPTIONS AS TO WATER RIGHTS SUPPLEMENT

TO

REPORT ON 1956 COOPERATIVE STUDY PROGRAM

WATER USE AND WATER RIGHTS ALONG SACRAMENTO RIVER AND IN SACRAMENTO-SAN JOAQUIN DELTA

BY

United States Department of the Interior, Bureau of Reclamation
Department of Water Resources, Division of Resources Planning
Sacramento River and Delta Water Association

GOODWIN J. KNIGHT
Governor

HARVEY O. BANKS
Director of Water Resources

APRIL 1958

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DIVISION OF RESOURCES PLANNING

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Isabel C. Messler . . . . Coordinator of Reports

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A. Frew, Vice Chairman, King City

John P. Bunker, Gustine

Richard Fuidge, Marysville

Everett L. Grubb, Elsinore

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Llano Seco Rancho, Chico

C. D. Bouton . . . . Vice-President
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L. D. Wood . . . . Woodland Farms, Inc., Woodland
Horace B. Wulff . . . . Reclamation District No. 108, Sacramento

Engineers

Prior to December 5, 1956, the Association retained the firm of Bleifuss, Greenwood and Hostetter, Consulting Engineers, and subsequent to January 1, 1957, the Association retained the firm of Bleifuss, Hostetter and Associates (Incorporated).

Supervisor of activities covered by this report

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assisted by

K. B. Mayo . . . . Civil Engineer

Subsequent to January 1, 1957, the Association also retained:

Gerald H. Jones . . . . Consulting Engineer

FOREWORD

This is the second of a series of supplements being published to present the basic supporting data to the "Report on 1956 Cooperative Study Program, Water Use and Water Rights Along Sacramento River and in Sacramento-San Joaquin Delta", dated March, 1957. The "Hydrology Supplement", dated March 1958, was the first.

This supplement presents data in support of Chapter III, "Assumed Water Rights", of the parent report. The cooperating engineering group wishes to reemphasize that the water right assumptions presented herein were made for study purposes only and that as such they might differ considerably from the rights that might be determined by a court of law.

Original copies of most supporting data and computations, except data pertaining to riparian lands, are filed in the office of the Department of Water Resources in Sacramento. Data pertaining to riparian lands are filed in the Regional Office of the United States Bureau of Reclamation in Sacramento.

I - INTRODUCTION

This supplement contains information on water rights and assumptions pertaining thereto that were made in the 1956 Cooperative Study Program conducted jointly by the United States Bureau of Reclamation, the California State Department of Water Resources, and the Sacramento River and Delta Water Association. Part I of this supplement contains general information and Parts II through VI are devoted to consideration of specific assumptions as to riparian, appropriative, and other water rights along the Sacramento River between Sacramento and Shasta Dam and in the Sacramento-San Joaquin Delta.

Values of the various rights considered in the 1956 Cooperative Study Program were assumed only for the irrigation months of April through October. An examination of available stream flow records showed that sufficient flows were available during the other months to satisfy all assumed local rights along the Sacramento River and in the Delta except possibly during critically dry years.

The study of water rights along the Sacramento River was limited to those on the main stem of that stream below Shasta Dam. No attempt was made to evaluate the effects of any vested or inchoate water rights that may exist above foothill gaging stations on the Sacramento River and on its tributaries. Neither was an attempt made to evaluate water rights to the flows of tributaries on the floor of the Sacramento Valley, except in the case of the American River, as described hereinafter. However, the assumptions of historical impairments of such tributary flows during the study period makes allowance for historical diversions and use of water under those rights both in the valley and in upstream areas.

Although water rights in the Feather River area were not considered specifically, the parent report and the hydrology supplement describe a study involving diversions from the Feather and Yuba Rivers and from Butte Creek, Butte Slough, Sutter By-Pass, and Sacramento Slough. Historical flows of the Sacramento River at Verona were adjusted for the differences between historical and 1954 net diversions to the extent that historical flows at foothill gaging stations and in some cases return flows from Feather River diversions were available to meet such differences. This adjustment was made because historical diversions from several of these Sacramento River tributaries had increased substantially during the period of study, and it was believed that 1954 diversions were more nearly representative of existing water rights than other historical diversions. Because of the negligible historical valley floor diversions from the Bear River, no adjustment of the flows of the Sacramento River at Verona were made for changes in diversions from that stream.

In most studies of the yields of assumed water rights, historical flows of the American River at Sacramento as impaired by historical diversions on the valley floor and upstream therefrom were utilized. However, in the studies designated A-2 Modified, and B-2 Modified, existing water rights along the American River below Fair Oaks were accounted for. The assumptions made in this regard are described in Parts II and III of this supplement.

Water rights along the Colusa Basin Drain, parts of which are called the Colusa Trough and Back Borrow Pit, were not considered specifically in the cooperative studies. However, they were considered indirectly through the method used to determine return flow factors for diversions made from the Sacramento River and the application of the factors to diversions under assumed water rights along the river. Water available in the drain during the irrigation season results from return flows from part of the diversions made from the right bank of the Sacramento River between Knights Landing and Mile 124 and from those diversions at Mile 154.8 which are made by Glenn-Colusa and Jacinto Irrigation Districts. As explained in the parent report and in the hydrology supplement, the return flow factors were based upon streamflow and diversion records for the years 1950 through 1954, and therefore reflect the average high level of diversions from the drain commensurate with the average high level of diversions from the Sacramento River during those years. In determining yields of assumed water rights along the Sacramento River, these return flow factors were applied to face values of assumed river diversion rights or to portions thereof depending upon the availability of modified natural flow. By this method of computation, diverters of drainage water from Colusa Basin Drain were assumed to divert an amount bearing the same ratio to their 1950-1954 mean diversions that the yield under the face values of all assumed rights along the Sacramento River bears to the 1950-1954 average diversions from the river. The assumed drain diversions would have been about 34 per cent greater than the 1950-1954 average level of such diversions if sufficient modified natural flow were available to meet the full face values of those assumed water rights on the river. On the other hand the assumed drain diversions would have been less if insufficient flow were available to fully satisfy those river rights. The various estimates of flows of the Sacramento River at Verona reflect such diversions in Colusa Basin.

No study was made of water rights along other tributaries of the Delta than the Sacramento River except in those cases where yields of state water right applications were considered. This exception is discussed hereinafter. Generally speaking, the hydrologic studies, in which historical inflow to the Delta from other sources than the Sacramento River was assumed, allowed for historical diversions and use of water under existing water rights on the tributaries.

Assumptions regarding salinity control in the Delta have been covered in detail in the parent report and quantities pertaining thereto are presented in Table 6, page D-26 of Volume I of that report.

Navigation requirements along the Sacramento River were not considered in the cooperative studies. Also no attempt was made to evaluate the effect of either the County of Origin Law or the Watershed Protection Act.

II - PHYSICALLY RIPARIAN LANDS

Physically riparian lands considered for study purposes were divided into three groups: those along the main stem of the Sacramento River between Sacramento and Redding, those in the Sacramento-San Joaquin Delta and those along the American River below Fair Oaks. Information and data pertaining to these three groups together with assumptions made for study purposes are presented herein.

Sacramento River

Estimates of the extent of physically riparian land along the Sacramento River between Sacramento and Redding were based upon extensive work by the Bureau of Reclamation which began about 1950. This work did not consider possible riparian lands between Redding and Shasta Dam because it was believed that the topography of such lands would be such as to preclude irrigation in the foreseeable future of any but several isolated parcels, and that water requirements for other possible uses would be negligible. The first stage of this work was the contracting with title companies for title reports on each parcel of land which abutted present and old channels of the river. Physically riparian land is defined for use herein as the smallest parcel of land physically abutting present or old channels of the Sacramento River that has been in continuous ownership since the date of patent. Title companies did not search for riparian backlands, i.e., lands which have been severed from physically riparian lands but which may have retained a riparian right to use of river water due to conveyance of such a right as part of the deed at time of severance.

A Bureau serial number was given each title report received from the title companies in order to insure individual identification by parcel as well as relative location along the river. From descriptions and information contained in a title report, the boundary of the smallest separate ownership was determined. This boundary, excluding exceptions and non-abutting lands, was then plotted to obtain an individual ownership map. When pertinent, additional information obtained from General Land Office Plats, Swamp and Overflow Survey Records, original patent and grant plats, and recorded subdivision plats was also used. All information and data were correlated to controlled aerial mosaics to insure a high degree of accuracy. The controlled aerial mosaics were compiled from photography flown in 1949 and 1951 and reproduced in two scales: one-inch to 800 feet and one-inch to 2,000 feet. The area bounded by the property description was as stated in the title report, or computed by metes and bounds, or was planimetered. This area determination was checked by different methods to insure accuracy. Lands of accretion or erosion were determined as the area which lay between the river meanderline as described in the title report and the water line as determined from the aerial mosaics. The area between these two lines was planimetered and classified as accreted or eroded land. The area bounded by the property description was then either increased by accreted area or reduced by the eroded area to obtain the assumed riparian area of a given holding or ownership. A map showing the assumed riparian area was then prepared for each holding.

The assumed riparian area of each holding was superimposed on a set of base maps covering the Sacramento River Service Area which had been prepared by the former California State Division of Water Resources at a scale of one to 2,000. These areas were shown in contrasting colors and labeled with their respective identification numbers in order to prevent omission and to insure completeness of coverage. Using this depiction as a basis, the backline of the assumed physically riparian lands was delineated as shown on Plate 2, Volume I of the "Report on 1956 Cooperative Study Program", dated March 1957. The 1208 individual assumed riparian holdings along the Sacramento River between Sacramento and Redding, including certain islands, and Federal, State, and County lands for which title reports were not obtained but which were assumed to be riparian, totaled 169,012 acres.

The backline of the assumed physically riparian areas was projected onto large-scale maps, reductions of which are contained in Bureau of Reclamation Factual Reports (a). The maps involved were those entitled, "Areas Susceptible of Irrigation" and "Place of Use Under Applications, Permits, and Licenses".

The "Area Susceptible of Irrigation" maps, on which the assumed riparian backline had been projected, were then compared with other Bureau Factual Report maps showing irrigation facilities, land classification, and crops and also with aerial mosaics and U.S.G.S. quadrangle sheets showing topography to determine riparian areas which would ultimately be susceptible of irrigation and require a water supply from the Sacramento River. These areas were depicted on the maps entitled, "Areas Susceptible of Irrigation". Riparian lands that were unsuitable for irrigation due to topography, land classification, or cultural relief such as roads, levees, etc., were excluded.

(a) See Annex A

The gross assumed riparian area of 169,012 acres was determined by planimetering or computation to include: (1) 13,493 acres of water demanding area between the river edge and the toe of the levee, i.e., land covered with native vegetation that has in the past and will continue to utilize river or seepage water, the water supply for which is automatically reflected in historical flow records and, therefore, need not be reserved for future use; (2) 4,181 acres of non-water demanding area between the river edge and the toe of the levee; (3) 1,443 acres non-water demanding area devoted to levee, including road; and (4) 39,988 acres of non-water demanding area which consists of cultural relief such as roads, canal right-of-way, building areas, and land classified as non agricultural due to topographic position or land classification. The total assumed physically riparian area requiring a water supply was determined to be 109,907 acres. The distribution of the 109,907 acres by river reach and by Bureau of Reclamation Factual Report area is presented in Table 1. This determination further revealed that of the 109,907 acres, about 57,000 acres were under existing irrigation systems diverting from the Sacramento River during the year in which the field survey of irrigation facilities was made between 1950 and 1954. However, the 57,000-acre figure was not used in the Cooperative Study Program. The foregoing work by the Bureau of Reclamation was spot checked under the 1956 Cooperative Study Program to confirm the validity of the methods used and the accuracy of the computations.

Water requirements of the 109,907 acres were estimated in the cooperative studies by assuming that 85 percent of the irrigable area will be irrigated in any one year with a unit duty of one second-foot per 70 acres.

This is equivalent to a diversion demand of approximately 82,000 acre-feet or 1,335 second-feet in the month of July. The assumed April through October irrigation demand of the riparian lands was estimated to be as shown in the following tabulation.

Month	Monthly demand in percent of seasonal (a)	Monthly demand in percent of max. month (b)	Riparian demand		
			c.f.s.	Total 1000 a.f. (c)	Total (rounded)
April	5	23		18.9	19
May	16	73		59.9	60
June	20	91		74.7	75
July	22	100	1335	82.1	82
Aug.	20	91		74.7	75
Sept.	12	55		45.2	45
Oct.	4	18		14.8	14
TOTALS				370.3	370

(a) Page 122 of State Bulletin No. 26, dated 1931. See Annex A.
(b) Monthly demand in percent of seasonal divided by maximum month figure (22).
(c) Monthly demand in percent of maximum month times July value of 82.1.

The monthly demand of the riparian lands by river reaches was estimated in a similar manner to be as shown in the following tabulation.

(In thousands of acre-feet)

Month	Sacramento to Knights Landing	Knights Landing to Redding	Sacramento to Redding
April	2.5	16.4	18.9
May	7.7	52.2	59.9
June	9.6	65.1	74.7
July	10.6	71.5	82.1
Aug.	9.6	65.1	74.7
Sept.	5.9	39.3	45.2
Oct.	1.9	12.9	14.8
TOTALS	47.8	322.5	370.3

Values shown in the preceding tabulation were rounded for use in the several studies of the "B" and "C" Series. The rounded values are shown in the following tabulation.

(In thousands of acre-feet)

Month	Sacramento to Knights Landing	Knights Landing to Redding	Sacramento to Redding
April	2	17	19
May	8	52	60
June	10	65	75
July	10	72	82
Aug.	10	65	75
Sept.	6	39	45
Oct.	2	12	14
TOTALS	48	322	370

As part of the study of physically riparian lands, the Bureau of Reclamation estimated the acreage of overlap between those lands and places of use under assumed appropriative rights. The area under application, permit or license lying within the riparian area as depicted on the aforementioned maps entitled "Place of Use Under Applications, Permits and Licenses" were planimetered except for certain places of use lying wholly within the riparian area. In these instances, acreages as stated in the factual reports were used. In this manner it was determined that of the 109,907 acres of land assumed to be riparian and to require a water supply, 31,620 acres were overlapped by places of use under applications, permits or licenses. The determinations of the extent of overlap were checked in the 1956 Cooperative Study Program to determine the reasonableness of the method of derivation and the accuracy of that work.

Water requirements for the overlap areas were estimated by assuming that such areas would retain the same duties of water as specified in the applications, permits, or licenses covering the areas. The overlap allowance was then deducted from the total allowance for the area covered by the appropriation. Estimates covering the acreages and water requirements of assumed riparian and appropriative overlap areas are presented by river reach in Table 2. Further information and data pertaining to overlap are given in Part III.

Sacramento-San Joaquin Delta

The assumption was made that all of the Delta Lowlands, shown on Plate 3 of Volume I of "Report of 1956 Cooperative Study Program", are riparian to channels of the Delta. Estimates of the water requirements of Delta Lowlands were based on data contained in the 1955 Trial Water Distribution Report (a). The method and results of an estimate of consumptive use requirements for the Delta Lowlands is given in Table 3. Modified consumptive use, shown in the last column of Table 3, is defined as consumptive use less effective or utilizable precipitation, including that carried over as soil moisture from earlier precipitation. Table 3 is in support of Column 5 of Table 6, Appendix D of Volume I of the parent report.

American River

Estimates of the extent of physically riparian land along the American River between Fair Oaks and its mouth were based on extensive work which was begun about 1950 by the Bureau of Reclamation. Basic data utilized and the evaluation thereof was similar to that described previously under the heading "Sacramento River". The total assumed physically

(a) See Annex A.

riparian area requiring a water supply was estimated to be about 4,720 acres of which about 1,200 acres have been and continue to be irrigated from wells.

Water requirements of the 4,720 acres were estimated by assuming that 80 percent of the area would be irrigated in any one year with a unit duty of one second-foot per 80 acres. This is equivalent to a diversion demand of 47 second-feet. However, the 1,200 acres irrigated from wells having an equivalent demand of 12 second-feet were assumed to be reflected in historical flow records at the H Street Bridge (American River at Sacramento). Therefore, an assumption was made that physically riparian lands for which a water supply should be reserved total 3,520 acres and would have a water requirement of 35 second-feet in the month of July. The April through October irrigation demand for these assumed riparian lands was estimated to be as shown in the following tabulation.

Month	Monthly demand in percent of seasonal (a)	Monthly demand in percent of max. month (b)	Riparian demand	
			c.f.s.	1000 a.f. (c)
April	5	23		1
May	16	73		2
June	20	91		2
July	22	100	35	2
Aug.	20	91		2
Sept.	12	55		1
Oct.	4	18		1
TOTAL				11

(a) Page 122 of State Bulletin No. 26, dated 1931. See Annex A.
(b) Monthly demand in percent of seasonal divided by maximum month figure.
(c) Monthly demand in percent of maximum month times July value of 2, rounded.

By coincidence, the requirement for assumed riparian lands is in the same order of magnitude as historical diversions from the American River between Fair Oaks and the mouth. Historical diversions in this reach, whether to riparian lands or not, have been relatively constant during the period of record. In July, 1927, they totalled 28 second-feet, and in July, 1954, they had increased to only 32 second-feet. Thus for purposes of studies A-2 Modified and B-2 Modified, in which it has been indicated consideration was given specifically to assumed American River water rights, it was convenient to assume that historical diversions from the American River below Fair Oaks were equivalent to riparian rights, and that the historical flows at the Sacramento gaging station could be considered equivalent to flows remaining after depletion by riparian rights.

III - APPROPRIATIVE WATER RIGHTS OF LOCAL WATER USERS

Appropriative water rights considered for study purposes were divided into three groups: (1) local rights along the main stem of the Sacramento River between Sacramento and Shasta Dam, (2) local rights in the Sacramento-San Joaquin Delta, and (3) local rights along the American River below Fair Oaks. Local appropriative water rights are defined as all appropriative rights other than those of the United States and the State of California. This part presents information and data pertaining to these three groups together with assumptions made for study purposes.

As presented by Tables 2 through 12 of Volume I of the parent report, certain minor variations will be noted in the monthly values of the assumed rights. These minor variations, during certain months, amounting to one or two units among the various studies, are due to application of monthly demand curve percentages to the maximum monthly demand and rounding to the nearest 1,000 acre-feet. The several studies of the "A" and "B" Series were made concurrently and the variations were not noted until the final results of the several studies were tabulated together.

Sacramento River

Information on appropriations initiated prior to December 19, 1914, the effective date of the Water Commission Act, were taken from various sources including State Water Utilization Reports and Bureau of Reclamation Factual Reports (a). Approximate face values of such postings

(a) See Annex A.

STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
DIVISION OF RESOURCES PLANNING

REPORT ON 1956 COOPERATIVE STUDY PROGRAM

WATER USE AND WATER RIGHTS ALONG SACRAMENTO RIVER AND IN SACRAMENTO-SAN JOAQUIN DELTA

By

United States Department of the Interior, Bureau of Reclamation
Department of Water Resources, Division of Resources Planning
Sacramento River and Delta Water Association

VOLUME I

GOODWIN J. KNIGHT
Governor

HARVEY O. BANKS
Director of Water Resources

MARCH 1957

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Sacramento, California
March 1, 1957

The Diverters of Water Along the Sacramento River
and in the Delta

Gentlemen:

The attached publication entitled "Report on 1956 Cooperative Study Program, Water Use and Water Rights Along Sacramento River and in Sacramento-San Joaquin Delta" is presented for your information and use. This report has been prepared through the cooperative effort of the United States Bureau of Reclamation, the California State Department of Water Resources, and the Sacramento River and Delta Water Association.

It is believed that the information contained in this report will be useful in negotiations aimed at reaching an agreement on water rights along the Sacramento River and in the Delta. The Bureau of Reclamation and the Department of Water Resources will make available the services of their respective staffs for consultation or for the provision of data and information as required prior to and during negotiations.

Very truly yours,

Clyde H. Spencer
Regional Director, Region 2
United States Bureau of Reclamation

Harvey O. Banks
Director of Water Resources
State of California

W. H. Baber
President
Sacramento River and Delta Water Association

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Horace B. Wulff . . . . . . Reclamation District No. 108, Sacramento

Engineers

Prior to December 5, 1956, the Association retained the firm of Bleifuss, Greenwood and Hostetter, Consulting Engineers, and subsequent to January 1, 1957, the Association retained the firm of Bleifuss, Hostetter and Associates (Incorporated).

Supervisor of activities covered by this report

L. A. Hostetter . . . . Civil Engineer

assisted by

K. B. Mayo . . . . Civil Engineer

Subsequent to January 1, 1957, the Association also retained:

Gerald H. Jones . . . . Consulting Engineer

Foreword

This report covering water use and water rights along the Sacramento River and in the Sacramento-San Joaquin Delta, presents the results of a cooperative effort among engineers representing the United States Bureau of Reclamation, the California State Department of Water Resources, and the Sacramento River and Delta Water Association. Each group has contributed substantially through the making of decisions as to technical details of the work and through actual performance of the comprehensive computations involved in these studies. These engineers have agreed upon the basic hydrology, water right assumptions used in the studies, and computation procedures by which the results were achieved. In many cases certain assumptions were suggested by one or more of the parties in order that the information desired by those parties might be obtained and the agreement by the remaining parties to participate in studies of such assumptions demonstrates their willingness to cooperate in the development of all pertinent facts.

The cooperating engineering group wishes to emphasize that water right assumptions made for study purposes may differ considerably from the rights as they might be determined by a court of law. The purpose of these assumptions was to demonstrate the effect of variation of water right criteria on the yields of the water rights and on amounts of supplemental water required to firm up the yields to meet the 1954 or 1955 level of diversions.

The purpose of this report is to present a summary of information believed to be essential for commencing negotiations that will be aimed at reaching an agreement on water rights along the Sacramento River and in the Delta. It is anticipated that there will be many questions left unanswered by this report. However, the findings presented herein will provide a basis for evaluating the relative importance of alternative assumptions as to water rights. Those that appear worthy of further study may be used in additional computations as the negotiations proceed.

Information in this report is presented in two volumes. Volume I contains brief descriptions of the methods and summaries of the findings of the various analyses under the 1956 Cooperative Study Program. Volume II contains 606 tables which present in detail the salient results of the studies.

Basic data and detailed explanations of assumptions and methods used in the studies described in this report, as well as results not shown herein, will be made available for limited distribution at a later date. Original copies of supporting data and computations are filed in the office of the Department of Water Resources in Sacramento.

I - INTRODUCTION

The question as to the relative rights of water users along the Sacramento River and in the Sacramento-San Joaquin Delta has long been a significant one in the affairs of this region. As early as 1920 there was indication of an inadequate water supply to satisfy all water requirements in summer months along the river. In that year the City of Antioch sought an injunction to prevent appropriators of water from the Sacramento River from reducing the flow past the City of Sacramento below 3,500 cubic feet per second so as to prevent impairment of the quality of water available for diversion by the City of Antioch. A temporary injunction was ordered by the superior court, but the order was reversed by the Supreme Court of the State of California. This was followed by the filing of a similar action by the Holland Land Company and other water users in the Delta against the Williams Irrigation District and other upstream interests. However, this case was never brought to trial.

The dry year of 1924 caused serious concern among water users in the area and led to the first Sacramento-San Joaquin River problems conference held in that year. This conference resulted in an agreement whereby the water users pledged to exercise their respective rights to the use of water in such a manner as to accomplish the maximum degree of water conservation. The Sacramento-San Joaquin Water Supervisor was appointed in the State Engineer's staff as a result of this conference in order that a record of the diversions and streamflow might be obtained and in order to promote maximum conservation of water. The water supervisor's staff was again called upon to assist in prevention of waste of water during the critical year of 1931. However, it was apparent that this method alone would not solve the problem with respect to the Delta and that a more positive limitation of upstream diversions in accordance with water right criteria would be necessary if the Delta were to get its share of the water supply.

Members of the staff of the State Engineer's office recognized as early as 1924 that the Sacramento River was over-appropriated at that time with respect to low flow conditions that occur in such critical years as 1924. It was also recognized that the only solution to this situation was the construction of projects which would store water in months of surplus runoff and release it for use during the summer months. This fact was an important consideration in the recommendation by the staff of the Division of Water Resources for implementation of The State Water Plan presented to the Legislature in 1931. In 1927, anticipating the presentation of this plan, the Department of Finance of the State of California filed upon unappropriated waters of the Sacramento River and other major tributaries of the Central Valley in order that water rights might be obtained to permit such storage of surplus water.

Although it was contemplated that the Central Valley Project, the initial unit of The State Water Plan, would be built by the State of California, it was found necessary to call upon the Federal Government for assistance in implementing this project. As a result, the United States Bureau of Reclamation commenced construction of the Central Valley Project in 1937. Applications for water rights that had been filed by the State Department of Finance in 1927 were assigned to the United States for project purposes. In addition the State Department of Finance filed supplemental applications required for Central Valley Project operation in 1938 and these filings were also assigned to the United States. Subsequently the Bureau of Reclamation made independent application for water rights for its Central Valley Project. The present status of these water right applications held by the Bureau of Reclamation is that they have been protested by various parties along the Sacramento River and in the Delta, and action granting permits is being withheld pending the outcome of current negotiations which this report is designed to assist.

Subsequent to 1944 the Bureau of Reclamation began to interview diverters along the Sacramento River with the view of attempting to settle the water rights problem. Results of the interviews and exchange of correspondence with individuals and with water user organizations appeared to indicate that such attempts would be fruitless. Subsequently it became the conviction of many persons involved in the water rights problem that litigation would be required in order to determine the various water right priorities and quantitative entitlements thereunder including the priority of the right of the United States to divert and store water for purposes of the Central Valley Project.

This fact was called to the attention of various leaders in the Congress and the State Legislature and the result was the so-called "Engle Committee Hearing."* At this hearing apprehension

*Hearings at Sacramento, California, before a Special Subcommittee on Irrigation and Reclamation of the Committee on Interior and Insular Affairs, House of Representatives, 82nd Congress, 1st Session, and a Joint Interim Committee on Water Problems of the California State Legislature on Central Valley Project, California, Water Rights, Supplies and Uses, October 29, 30, 31, 1951.

was expressed by representatives of the water users, by State Legislators, and by Congressmen in attendance as to the [illegible]-ties, expense and time that would be involved in a lawsuit of the magnitude required to settle the water right problems along the Sacramento River and in the Delta. It was the general conclusion of the hearing that a lawsuit should be avoided if at all possible and that a practical operating agreement should be obtained by negotiation.

Memorandum of Understanding

Subsequent to the Engle Committee Hearing, an exchange of correspondence took place between the Secretary of the Interior and the Governor of California to discuss the means by which the rights of various claimants to use of water along the Sacramento River and in the Delta might be settled by negotiation. As a result, the Governor arranged a series of conferences among the various claimants to the waters involved which led to the execution on July 7, 1952, of the "Memorandum of Understanding Relating to a General Approach to Negotiations for Settlement of Water Diversions from the Sacramento River and Sacramento-San Joaquin Delta with the Objective of Avoiding Litigation." The parties who signed this agreement were the Bureau of Reclamation, the Sacramento Valley Water Users Committee and the Division of Water Resources of the State of California. A copy of the Memorandum of Understanding is presented in Appendix A. Under this memorandum the parties did not guarantee a final agreement, but they did "agree to explore the full ramifications of the approach, with good faith and with hope of agreement".

Trial Distribution Agreements

Further negotiations among the water users, the Bureau of Reclamation, and the State Engineer, pursuant to the general approach set forth in the Memorandum of Understanding, resulted in the "Agreement for Trial Distribution of Water of the Sacramento River during 1954" and the "Sacramento River and Delta Trial Water Distribution Agreement for 1955." Copies of these agreements are presented in Appendixes B and C, respectively.

These agreements provided for a substantial increase in the scope of hydrographic measurements within the service area of the Sacramento River and Delta and for a number of analyses pertaining to data gathered during the Trial Distribution Program and to data available as a result of earlier hydrographic measurements by the State and by agencies of the Federal Government. Monthly reports of hydrographic data accumulated on a current basis were submitted by the State Engineer for the months of March through October in the years 1954 and 1955. In addition summary reports entitled "Sacramento River Trial Water Distribution 1954, Summary Report of Data" dated December 1954, and "Sacramento River and Sacramento-San Joaquin Delta Trial Water Distribution 1955, Summary Report of Data" dated January 1956 were prepared by the State Engineer. A report entitled "Sacramento River and Sacramento-San Joaquin Delta Trial Water Distribution 1954 Report of Analyses" dated April 1955 was also submitted as a result of the studies pursuant to the 1954 agreement.

There was a series of conferences among representatives of the water users, the Bureau of Reclamation, and the State Engineer, which took place in the fall of 1955 and the early part of 1956. The concensus of these conferences was that sufficient data on physical facts were available to permit final computations of the [illegible] information which the conferees agreed should form the basis for negotiation of a water rights settlement. They believed that such negotiations should take place as early as possible. Specifically, it was thought essential that the studies include consideration of water rights which had not been taken into account in earlier trial distribution studies. Consequently, on May 14, 1956, engineer representatives from the then State Engineer's office began the work program in cooperation with the consulting engineer for the Sacramento River and Delta Water Association. Following a meeting on May 23, 1956, the United States Bureau of Reclamation designated engineering personnel to participate in this program on its behalf. This work has been designated the "1956 Cooperative Study Program."

Scope of 1956 Cooperative Study Program

Data on stream flows, diversions and return flows available from records of the United States Geological Survey and of the water supervision activity of the Department of Water Resources were used as a basis for estimating various facts relating to water right claims along the Sacramento River and in the Sacramento-San Joaquin Delta. Estimates were made of modified natural flows that would have existed at the major gaging stations along the Sacramento River and at other points if diversions from the river had not been made, but if certain assumed diversions from tributaries to the river and to the Delta had been made. These estimates pertained to the months of April through October from 1924 through 1954. Determinations of lands physically riparian to the Sacramento River upstream from

Sacramento made by the Bureau of Reclamation on the basis of detailed title searches were spot-checked to satisfy the other participating engineering representatives that the methods used were reasonably accurate. These determinations included estimates of the net areas of riparian lands that have been irrigated historically and of those lands susceptible of irrigation by reason of their topography and soil quality. Information on appropriative water rights was tabulated from the files of the State Water Rights Board for those appropriations initiated subsequent to the Water Commission Act of 1914. Information on appropriations initiated prior to the effective date of that act was obtained and assumptions were made as to the portions of such water right claims that have been vested by reason of beneficial use. Estimations originally made by the Bureau of Reclamation of the extent of overlap between lands covered by appropriative water rights and physically riparian lands were spot-checked in order to confirm the method used and to permit an assumption of its accuracy. Studies had been made by the Bureau of Reclamation to determine areas irrigated historically that were neither physically riparian nor covered by appropriative water rights. These estimates were checked under the cooperative study program. Tabulations of assumed water rights for purposes of studies were made from the foregoing information on a monthly basis under assumed demand schedules. Estimates of modified natural flows and assumed entitlements under various water rights were used to estimate the yields of those rights, the deficiencies or differences between the yields and the 1954 or 1955 level of diversion, and requirements for supplemental water. Other information such as water remaining at various points in the

Sacramento River and in the Delta after satisfaction of [illegible] rights of various priority was also computed. Tabulat[illegible] [illegible] information estimated by the various studies are presented in Volume II of this report.

Information on water right yields, deficiencies, and supplemental water requirements were used by the engineers representing the Department of Water Resources to arrive at a number of possible alternative allocations of responsibility for payment for supplemental water among individual major entities. The division of responsibility for salinity control, which is essential to water utilization within the Delta and for exportation from the Delta, was also considered. Findings of these studies and discussion thereof are presented as Chapter VI of this report.

Not considered in this discussion of allocation of responsibility for payment are actual monetary considerations that might be involved by reason of the unit cost of supplemental water. Furthermore, no consideration is given in these studies to the capability of the Central Valley Project to meet the level of local diversions corresponding to the 1954 or 1955 condition which is assumed in the water deficiency and supplemental water requirement studies. However, it is generally considered that the project is capable of supplying at least that level of local water utilization provided appropriate deficiencies are taken in critically dry years such as 1924, 1931, and 1934.

Area of Investigation

The area covered by the 1956 Cooperative Study Program is shown on Plate 1, entitled "Location of Sacramento River-Delta Service Area." This area comprises roughly 1,600,000 acres, of which approximately 900,000 acres are north of the latitude of Sacramento and approximately 700,000 acres are in the Delta. In 1954, approximately 325,000 acres of that portion north of Sacramento were irrigated by direct diversion from the river, and in 1955 about 520,000 acres were irrigated in the Delta. Those are the years when detailed land use surveys were made by the State in the respective areas.

Within this general service area an extensive agricultural industry is located. There are many varieties of orchard, truck, and field crops, but north of Sacramento the major crop for many years has been rice. In 1954, the year of maximum planting of that crop, about 185,000 acres of the aforesaid area irrigated from the river was planted to rice alone. "Grain and hay" was the major crop group in the Delta in 1955, covering about 96,000 acres. Important urban areas within the Sacramento River service area are the Cities of Redding and Sacramento. The City of Red Bluff is also within this service area, and its industrial significance has taken on added stature in recent years.

The source of the major water supply available to this area is the snow deposited upon the mountains of the Sierra Nevada and Cascade Ranges during winter months. The melting snow in the course of the season provides the water supplies of the Sacramento, Feather, American, Mokelumne, and San Joaquin Rivers and other minor tributaries. However, the largest part of the runoff occurs in the winter, spring, and early summer months, and a relatively [illegible] amount occurs during late summer and early fall months [illegible] water is required for large irrigation demands. Shasta R[illegible] on the Sacramento River north of Redding, Lake Almanor on the Feather River, and Folsom Reservoir on the American River are the largest of the artificial storage units that have been provided to store winter and spring runoff in order that it may be available for summer irrigation and for generation of hydroelectric power.

Water requirements in the Sacramento River-Delta service area are of a number of different types, but the most important of these is the irrigation requirement. Diversions from the Sacramento River north of the City of Sacramento in 1954, the year of maximum diversions, amounted to approximately, 2,088,000 acre-feet during the seven-month irrigation season from April through October. Consumptive use in the Sacramento-San Joaquin Delta Lowlands from April through October was estimated on the basis of a 1955 land use survey to be approximately 1,059,000 acre-feet. Diversions to the Delta Uplands in 1955 totaled about 385,000 acre-feet during the same months. Neglecting the fact that one of the foregoing quantities is a consumptive use value and that the remainder are gross diversions, the water utilization totals approximately 3,532,000 acre-feet during the seven-month irrigation season. Also, over 1,000,000 acre-feet are presently being exported annually from the Delta through facilities of the Central Valley Project and of the City of Vallejo. Of the foregoing quantities, requirements for municipal and industrial use amount to in the order of only one per cent of the totals.

Other recognized requirements for water in the Sacramento River-Delta service area are the substantial requirements for salinity control necessary to prevent water in the channels of the Delta from being degraded by salt water from Suisun Bay, requirements for navigation to allow barge traffic between Knights Landing and the vicinity of Colusa, requirements for protection and propagation of fish life below the major reservoirs of the Central Valley Project and requirements for power generation incidental to the other primary water requirements.

II - MODIFIED NATURAL FLOWS

The first step in studies of the yields of assumed water rights along the Sacramento River and in the Delta was the estimation of modified natural flows at various points. Modified natural flows, as defined for use in these studies, comprise flows that would have existed without diversions from the Sacramento River but with historical impairment or with impairment at an assumed present level of diversions on tributaries either to the Sacramento River or to channels of the Delta. It was also defined to include those flows that would have existed without regulation by Shasta or Folsom Reservoirs.

Methods of Estimation

Modified natural flows of the Sacramento River were estimated for points (1) at Shasta Dam, (2) above the mouth of Colusa Basin Drain near Knights Landing, taken as the point of minimum flow during the irrigation season, and (3) above the mouth of the American River, assumed to be a point of inflow to the Delta. Additional modified natural flows available to the Delta were taken to be historical flows of all other Delta tributaries. A further allowance was included for return flow from diversions to the Delta Uplands at the 1955 level. Also estimated were quantities of modified natural flows of the Sacramento River at Red Bluff, Butte City, Colusa, Wilkins Slough, Knights Landing, and Verona, but these were not used in studies described hereinafter. Values of modified natural flows were estimated or taken from records for the period April through October of each year from 1924 through 1954.

The months of November through March were excluded from the study period because sufficient flows were found to exist during those months to satisfy all assumed local rights along the Sacramento River and in the Delta except during critically dry years. Local water rights are defined as all rights other than those of the United States and those of the State of California.

Estimations of modified natural flows at gaging stations and at other points along the Sacramento River were based upon records of streamflow, diversions, and return flows maintained by the United States Geological Survey and by the Department of Water Resources and its predecessors under the Sacramento-San Joaquin Water Supervision activity. Historical streamflow quantities for months in which no actual records of flow were available were estimated by correlation with flows of the river and/or tributary flows by standard methods. Next, the historical diversions as recorded in the reports of the Sacramento-San Joaquin Water Supervision were added to the recorded or estimated historical streamflows. Then the return flows tributary to the river above each of the points considered were estimated by application of return flow factors to the historical diversions within the appropriate reaches of the river. Finally, such return flows were subtracted from historical flows. Return flow factors were taken as the ratios between average measured accretions to the river, other than accretions from natural streamflows, and the corresponding average monthly diversions within the same month for the period from 1950 through 1954. However, for the dry years of 1924 and 1931 special return flow factors were computed to reflect conditions under deficient water supplies in those seasons.

The second adjustment to measured or estimated historical flows of the Sacramento River at the aforesaid points involved an adjustment for the operation of Shasta Reservoir. This adjustment was made for the years 1943 through 1954. The amounts of increase or decrease in flow were estimated on the basis of the historical monthly changes in Shasta Reservoir storage as corrected for evaporation and precipitation. These data were obtained from the monthly reports of operation for Shasta Reservoir as published by the United States Bureau of Reclamation.

The final adjustment to measured or estimated historical flows of the Sacramento River was to reflect the effect of the 1954 level of diversions in the Feather and Yuba River service areas and in the Butte Creek, Butte Slough and Sutter By-Pass areas. Flows that historically entered the Sacramento River through the Butte Slough outflow gates, in Sacramento Slough and in the Feather River at Nicolaus were adjusted for the differences between historical and 1954 net diversions, to the extent that historical flows were available to meet such differences. Net diversions were taken as the differences between gross diversions and estimated return flows therefrom. Return flow estimates were based upon return flow factors which were computed by a method similar to that described for the Sacramento River.

Modified natural flows of the American River and other tributaries to the Delta were taken as historical flows of those tributaries. Changes in utilization of waters of those tributaries during the study period from 1924 through 1954 has affected water supplies available to the Delta to some extent. However, the amounts are relatively small, and are believed to be negligible for purposes of the present studies as compared to magnitudes of modified natural flows of the Sacramento River and to possible errors in estimation of such natural flows.

Tables in Volume II indicate estimated quantities of modified natural flows of the Sacramento River at Shasta Dam, at a point above the mouth of Colusa Basin Drain, and at a point above the mouth of the American River, as well as historical flows of the American River at Sacramento and of other Delta tributaries. This information covers the months of April through October from 1924 through 1954. These quantities indicate amounts of water that were initially available to meet assumed diversion rights.

III - ASSUMED WATER RIGHTS

For purposes of the studies described hereinafter, it was necessary to make assumptions as to the water rights of diverters along the Sacramento River and in the Delta. These assumptions pertained to the extent of so-called physically riparian lands, to the extent of appropriative water rights initiated both before and after the Water Commission Act of 1914, and to the extent of lands with a historical water use but not physically riparian and having no apparent claim of water right by virtue of a formal filing with the State. In addition, salinity control requirements and water right status thereof were assumed. It is recognized that the assumed rights may differ from rights that would be determined by the courts through legal processes. For this reason, it is to be emphasized that no claim is made by the parties to the 1956 Cooperative Study Program that these assumptions define the relative water rights involved. Nevertheless, it is believed essential that estimates of these rights be made in order that approximations may be developed of the extent to which such rights may be satisfied from the modified natural flows available.

Information in this chapter is discussed under the headings "Physically Riparian Lands," "Appropriative Water Rights," "Overlap between Physically Riparian Lands and Places of Use under Appropriative Rights," "Other Water Rights," and "Salinity Control."

Physically Riparian Lands

Decisions of the courts in California, including those confirming the 1928 constitutional amendment, have consistently upheld the right of owners of riparian land to divert from the adjacent streams those quantities of water reasonably required on such lands. Along the Sacramento River these riparian rights under State law are believed to be prior to any rights acquired by reason of appropriation.

Estimates of the extent of physically riparian land along the Sacramento River between Redding and Sacramento were based upon extensive work by the Bureau of Reclamation which began about 1950. This work consisted of contracting with title companies for title reports on each parcel of land believed to be physically riparian to the Sacramento River. These reports indicated the smallest parcels of land abutting the river that have been in continuous ownership since the date of patent, thereby meeting the requirements for riparian status. Upon receipt of the title reports, the Bureau of Reclamation delineated the boundaries of such smallest contiguous parcels on maps, using aerial photographs to assist in plotting. The boundaries of the physically riparian parcels were then projected upon maps showing the extent of irrigation systems in existence at the time of study and showing the lands within the boundaries that were considered to be irrigable.

The foregoing work by the Bureau of Reclamation was spot-checked under the 1956 Cooperative Study Program to confirm the validity of the methods used and the accuracy of the computations. This examination indicated that the basic studies had been carefully performed, and they were taken as acceptable for use in the cooperative studies. Plate 2, entitled "Assumed Physically Riparian Lands and Boundaries of Major Entities North of Sacramento", indicates the backline of physically riparian lands along the Sacramento River between Redding and Sacramento, as determined by the method described heretofore.

The aforesaid determination indicated that there are approximately 169,000 acres of physically riparian land along the Sacramento River between Redding and Sacramento, of which approximately 110,000 acres are either under existing water distribution systems or are irrigable areas not now served with water. Water requirements of these lands were estimated by assuming that 85 per cent of the irrigable area will be irrigated in any one year with a unit duty of one second-foot per 70 acres. This is equivalent to a diversion demand of approximately 82,000 acre-feet or 1,335 second-feet in the month of maximum demand.

It was assumed that all of the Delta Lowlands are riparian to channels of the Delta. The boundaries of this area are shown on Plate 3, entitled "Boundaries of Major Entities in and Subdivisions of Sacramento-San Joaquin Delta". Furthermore, in certain studies described hereinafter, it was assumed that such lands are riparian with respect to waters of the Sacramento River and to other tributary streams of the Delta. No search of individual title records, such as that described for the Sacramento River north of Sacramento, were made for this Delta Lowlands area. The boundary of the Delta Lowlands is the same as that shown on Plate 3 in the report entitled "Sacramento River and Sacramento-San Joaquin Delta Trial Water Distribution 1955 Summary Report of Data," dated January 1956. The gross area of the Delta Lowlands is approximately 469,000 acres, of which 386,000 acres were [illegible] field as agricultural in a land use survey made by the State. Water requirements for this area were estimated on the basis [illegible] areas of land use given in Table 18 of the aforesaid report and [illegible] unit consumptive use of water factors given in Table 20 of that report. Total amounts of consumptive use computed in that manner were reduced to account for the estimated portion of the total consumptive use that may be supplied by precipitation to determine the net demand upon Delta channels. These estimates considered both precipitation during the month in question and that carried over as soil moisture from earlier precipitation. The net consumptive use in the Delta Lowlands in the months of maximum demand was estimated to be 241,000 acre-feet or an average of 3,919 second-feet.

In the determination of physically riparian lands along the Sacramento River above Sacramento and in the Delta Lowlands, no study was made of the possible modification of the rights of such lands by reason of adverse use developing into a prescriptive right. It is believed that such studies would be in the nature of judicial determinations and are, therefore, beyond the scope of an engineering study of the type described in this report.

Table 1 of Appendix D summarizes the water requirements of assumed physically riparian lands north of Sacramento and in the Delta Lowlands. It includes estimates of water requirements of riparian land within the service areas of major entities above Sacramento, the boundaries of which are among those delineated on Plate 2.

Appropriative Water Rights

Appropriative water rights considered in the 1956 Cooperative Study Program include those initiated by posting and those initiated by filing pursuant to the Water Commission Act of 1914.

Information on appropriations initiated prior to December 19, 1914, the effective date of the Water Commission Act, were taken from various sources including the factual reports by the Bureau of Reclamation, covering the Sacramento River Service Area Investigations, and Bulletin No. 21 of the State Division of Water Resources entitled, "Report on Irrigation Districts in California" published in 1929. The right of Anderson-Cottonwood Irrigation District was assumed to be 400 second-feet as indicated in a certificate issued by the Water Commission which confirmed their 1914 posting. The amount of the appropriative right for Glenn-Colusa and Jacinto Irrigation Districts was assumed to be 2,400 second-feet or the capacity of the main canal.

In studies of the rights of individual water users described in the next chapter, pre-1914 posting information was also obtained for several of the major diverters in the Delta Uplands. The assumed amounts of vested rights under these postings were taken as the maximum historical monthly average diversions thereunder.

Appropriations initiated under the Water Commission Act of 1914 were evaluated from the information given in the application, permit, or license on file with the State Water Rights

Board. The assumed amounts of such rights were taken as the face values given in those documents without modification for absence of development or for loss of right by reason of non-use. Applications for water rights were considered and tabulated if the date of application was December 31, 1954, or earlier. The values of State Department of Finance filings made in 1927 and subsequently, including those assigned to the United States, were also taken from the files of the State Water Rights Board.

Appropriative rights in the Delta Uplands were not studied in detail for the first two series of studies described in the following chapter. By inspection of records of diversions in the Delta Uplands in 1955, it was found that approximately 70 percent of such diversions were made under appropriations antedating the State filings of 1927. It was also found that the remaining portion,or approximately 30 percent of the 1955 diversions, were made under water right applications subsequent to 1938, the date of the second group of State filings assigned to the United States for the Central Valley Project. In later studies of individual water users in the Delta Uplands, application, permit, and license data were taken as the bases for appropriative water rights initiated subsequent to 1914.

Table 2 of Appendix D presents assumed values of vested appropriative rights under postings and Table 3 of that appendix presents a chronological tabulation of the assumed appropriative water rights initiated between 1914 and 1954. Those tables show the names of only those major appropriators assumed to have pre-1927 water rights which were studied individually as described in the next chapter. The present holders of other applications, permits, or licenses were not determined. The boundaries of the properties and districts to which the major pre-1927 appropriative water rights pertain are among those indicated on Plate 2. Table 5 of Appendix D presents information on the various State filings considered in this report.

Overlap Between Physically Riparian Lands and Places of Use Under Appropriative Rights

As indicated on Plate 2, the boundaries of certain of the entities that have claimed appropriative water rights overlap the physically riparian lands also shown on that plate. Therefore it was necessary to eliminate the duplication of coverage by appropriative water right service areas and physically riparian lands.

The Bureau of Reclamation had made a study of the extent of the overlap between lands covered by these two different categories of water rights. This study involved plotting the respective areas on a set of maps similar to the maps shown as Plate 2 of this report, but at a larger scale. The determinations of the extent of overlap were checked in the 1956 Cooperative Study Program to determine the reasonableness of the method of derivation and the accuracy of that work.

Water requirements for the overlap areas were estimated by assuming that such areas would retain the same duties of water as specified in the applications, permits, or licenses covering the areas. The overlap allowance was then deducted from the total allowance for the area covered by the appropriation.

Table 3 of Appendix D also presents the estimated requirements for overlap areas, and the net assumed appropriative water right entitlements after correction for overlap. These assumed net rights total 412,000 acre-feet or an average of 6,700 second-feet during the month of maximum demand.

Other Water Rights

It has been mentioned heretofore that records of water use on lands along the Sacramento River between Redding and Sacramento indicate that there are parcels of land which are not covered by assumed riparian or appropriative rights but which, nevertheless, have been irrigated from the river over long periods of time and were irrigated in 1954. Whatever the basis or claim of right may be for these lands, it was assumed in the 1956 Cooperative Study Program that such lands do have a right to divert water. Further, it was assumed that such rights have a priority in accordance with the approximate date on which the use of water was initiated as shown by the historical records. The work of determining such "other" rights was originally done by the Bureau of Reclamation and was checked in the cooperative studies.

Table 4 of Appendix D indicates the quantities of assumed "other" water rights along the Sacramento River between Redding and Sacramento. These assumed rights total 16,780 acre-feet or an average of 273 second-feet during the month of maximum demand.

Salinity Control

It has been indicated heretofore that use of water within the Delta Uplands and Lowlands and diversion of water from the Delta through facilities of the Central Valley Project and diversion works of the City of Vallejo require salinity control in order to prevent harmful degradation of the quality of water in Delta channels. Under natural conditions such salinity control was probably provided in most years by surplus outflow of fresh water from the large tidal swamp which then comprised the area at the confluence of the Sacramento and San Joaquin Rivers, which we now call the Delta. Gradually, as reclamation of the Delta and development of the use of water took place upstream, the amount of water available for natural salinity control decreased until in 1924, 1931, and other dry years, the encroachment of saline waters reached serious proportions. During the late summers of those years irrigation in a large part of the Delta was made impossible by the degree of concentration of salinity in the waters of the channels.

One of the functions of the Central Valley Project is to regulate surplus runoff from the Sacramento and American Rivers so as to provide sufficient outflow from the Delta to repel salinity. Since actual operation of Shasta Reservoir commenced in 1944, incursion of sea water to the extent that took place in the former years of uncontrolled runoff has been largely prevented. However, in some recent years concentrations of chlorides have exceeded 1,000 parts per million in the channels adjoining some of the westernmost Delta islands and have, therefore, exceeded the standard that was adopted by the State as a minimum for use of the water for agricultural and other purposes.

Bulletin No. 27 of the State Division of Water Resources entitled "Variation and Control of Salinity in Sacramento-San Joaquin Delta and Upper San Francisco Bay" and published in 1931, presented an analysis of the historical records of saline water incursion and recommended that salinity control outflows from the Delta be maintained at a minimum constant flow value of 3,300 second-feet. It was estimated in that bulletin that such outflows would prevent cursion of chloride ion concentrations of 1,000 parts per beyond points in the San Joaquin and Sacramento Rivers approx six-tenths of a mile west of Antioch.

In certain of the studies described in this report, the assumption was made that salinity control flows of 3,300 second-feet had, in effect, a status as a riparian water right associated with the assumed riparian rights of the Delta Lowlands since such salinity control outflows would be required to make such riparian diversions possible. However, there is some question as to the economic value of providing a full 3,300 second-feet outflow for salinity control, which would be required to protect diverters in the westernmost part of the Delta. It has been suggested by some investigators that the amount of water allowed to waste to Suisun Bay for control of salinity should be reduced below the amount of 3,300 second-feet and that direct overland service of fresh water be provided to those westernmost areas that would be unable to divert directly from the channels with such lesser amounts of salinity control. Therefore, certain of the studies described in this report were based upon the assumption that salinity control flows having a riparian water right status would be 2,000 second-feet instead of 3,300 second-feet. In addition one of the cooperative studies was based upon the assumption that salinity control requirements of 3,300 second-feet would have a water right priority subsequent to 1954, following the priority dates of all appropriative rights assumed for the studies. This assumption was made for illustrative purposes only.

IV - YIELDS OF ASSUMED WATER RIGHTS

On the basis of estimated modified natural flows and assumed water rights described in the preceding chapters, estimates were made of the yields of assumed water rights under several combinations of assumptions. Three different general groups of studies were made in this connection. The so-called "A" and "B" Series of studies considered large groups of local water right claimants separated by the priority dates in 1927 and 1938 pertaining to the State filings which were assigned to the United States for construction of the Central Valley Project. In these series, the yields of assumed local rights and of the 1927 and 1938 filings assigned to the United States were estimated. In addition, one study under each series produced estimates of yields of those State filings still retained under the jurisdiction of the State Department of Water Resources. The "C" Series of studies considered the yieldsof individual major appropriative water right claims of 25 major entities along the Sacramento River above Sacramento and in the Delta Uplands, as well as the yield of assumed riparian rights of the Delta Lowlands and of other water users as a group. As indicated heretofore, assumptions as to the amounts and water right status of requirements for salinity control were made for the various studies.

The general procedure for making these studies involved deducting gross diversions from amounts of modified natural flows available in various reaches and crediting amounts of return flows from such diversions to permit additional use of water. Further details with respect to each of the studies is presented in the following sections pertaining specifically to each of the study series.

"A" Series

For purposes of the "A" Series of studies, assumed water rights were divided into five groups in order of priority as follows: (1) riparian and pre-1927 appropriative and other rights of local water users, (2) 1927 State filings, (3) appropriative and other rights of local water users with priority between 1927 and 1938, (4) 1938 State filings, and (5) post-1938 appropriative and other rights of local water users. These water rights were further subdivided geographically into two reaches above Sacramento, namely, Redding to Knights Landing and Knights Landing to Sacramento. The pre-1927 rights assumed for the Delta Lowlands and Delta Uplands were taken as one geographical group.

The general procedure for determining yields which was followed in each study of the "A" Series involved the assumption that local water rights within each priority group would be satisfied in geographical order proceeding downstream from Redding. Modified natural flows in the reach Redding to Knights Landing were assumed to be available first for satisfaction of all rights of the first priority group within that reach. Return flows from diversions under such rights were estimated by using return flow factors previously described in the chapter on modified natural flows. Such return flows were assumed to be available for one level of rediversion if needed to meet the rights of the first priority group. Return flows from such rediversions were assumed to be unavailable for further diversions in the reach. It was believed that such return flows would occur in a manner that would make a second rediversion in the same reach impracticable. The sum of any modified natural flows remaining after the aforesaid diversions and return flows from upstream diversions was assumed to be available to satisfy water rights of the first priority group in the second reach between Knights Landing and Sacramento. The extent of satisfaction of the assumed water rights for the second reach was then determined in the same manner as in the first reach. Finally, the assumed water rights of the first priority group in the Delta, including the requirements for salinity control at 3,300 second-feet, were assumed to be satisfied to the extent possible from any residual modified natural flows and from return flows from diversions in the upper reaches.

Yields of assumed water rights in the second priority group, the 1927 State filings, were estimated next. They were taken as being satisfied to the extent possible from any water available after satisfaction of all assumed water rights in the first priority group. At this point, the differences between the three studies of the "A" series are to be found in part. For Study A-1, only the 1927 State filings on the Sacramento River at Shasta Dam, which were assigned to the United States, were considered. For that study, the portion of the demand under those filings for diversion into the Delta-Mendota Canal was assumed to comprise a constant diversion rate in all months studied, amounting to 4,600 second-feet.

Study A-2 was the same as Study A-1, except that the diversions from the Delta into the Delta-Mendota Canal under 1927 State filings were assumed to follow an irrigation demand schedule with a peak in July and with lesser amounts in other months instead of the constant rate of demand assumed for Study A-1. Study A-2 (Modified) differed from the other two studies of the "A" Series in that assumed amounts of 1927 State filings on the Feather, Yuba, Bear, American, Middle Fork of the Stanislaus, and San Joaquin Rivers, in addition to State filings of 1927 priority at Shasta Dam assigned to the United States, were assumed to be a demand upon waters remaining in those streams after satisfaction of assumed pre-1927 rights of local water users. This had the effect of reducing quantities of water available to the Bureau of Reclamation.

In all of the studies described pertaining to computation of the yields of water rights of the second or 1927 priority group, it was assumed that direct diversion rights would be satisfied first and that storage rights would be satisfied second. In Study A-2 (Modified) assumed State filings on the Stanislaus and San Joaquin Rivers were taken as being satisfied before any other 1927 rights. To the extent that flows were available at or near points referred to in those filings, historical flows of the San Joaquin River at Vernalis were reduced to meet the filing quantities. The portions of such reductions that in turn would increase deficiencies in yields of pre-1927 Delta rights were made up from surplus waters of the Sacramento River and its tributaries in the Sacramento Valley. Remaining waters available for State filings on the Sacramento, Feather, Yuba, Bear, and American Rivers were assumed to be used to satisfy those filings in proportion to historical flows at the points referred to in the filings. 1934 State filings on the American River were considered along with 1927 filings because there were no assumed local rights having priorities between those years.

Yields of assumed appropriative and other water rights of local water users in the third group, having priorities between 1927 and 1938, were estimated next. They were taken as being satisfied insofar as possible from water still available after satisfaction of the pre-1927 water rights of local water users and 1927 State filings. The procedure was the same as that followed in determining yields of assumed pre-1927 water rights, in which assumed rights were satisfied in geographical order beginning with the highest reach on the river, proceeding downstream, and utilizing return flows.

Following this, yields of assumed water rights in the fourth priority group, the 1938 State filings were determined. The 1938 State filings in the Delta were considerably larger than the capacities of diversion works of the Central Valley Project. Consequently those filings were assumed to be utilized only to the extent necessary to complete the satisfaction of demands for the Delta-Mendota and Contra Costa Canals not met under the assumed 1927-priority rights at Shasta Dam.

As in the case of the assumed 1927-priority State filings, there are differences in assumptions as to amounts of the 1938 filings as among the three studies of the "A" Series. In Study A-2, amounts of water required to make up the differences between

Delta-Mendota Canal diversions under an irrigation demand ... diversions at a constant rate of 4,600 second-feet were ... flows available in the Delta. This caused yields of assumed rights of the United States to be larger under Study A-2 than Study A-1. In addition, under the 1938 State filings assigned the United States, it was assumed for Studies A-2 and A-2 (Modified) that the demand for municipal and industrial purposes would be 1,000 second-feet instead of the figure of 100 second-feet assumed for Study A-1. The basis for the 1,000 second-foot value is Application No. 9363 listed in Table 5 of Appendix D.

The final step of the "A" Series studies was to determine the yields of the fifth group, assumed local rights having post-1938 priorities. These local water rights were assumed to be satisfied by waters remaining after satisfaction of 1938 State filings in geographical order starting with the highest reach on the river, proceeding downstream, and utilizing return flows.

Tables 1 through 12 present average monthly values of yields of assumed rights of local water users and of the Bureau of Reclamation under the "A" Series for the years 1924 through 1954. Those tables also show assumed water rights for the respective studies to permit ready comparison with corresponding values of average yield. Included in Volume II are tables showing the estimated yields of the various water right priority groups for each month of the 31-year period from 1924 through 1954. Plate 4, entitled "Assumed Water Rights, Yields, and Supplemental Water Requirements 1924-1954 Under Study A-2" includes a graphical representation of the yields of the assumed rights of all local water users, those of the Bureau of Reclamation, and that for salinity control.

"B" Series

The computation procedures to estimate water right yields under the "B" Series were similar to those described for the "A" Series with one principal exception. In the "B" Series all of the assumed riparian rights, both above Sacramento and in the Delta Lowlands, and the salinity control requirement, when it was assumed to have a riparian water right status, were taken as being satisfied before any appropriative water rights. After such riparian rights were satisfied to the extent of available water supplies, the remaining flows at points along the Sacramento River and in the Delta were assumed to be available to satisfy appropriative water rights. Yields of assumed appropriative rights of local water users within each priority group were estimated by assuming that rights in the uppermost reach of the river between Redding and Knights Landing would be satisfied first, followed in succession by rights in the reach between Knights Landing and Sacramento and by rights in the Delta Uplands. Return flows from diversions within each reach were treated in the same manner as that described for the "A" Series of studies in order to compute the total amount of water available for diversion in each reach.

For Studies B-1, B-2, and B-2 (Modified), the water right assumptions and computation procedures pertaining to rights under State filings assigned to the United States and State filings remaining unassigned were the same as assumptions for the three studies of the "A" Series, respectively. Water right assumptions for Study B-3 followed assumptions for Study B-2 with the exception that salinity control outflows from the Delta assumed to have a riparian water right status were taken at 2,000 second-feet instead of 3,300 second-feet. Assumptions for Study B-4 were the same as those for Study B-2 except that a salinity control requirement of 3,300 second-feet was assumed to have a water right priority subsequent to 1954 following all appropriative rights considered in the studies. As indicated heretofore, this assumption was made for illustrative purposes only.

Average monthly values of water-right yields for the period 1924 through 1954 for the studies of the "B" Series are also summarized in Tables 1 through 12 of this report. Included in Volume II are tables showing the yields of the various water right groups for each month of the 31-year period 1924 through 1954. Plates 5, 6, and 7, under the general title "Assumed Water Rights, Yields, and Supplemental Water Requirements 1924-1954", show graphically the yields of the various water rights groups under Studies B-2, B-3, and B-4, respectively.

<u>Comparison of Average Yields of Water Rights Under "A" and "B" Series</u>

The studies of the "A" and "B" Series demonstrate the range of yields that result from those variations of water right assumptions used in the studies. As indicated heretofore, comparisons of the yields are presented in Tables 1 through 12. Such comparisons are also shown graphically on Plate 8, entitled "31-Year Average Yields of Assumed Rights of Bureau of Reclamation and Local Water Users". Plate 9, entitled "31-Year Average Difference or Deficiencies Between the Yields of All Assumed Rights and the 1954 Level of Diversions and Supplemental Water Requirements by Local Water Users", presents diagrammatically a comparison of information pertaining to assumed water rights and yields thereof fo... y of the "A" and "B" Series.

A number of conclusions may be drawn from the ... of the various studies of the "A" and "B" Series presen... aforesaid tables and plates. Some of the more important ... conclusions are as follows:

1. The total-irrigation-season yields of the assum... Delta Lowlands rights are greater in the "B" Se...es than in the "A" Series because in the "B" Series those rights are generally satisfied before any appropriative water rights. Conversely, yields of assumed rights along the Sacramento River ... above Sacramento are greater in the "A" Series than in the "B" Series.

2. The yields of all assumed local water rights u...r the first three studies of the "A" Series do n... differ greatly because of the large percentage ... such local water rights assumed to have a pre-...7 water right status and because variations in as...mp-tions affected only water rights of 1927 and ...r priorities. The same is true of the first thr... studies of the "B" Series.

3. The yields of assumed 1927-38 and post-1938 ri...s of local water users are small in the months o... July through October.

4. The total yields of assumed rights of the Unit... States under Studies A-2 and B-2 are greater th...

yields under Studies A-1 and B-1, respectively, because greater water demands for municipal and industrial purposes under the 1938 State filings were assumed in Studies A-2 and B-2.

5. The total yields of assumed water rights of the United States are lower under Studies A-2 (Modified) and B-2 (Modified) than under A-2 and B-2, respectively, because portions of the available water supplies after satisfaction of the assumed pre-1927 rights are required to supply the assumed values of unassigned State filings.

6. The total yields of assumed rights for both local water users and the United States are greater in Study B-3 than in Study B-2, both of which are based largely on the same water right assumptions, because in Study B-3 salinity control requirements having a riparian status were assumed to be 2,000 second-feet instead of 3,300 second-feet, thereby increasing amounts of water available for appropriators.

7. Similarly, the total yields of assumed rights of local water users and of the United States are greater in Study B-4 than in the Study B-3 because of the assumption for Study B-4 that all salinity control requirements have a late priority status.

"C" Series

As previously discussed, the "A" and "B" Series considered only broad priority groups which were separated by the dates in 1927 and 1938 when State filings were made which were later assigned in part to the United States. An essential objective of the 1956 Cooperative Study Program is the derivation of methods of allocation of responsibility for purchase of supplemental water among the individual water users so that each might pay for the water required to firm up the estimated yield of his right. Studies of the "C" Series were designed specifically to provide parameter values for use in allocating responsibility for supplemental water.

The "C" Series produced estimates of the yields of assumed water rights of the Delta Lowlands and of assumed riparian and appropriative water rights of 26 major water diverters along the Sacramento River above Sacramento and in the Delta Uplands. The 26 water diverters were selected on the basis of their having large assumed riparian or appropriative water rights of pre-1927 priority. One of these entities was assumed to base its water right claim entirely upon its riparian status and the remaining 25 were assumed to base their claims upon appropriation alone or upon appropriation plus possession of riparian land. Studies of the "C" Series also determined the collective yields of water rights of other water users not considered individually.

Two "C" Series studies were made. Study C-1 was based upon the first phase of Study B-1 up to the point of determining the yield of assumed riparian rights, and Study C-2 was similarly based upon the first phase of Study B-4. Each of these "C" Series studies then involved estimation of the yields of the assumed appropriative rights of each of the 25 major water diverters in order of priority regardless of location along the Sacramento River or in the Delta Uplands.

The method involved first the tabulation of net requirements of assumed appropriative water rights with consideration being given to the appropriate return flow factor for the reach to which the appropriation applied. All assumed net appropriative rights were then arranged in order of decreasing priority. The extent to which water remaining at various points along the river and in the Delta after satisfaction of riparian rights could satisfy assumed appropriative rights was determined for each month by reference to this tabulation. If there was water available in a given month after satisfaction of all pre-1927 appropriative rights, the remainder was assumed to be available to satisfy the assumed rights of the United States under the water right assumptions of the corresponding "B" Series studies. Similarly if water remained after satisfaction of 1927 State filings assigned to the United States, the remainder was distributed among local rights of 1927 to 1938 priority, 1938 State filings, or post-1938 local water rights, depending upon the amount of water available.

Tables 13 and 14 indicate the estimated average monthly water-right yields during the study period 1924 through 1954 for each of the 26 major water users and for the Delta Lowlands. The tabulations indicate the yields of assumed riparian rights of each of the 26 major water users as well as yields of their appropriative rights.

Comparison of Tables 13 and 14 indicates that greater yields for the local water users result from the assumption [illegible] salinity control requirements have a late priority status, as in Study C-2, than if such requirements are assumed to have a riparian water right status, as in Study C-1.

V - DEFICIENCIES AND SUPPLEMENTAL WATER REQUIREMENTS

In order to evaluate the amount of water required by local water users along the Sacramento River and in the Delta from storage facilities of the Central Valley Project, from other storage facilities, or from importation it is desirable to determine the deficiencies in yields of assumed water rights from available flows and amounts of supplemental water required in order to permit a given level of diversions. "Deficiencies" are defined for purposes of this report as the differences between the individual or collective yields of assumed local water rights and the face values of such rights or a given level of water utilization. For most studies, the 1954 level of diversion along the Sacramento River, and the 1955 level of water utilization in the Sacramento-San Joaquin Delta for purposes other than salinity control were selected for determination of deficiencies. Those levels of water utilization were chosen because they are the maximum historical levels. In negotiation of an agreement the water users may wish to choose a different level of diverions from the 1954 and 1955 levels. The effects of such different diversion levels may be estimated on the basis of values given in this report.

The term "supplemental water requirement" is defined for purposes of this report as the actual release of water required from reservoirs of the Central Valley Project or from any other reservoirs or sources in order to overcome the aforesaid deficiencies. Supplemental water requirements are less than corresponding deficiencies by the amount of return flow available for rediversion. Estimates of supplemental water requirements also pertain to the 1954 level of diversions along the Sacramento River and to the 1955 level of water utilization in the Delta.

Deficiencies

Deficiencies for the "A" and "B" Series were taken as the differences between the yields of assumed water rights and the 1954 level of diversion along the Sacramento River or the 1955 level of water utilization in the Delta. Values of those levels of diversion and water utilization are given in Table 6 of Appendix D. The aforesaid differences were determined for each of the three priority groups of local water rights as divided by the years 1927 and 1938. Total deficiencies were computed by adding together the deficiencies for all of the priority groups.

Deficiencies were also estimated for the various subdivisions of water rights considered in the "C" Series. These deficiencies were not based upon the 1954 or other recent level of diversions but were assumed to be the differences between the yields of the individual or collective water rights considered and the full face value of those respective rights. This assumption was necessary because the pattern of individual diversions varies considerably from year to year making application of the 1954 level of diversions by each water diverter unrealistic over a long period of years. Therefore deficiencies determined for the "C" Series were used only for the purpose of computing possible parameters for allocation of requirements for supplemental water as determined for the "A" and "B" Series.

Tables 15 through 19 present estimates of avera
ciencies in yield of assumed local water rights as determ
the "A" and "B" Series. Tables 20 and 21 present the esti
deficiencies for the "C" Series.

Comparison of the average deficiencies in yields of rights of local water users, as shown by the results of the various studies of the "A" and "B" Series, reveals that as the assumptions vary so as to increase the yields of the local water rights the deficiencies decrease and vice versa. Similarly in the "C" Series, the individual water rights are satisfied to a greater extent and the deficiencies are less in the C-2 Study than in the C-1 Study because the C-2 Study is based upon the assumption that all salinity control requirements have a late priority status.

Supplemental Water Requirements

Supplemental water requirements were estimated for both the "A" and "B" Series on the basis of the deficiencies described in the preceding section. Such requirements were estimated by reducing the deficiencies to allow for reuse of return flows. Return flows were based upon application of return flow factors previously discussed.

Tables 22 through 26 indicate the estimated supplemental water requirements under the "A" and "B" Series. These are average monthly values for the period of study from 1924 through 1954 based upon the 1954 level of diversion along the Sacramento River and the 1955 level of water utilization in the Delta.

No supplemental water requirement estimates were made under the "C" Series for reasons previously discussed in connection with deficiencies. Supplemental water requirements for individual water users were estimated from the results of the "A" and "B" Series by application of allocation parameter values based upon results of the "C" Series. These allocation studies are described in the next chapter.

VI - ALLOCATION STUDIES

As indicated heretofore, various water right assumptions were made in this report for study purposes. It has also been indicated that the quantities of such rights as they might be determined by a court of law could differ substantially from the values presented in this report. Some of the reasons for these differences could could be consideration of diligence in the development of beneficial use under the various appropriative water right applications, the loss of appropriative rights by non-use, the actual extent of lands having a riparian right upon waters of the Sacramento River both above Sacramento and in the Delta, the effect of prescription upon the various water rights assumed, and the status of water requirements for salinity control with relation to other water rights along the river and in the Delta. These factors suggest the possible wide range in amounts of supplemental water supplies that each water user might be considered to be responsible for in view of the yield of his water rights and the level of diverion which he might wish to maintain.

The foregoing consideration indicated to the cooperative engineering group the desirability of developing formulae for determining (1) the amount of supplemental water that the water users as a group should acquire and (2) the manner in which this obligation should be distributed among the individual water users. Because of the uncertainties as to the specific water rights involved, it is believed that the only practicable method of accomplishing those objectives is by compromise based upon estimated requirements for supplemental water such as those indicated by studies in this report. The studies described in the preceding sections are believed to present a reasonable range of assumptions with relation to the extent of water rights under State filings and to the water right status of salinity control requirements. As previously indicated no attempt has been made to evaluate the effects of diligence or loss of right by nonuse or prescription. This course was taken because (1) it was believed that such matters are primarily of a legal and judicial nature beyond the scope of an engineering study and (2) the conceivable combination of assumptions related to those matters was so great as to be impracticable within the limitations of time and personnel available for the 1956 Cooperative Study Program.

This section presents some of the possible ways by which the deficiencies in yields of assumed individual and collective rights, as estimated in the "C" Series, might be used to allocate among the diverters the overall obligations of the water users for purchase of supplemental water, as derived by the "A" and "B" Series. Possible means of allocation and examples of such allocations of responsibility for supplemental water requirements for irrigation and municipal purposes are discussed separately from possible allocations of the responsibility for salinity control.

Allocation of Responsibility for Supplemental Water Requirements for Irrigation and Municipal Purposes

The following discussion pertains to the average allocation of responsibility for supplemental irrigation and municipal water requirements based upon the historical water supply conditions that prevailed during the months of April through October in the years 1924 through 1954. These quantities give an indication of the average allocation that might apply over a long period of years under conditions of water utilization approximating those in 1954 and 1955.

The allocation procedure involved multiplying the total indicated requirements for supplemental water for all local water users by parameter values comprising ratios between the individual deficiencies and the total deficiency of all water users under the "C" Series. Parameter values are shown in Appendix E. Supplemental water requirements for all local water users as determined in Studies A-2, B-2, B-3, and B-4 were utilized together with the results of studies C-1 and C-2 to derive examples of possible allocations. Other similar allocations might also have been made by application of parameter values given in Appendix E to total seasonal values of supplemental water requirements for Studies A-1, B-1, A-2 (Modified), and B-2 (Modified), as given in Table 24, or to any other values.

Presented in Table 27, is a summary of allocation results which were obtained by applying the allocation parameters, based upon Studies C-1 and C-2, to the total supplemental irrigation and municipal water requirements as determined by the various studies of the "A" and "B" Series. In addition, unallocated total supplemental water requirements for salinity control are shown for each study.

The aforesaid examples indicate relatively small differences in allocations for most major water users as between the results of applying the C-1 and C-2 parameters. This is true despite the significant differences between Studies C-1 and C-2 with regard to assumptions of the water right status of salinity control. The principal exceptions to the aforesaid rule are in the cases of the Glenn-Colusa Irrigation District and of "Other Water Users".

Allocation of Responsibility for Salinity Control

All of the uncertainties as to legal bases for final allocation of available natural flow described in the first paragraph of this chapter are applicable to salinity control. However, it may be said in general that the Delta water users and the Central Valley Project now receive, and that the State's Feather River Project will receive direct benefits from salinity control. It may also be said that upstream water users along the Sacramento River and other tributaries of the Delta receive certain indirect benefits from such control. Thus an interrelationship exists among the aforesaid benefits.

There may be differences of opinion both as to the relative responsibilities for salinity control among the governmental agencies concerned and among groups of water users and as to the degree of control that should be provided. There may also be various opinions regarding alternative economical and reasonable methods of providing water of good quality for diversion from the Delta. No attempt is made to in this report to a... these matters, because it appears that such determination... beyond the scope of an engineering study and are in the re... arbitrary compromise. Therefore no specific method of allo... of responsibility for flood control is suggested in this repo...

Allocation Under Operating Conditions

It has been indicated that the methods of allocation of responsibility for supplemental water requirements, suggested in this report, pertain to average conditions under water supplies prevailing in the years from 1924 through 1954. It has also been stated that this procedure permits the water users to view the average results of the various assumptions as to allocation methods that might apply over such a period.

This does not preclude use of this type of allocation procedure under operating conditions, if it is decided to base the annual payment for supplemental water upon anticipated water supply conditions and conditions of demand occurring during each specific year. On the basis of these conditions, estimation of the total responsibility of all local water users could be accomplished without difficulty at the beginning of each irrigation season. A number of possible alternatives are available for allocation of this overall responsibility. One would involve multiplying the total requirement for supplemental water for all local water users by average allocation parameter values, such as those mentioned previously, to determine the obligation of each water user during the year in question. This might be considered reasonable if each water user were willing to concede that over a period of years his water diversions with relation to diversions by other water users would average about the same as the bases upon which the parameter values were based.

A second method of allocation under actual operating conditions might be based upon parameters computed specifically for each season. Such parameters would depend upon each water user's contemplated diversions and the probable yield of his water rights for the season in question as compared to such data for all local water users. It is believed practicable to devise a formula whereby parameters, such as those described in this chapter, might be modified in an approximate manner to accomplish this end.

VII - SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This chapter presents a brief summary of the as[illegible] and procedures in studies under the 1956 Cooperative Study Program and the more significant conclusions resulting therefrom. Recommendations for future action on matters with which this report is concerned, are presented.

Summary

The 1956 Cooperative Study Program was commenced in May, 1956, cooperatively by the United States Bureau of Reclamation, the State Department of Water Resources, and the Sacramento River and Delta Water Association. The purpose of these studies was to indicate the effects upon the United States and upon local water users of different assumptions as to water rights, particularly as to rights along the Sacramento River and in the Sacramento-San Joaquin Delta, with respect to the adequacy of unregulated stream flow to meet the current needs of the water users for irrigation and for salinity control in the Delta and conversely the need for supplemental water from the Central Valley Project under these varying assumptions. It was intended for these studies to produce information that would be used to further negotiations aimed at reaching agreement on water rights along the Sacramento River and in the Delta.

A total of ten complex studies was made to evaluate, under different assumptions as to water rights, yields of water rights the monthly quantities of water available for satisfaction of such rights from flows of the Sacramento River and from Delta channels without regulation by reservoirs of the Central Valley Project in the Sacramento Valley. The 31-year period 1924 through 1954 was used for study purposes because essential hydrographic records were available in sufficient detail for that period. The years 1955 and 1956 were not included because a number of final hydrographic records were not available. Only the months of the irrigation season from April through October of each of those 31-years were studied because it was found that unregulated water supplies in all other months were generally ample for all requirements. Average values for the irrigation seasons in those years are referred to in this chapter as "31-year-average-irrigation-season" values. Monthly deficiencies were also estimated for each study as the differences between water right yields and the 1954-55 diversion level or, in several cases, the values of assumed rights. Monthly quantities of supplemental water required to firm the water right yields to the 1954-55 diversion level were also estimated. Finally, quantities of water remaining at the various points along the River after satisfaction of various water rights were computed. These results are shown in Volume II of this report but are not discussed in Volume I.

The water right assumptions, which were made for this report, were solely for the purpose of evaluating the effects of these assumptions upon water right yields, deficiencies, and supplemental water requirements, and no implications as to the legal status of such assumed rights are intended. Assumed quantitative values, or "face" values, of water rights were based upon estimated water requirements for areas of physically riparian land along the Sacramento River above Sacramento as derived from title search records; upon records of historical use of water under appropriations by postings made prior to 1914, as shown in county records; upon records of appropriation made subsequent to 1914, as shown in the files of the State Water Rights Board; and upon records of water use over a substantial period of years on lands not assumed to be physically riparian and having no apparent claim of appropriative water right referred to hereinafter as "other" water rights. It was assumed that all Delta Lowlands as shown on Plate 3 are riparian to the channels of the Delta and to waters of tributary streams. Navigation requirements along the Sacramento River were ignored. For purposes of studies of the "A" and "B" Series, described hereinafter, the assumed water rights were assembled into five priority groups as follows:

<u>Priority Group 1</u> - Assumed local rights of pre-1927 (July 30, 1927) priority including water requirements of assumed physically riparian lands along the Sacramento River north of Sacramento and in the Delta Lowlands, pre-1914 appropriations by posting, 1914-1927 appropriations under the Water Commission Act of 1914 and assumed pre-1927 "other" water rights. In some studies, salinity control requirements of 3,300 or 2,000 second-feet were assumed to be analogous to riparian rights and were considered in this priority group.

Priority Group 2 - Assumed rights under Sta... ment of Finance applications filed July 30, 192... those at Shasta Dam assigned to the United States ... Central Valley Project and in some studies other Sta... filings on the Feather, Yuba, Bear, American, Stanislaus, and San Joaquin Rivers.

Priority Group 3 - Assumed local appropriative and "other" rights of priority between July 30, 1927 and August 2, 1938.

Priority Group 4 - Assumed rights under State Department of Finance applications filed on August 2, 1938, and assigned to the United States for the Central Valley Project.

Priority Group 5 - Assumed local appropriative and "other" rights of priority between August 2, 1938 and December 31, 1954, and in some studies assumed rights under State filings on the Feather River in 1951. In two studies a salinity control requirement of 3,300 second-feet was assumed to have a status analogous to an appropriative water right of post-1954 priority.

Several of the assumptions were the same for each study but other assumptions were varied among the studies. In all studies, the face value of 1927 State Application No. 5626 at Shasta Dam, assigned to the United States, was assumed in full but with variation in the monthly distribution of demand as explained hereinafter. The 1938 State Applications No. 9364, 9366, 9367, and 9368, assigned to the United States, were utilized to augment the direct diversions under the aforesaid 1927 State application, but limited to the face value of the application. The requirement for the Contra Costa Canal, under both the assumed 1927 and 1938 rights of the United States was taken under a municipal and industrial demand schedule with a maximum value of 350 second-feet in July and with lesser values in other months. Variable assumptions as to demands under assumed rights of the United States are discussed subsequently.

The basic difference between studies of the "A" and "B" Series is that under the "A" Series all water rights in Priority Group 1 were assumed to be satisfied in geographical order proceeding downstream without regard to any possible prior status of assumed riparian rights, while under the "B" Series, assumed riparian rights within that priority group were assumed to be satisfied before any appropriative rights regardless of location in the service area. Studies of the "C" Series differed from those of the "A" and "B" Series in that all assumed rights were taken as being satisfied in chronological order in accordance with their priorities. The salient assumptions and computation procedures that differ among the studies are described as follows:

<u>"A" Series</u> - Assumed local water rights within Priority Groups 1, 3, and 5 were assumed to be satisfied to the extent of available unregulated modified natural flows along the River and in the Delta in geographical order proceeding downstream from Redding, without regard to priorities in each group, and with

credit being given for return flows from the estimated diversions under these assumed rights. The full face values of local water rights shown in Tables 1 through 4 of Appendix D were assumed in each study except that 70% of historical 1955 Delta Uplands diversions were taken as pre-1927 water rights and 30% of such diversions were taken as post-1938 water rights. These percentages were based upon a cursory examination of the 1955 diversion records and upon information as to water rights under which such diversions were made. Salinity control requirements of 3,300 second-feet were assumed to have a status analogous to a riparian right.

<u>Study A-1</u> - The requirement for the Delta-Mendota Canal was assumed to be a constant demand of 4,600 second-feet under both 1927 and 1938 assumed rights of the United States. Municipal and industrial requirements of the United States in the Delta under State Application No. 9363 (made in 1938) were assumed to be 100 second-feet.

<u>Study A-2</u> - The requirement for the Delta-Mendota Canal, under assumed 1927 rights of the United States, was taken on an irrigation demand schedule, with a maximum value of 4,600 second-feet in July and with lesser values in other months. The differences between the irrigation demand and a constant demand schedule were taken as being made up under assumed 1938 rights of the

United States. Municipal and industrial requirements of the United States in the Delta under State Application No. 9363 were assumed to be 1000 second-feet.

Study A-2 (Modified) - Assumptions and procedures were the same as in Study A-2 except that certain other State filings on the Feather, Yuba, Bear, American, Stanislaus, and San Joaquin Rivers, as listed in Table 5 of Appendix D, were assumed to share the water available for Priority Group 2 with assumed rights of the United States. 1951 State applications on the Feather River were assumed to be satisfied after assumed 1954 local water rights because appropriations between 1951 and 1954 were small.

"B" Series - Within Priority Group 1, rights of assumed physically riparian lands above Sacramento and in the Delta Lowlands and salinity control requirements, when assumed to have a status analogous to riparian rights, were taken as being satisfied before any assumed appropriative or "other" water rights. The remaining assumed local appropriative and "other" water rights within Priority Groups 1, 3, and 5, were assumed to be satisfied in geographical order proceeding downstream from Redding without regard to priorities in each group. The full face values of local water rights shown in Tables 1 through 4 of Appendix D were assumed in each study except that 70% of historical 1955 Delta Uplands diversions were taken as pre-1927 rights and 30% of such diversions were taken as post-1938 rights.

Studies B-1, B-2, and B-2 (Modified) - Assumptions were the same with respect to assumed rights of the United States and other State filings as in corresponding studies of the "A" Series. Salinity control requirements of 3,300 second-feet were assumed to have a status analogous to a riparian right.

Study B-3 - The requirements for the Delta-Mendota Canal, under assumed 1927 rights of the United States, were taken on an irrigation demand schedule with a maximum value of 4,600 second-feet. The differences between the irrigation demand and a constant demand of 4,600 second-feet were taken as being made up under assumed 1938 rights of the United States. Municipal and industrial requirements of the United States in the Delta under State Application No. 9363 were assumed to be 1,000 second-feet. A salinity control requirement of 2,000 second-feet was assumed to have a status analogous to a riparian right.

Study B-4 - Assumptions and procedures were the same as for Study B-3 except that salinity control requirements of 3,300 second-feet were assumed to have a status analogous to a post-1954 appropriative water right.

"C" Series - Rights of assumed physically riparian lands above Sacramento and in the Delta Lowlands and salinity control requirements, when assumed to have a status analogous to a riparian right, were satisfied before any assumed appropriative or "other" water rights. Following this all assumed local appropriative and "other" water rights and assumed rights of the United States were taken as being satisfied in chronological order of priority regardless of location along the Sacramento River and in the Delta Uplands. The full face values of local water rights shown in Tables 1 through 4 of Appendix D, including those for the Delta Uplands, were assumed in each study. In these studies the degrees of satisfaction of assumed riparian and appropriative water rights of each of 26 major water users along the Sacramento River and in the Delta Uplands were estimated. The following are the differences between Studies C-1 and C-2:

Study C-1 - Assumptions were the same with respect to assumed rights of the United States as in Studies A-1 and B-1. Salinity Control requirements of 3,300 second-feet were assumed to have a status analogous to a riparian right.

Study C-2 - Assumptions were the same with respect to assumed rights of the United States as in Studies B-3 and B-4. Salinity control requirements of 3,300 second-feet were assumed to have a status analogous to a post-1954 appropriative water right.

Table 28 presents a summary of the important r s of the aforesaid ten studies that pertain to yields of a water rights of the local water users and of the United S and to deficiencies and supplemental water requirements rel ing to assumed rights of the local water users. It is to be noted that deficiencies computed for studies of the "A" and "B" Series are the differences between estimated yields of the respective assumed rights and the 1954-55 level of diversions. Similarly supplemental water requirements under studies of the "A" and "B" Series are the net amounts of water required to firm the yields of the respective assumed water rights to the 1954-55 level of diversions, with credit being given for return flows from use of such supplemental water supplies. Only deficiencies were computed for studies of the "C" Series, and those refer to the differences between yields of assumed water rights and the face values of those rights. These deficiencies were used to compute parameters, or factors, to derive illustrative examples of allocations of responsibility for supplemental water requirements, estimated in the "A" and "B" Series, among major local water users.

Conclusions

The following conclusions have been reached as a result of the analyses of data and information pertaining to water supplies, water use, and water rights along the Sacramento River, in the Sacramento-San Joaquin Delta, and on certain tributaries thereof, which are described in this report.

1. The total of face values of all local water assumed for studies of the "A" and "B" Series was 4,044,000 acre-feet during the irrigation season.

2. The total 1954-55 level of local diversions along the Sacramento River and in the Delta was about 3,532,000 acre-feet during the irrigation season excluding water required for salinity control.

3. Studies of the "A" Series indicate that the 31-year-average-irrigation-season yields of all assumed local water rights for beneficial use other than salinity control would have been about 3,200,000 acre-feet, with salinity control assumed to have a status analogous to a riparian right to available flows up to a maximum of 3,300 second-feet. Estimated yields of all assumed local water rights under the three studies of the "A" Series do not differ greatly from one another because of the large percentage of such rights which were assumed to have a pre-1927 priority and because variations in water-right assumptions affect only water rights of 1927 and later priorities.

4. Studies of the "B" Series indicate that the 31-year-average-irrigation-season yields of all assumed local water rights would have been about 2,700,000 acre-feet, with salinity control requirements up to a maximum of 3,300 second-feet assumed to have a status analogous to a riparian right; about 2,850,000 acre-feet, with salinity control requirements up to a maximum of 2,000 second-feet assumed to have a status analogous to a riparian right; and about 3,150,000 acre-feet

with salinity control requirements up to a maximum of 3,300 second-feet assumed to have a status analogous to a post-1938 appropriative water right. Estimated yields of all assumed local water rights under the first three studies of the "B" Series do not differ greatly from one another because of the large percentage of such rights which were assumed to have a pre-1927 priority and because variations in water-right assumptions affect only water rights of 1927 and later priorities.

5. Estimated yields of assumed local water rights of pre-1927 priority above Sacramento are greater under the "A" Series than under the "B" Series because such rights in the "A" Series were assumed to be satisfied in geographical order proceeding downstream from Redding, thus leaving the satisfaction of rights in the Delta to last priority within the pre-1927 priority group. Conversely, estimated yields of assumed local water rights of pre-1927 priority in the Delta are greater under the "B" Series than under the "A" Series.

6. Estimated yields of assumed 1927-1938 and post-1938 rights of local water users are small in the months of July through October.

7. The total requirements for salinity control during the irrigation season, April through October, are 1,400,000 acre-feet for a constant outflow from the Delta of 3,300 second-feet and 850,000 acre-feet for a constant outflow of 2,000 acre-feet.

8. Studies of the "A" Series indicate that the 31-year-average-irrigation-season quantities of water available to meet requirements for salinity control up to a maximum of

of 3,300 second-feet, taken as having a status analogous to riparian right, would have been about 960,000 acre-feet.

9. Studies of the "B" Series indicate that the 31-year-average-irrigation-season quantities of water available to meet requirements for salinity control would have been about 1,160,000 acre-feet with such requirements up to a maximum of 3,300 second-feet assumed to have a status analogous to a riparian right; about 740,000 acre-feet with such requirements up to a maximum of 2,000 second-feet assumed to have a status analogous to a riparian right; and 590,000 acre-feet with such requirements up to a maximum of 3,300 second-feet assumed to have a status analogous to a post-1954 appropriative water right.

10. Assumed irrigation season totals of water rights of the United States under 1927 direct diversion and storage filings and under 1938 direct diversion filings amounted to about 3,550,000 acre-feet for Studies A-1 and B-1 and about 3,800,000 acre-feet for all other studies of the "A" and "B" Series.

11. Total 31-year-average-irrigation-season yields of all assumed rights of the United States would have been about 1,500,000 acre-feet for Studies A-1, A-2 (Modified), B-1, and B-2 (Modified) with salinity control up to a maximum requirement of 3,300 second-feet assumed to have a status analogous to a riparian right. Lower yields than would normally be expected for greater assumed rights in the modified studies are caused by part of the available supply under these studies being required for State filings on the

other streams mentioned in this chapter under the heading "Summary".

12. Total 31-year-average-irrigation-season yields of all assumed rights of the United States under Studies A-2 and B-2 would have been about 1,700,000 acre-feet with salinity control requirements up to a maximum of 3,300 second-feet assumed to have a status analogous to a riparian right. Greater estimated yields under these studies than under Studies A-1 and B-1, respectively, are due to the assumption of greater municipal and industrial demands under the 1938 direct diversion rights in the Delta.

13. Total 31-year-average-irrigation-season yields of all assumed rights of the United States under Study B-3 would have been about 1,800,000 acre-feet, with salinity control requirements up to a maximum of 2,000 second-feet assumed to have a status analogous to a riparian right.

14. Total 31-year-average-irrigation-season yields of all assumed rights of the United States under Study B-4 would have been about 2,100,000 acre-feet, with salinity control requirements up to a maximum of 3,300 second-feet assumed to have a status analogous to a post-1954 appropriative water right.

15. Study C-1, with salinity control requirements up to a maximum of 3,300 second-feet assumed to have a status analogous to a riparian right, indicates that the total 31-year-average-irrigation-season yield of assumed riparian and appropriative water rights of 26 major entities along the Sacramento River above Sacramento and in the Delta Uplands

would have been about 1,330,000 acre-feet; that the average yield for the Delta Lowlands would have been about 1,040,000 acre-feet; that the average yield for water users other than the foregoing would have been about 420,000 acre-feet; and that the total average yield of all assumed local water rights would have been about 2,790,000 acre-feet.

16. Study C-2, with salinity control requirements up to a maximum of 3,300 second-feet assumed to have a status analogous to a post-1954 appropriative water right, indicates that the total 31-year-average-irrigation-season yield of assumed riparian and appropriative water rights of 26 major entities along the Sacramento River above Sacramento and in the Delta Uplands would have been about 1,750,000 acre-feet; that the average yield for the Delta Lowlands would have been about 1,040,000 acre-feet; that the average yield for other water users not considered in detail would have been about 460,000 acre-feet; and that the total average yield of all assumed local water rights would have been about 3,250,000 acre-feet. The greater yields under Study C-2 than under Study C-1 are due to differences of assumptions regarding salinity control.

17. The average irrigation deficiency, or the total 31-year-average-irrigation-season difference between the yields of all assumed local water rights and the 1954 level of diversions north of Sacramento and the 1955 level of water utilization in the Delta, would have been about 480,000 acre-feet as estimated by studies of the "A" Series

and 990,000 acre-feet as estimated by the first three studies of the "B" Series, with salinity control requirements up to a maximum of 3,300 second-feet assumed to have a status analogous to a riparian right. The average irrigation deficiency would have been about 830,000 acre-feet as estimated by Study B-3, with salinity control requirements up to a maximum of 2,000 second-feet assumed to have a status analogous to a riparian right. The average irrigation deficiency would have been about 560,000 acre-feet as estimated by Study B-4 with salinity control requirements up to a maximum of 3,300 second-feet assumed to have a status analogous to a post-1954 appropriative water right.

18. The average salinity control deficiency, or the total 31-year-average-irrigation-season difference between the salinity control requirements and the quantities of water available to meet those requirements, would have been about 430,000 acre-feet as estimated by studies of the "A" Series and 240,000 acre-feet as estimated by the first three studies of the "B" Series, with salinity control requirements up to a maximum of 3,300 second-feet assumed to have a status analogous to a riparian right. The average salinity control deficiency would have been about 110,000 acre-feet, as estimated by Study B-3, with salinity control requirements up to a maximum of 2,000 second-feet assumed to have a status analogous to a riparian water right; and about 780,000 acre-feet as estimated by Study B-4, with salinity control requirements up to a maximum of 3,300 second-feet assumed to have a status analogous to a post-1954 appropriative water right.

19. The average irrigation deficiencies for the Series were taken as the 31-year-average-irrigation-season differences between yields of assumed water rights and the values of such rights. Study C-1, with salinity control requirements up to a maximum of 3,300 second-feet assumed to have a status analogous to a riparian right, indicates that the average irrigation deficiency for 26 major entities along the Sacramento River above Sacramento and in the Delta Uplands would have been about 1,100,000 acre-feet; that the average irrigation deficiency for the Delta Lowlands would have been about 16,000 acre-feet; that the average irrigation deficiency for water users other than the foregoing would have been about 410,000 acre-feet; and that the total average irrigation deficiency for all local water users would have been about 1,530,000 acre-feet. The value of 1,530,000 acre-feet is greater than the corresponding irrigation deficiency for Study B-1, amounting to about 990,000 acre-feet, because the former is based upon the full assumed rights of local water users and the latter is based upon the lesser 1954-55 level of diversion.

20. Study C-2, with salinity control requirements up to a maximum of 3,300 second-feet assumed to have a status analogous to a post-1954 appropriative water right, indicates that the average irrigation deficiency for the 26 major entities along the Sacramento River above Sacramento and in the Delta Uplands would have been about 690,000 acre-feet; that average irrigation deficiency for the Delta Lowlands would have been about 16,000 acre-feet; that the average irrigation deficiency

for water users other than the foregoing would have been about 370,000 acre-feet; and that the total average irrigation deficiency for all local water users would have been about 1,070,000 acre-feet. The value of 1,070,000 acre-feet is greater than the corresponding figure for Study B-4, amounting to about 560,000 acre-feet, because the former is based upon the full assumed rights of local water users and the latter is based upon the lesser 1954-55 level of diversions.

21. The average supplemental irrigation water requirements, or those quantities of water needed to firm the 31-year-average-irrigation season yields of all assumed rights of local water users to the 1954-55 level of diversions, would have been about 420,000 acre-feet as estimated by studies of the "A" Series and about 670,000 acre-feet as estimated by the first three studies of the "B" Series, with salinity control requirements up to a maximum of 3,300 second-feet, assumed to have a status analogous to a riparian right. The average supplemental irrigation water requirement would have been about 580,000 acre-feet as estimated by Study B-3, with salinity control requirements up to a maximum of 2,000 second-feet assumed to have a status analogous to a riparian right. The average supplemental irrigation water requirement would have been about 410,000 acre-feet, as estimated by Study B-4, with salinity control requirements up to a maximum of 3,300 second-feet assumed to have a status analogous to a post-1954 appropriative water right.

22. The 31-year-average-irrigation-season-supplemental water requirements for salinity control would have been about 430,000 acre-feet as estimated by studies of the "A" Series and about 220,000 acre-feet as estimated by the first three studies of the "B" Series, with salinity control requirements up to a maximum of 3,300 second-feet assumed to have a status analogous to a riparian right. The average supplemental water requirement for salinity control would have been about 102,000 acre-feet, as estimated by Study B-3, with salinity control requirements up to a maximum of 2,000 second-feet assumed to have a status analogous to a riparian right; and about 780,000 acre-feet as estimated by Study B-4, with salinity control requirements up to a maximum of 3,300 second-feet assumed to have a status analogous to a post-1954 appropriative water right.

23. Total supplemental water requirements for irrigation and salinity control under each study would have been about 2.5 times the foregoing 31-year-average values during the critically dry year of 1931 and an average of about 1.4 times such values during the critically dry period from 1928 through 1934.

24. The results of illustrative allocations among individual water users of total supplemental irrigation water requirements are shown in Table 27. These were derived by applying allocation parameter values based upon deficiency information from the "C" Series to supplemental water requirements as estimated by several studies of the "A" and "B" Series. That table indicates for most of the 26 major entities

relatively small differences between allocations derived by using parameters based upon deficiency information from C-1 and those based upon C-2 information. In some cases the C-1 parameters result in a greater allocation of responsibility for supplemental water to a given water diverter and in other cases the C-2 parameters result in the greater allocated responsibility. However, results for the Glenn-Colusa Irrigation District indicate a substantial reduction of the allocated responsibility based upon C-2 parameters as compared to the responsibility based upon C-1 parameters. The result for all other appropriators not considered in detail indicate a substantial increase of the allocated responsibility based upon the C-2 parameters as compared to the responsibility based upon C-1 parameters.

25. Other illustrative allocations of responsibility for supplemental water might be made by applying the parameter values given in this report, or similar values, to results of studies of the "A" and "B" Series not shown on Table 27 or to results of any other similar studies.

26. The illustrative allocations of responsibility for supplemental irrigation water, mentioned above, are for average conditions during the period 1924 through 1954. It is believed that this allocation approach with modification might also be used under operating conditions if it is decided to base the annual payment for supplemental water upon anticipated water supply conditions and conditions of demand occurring during each specific year.

Recommendations

It is recommended:

1. That representatives of the water user associations study in detail the results contained in this report, and if necessary the detailed computations on file with the Department of Water Resources, in order to evaluate the conclusions and the adequacy and soundness of the underlying assumptions and computation procedures.

2. That representatives of the Bureau of Reclamation, the Department of Water Resources, and all interested water user organizations meet as soon as possible to discuss the adequacy of the findings contained herein for negotiations to follow and, if necessary, to recommend certain minimum additional studies in order that the essential data may be made available.

3. That negotiations among representatives of the interested parties be commenced as soon as possible on a continuous basis.

4. That the various problems facing the parties in reaching and negotiating an agreement on water rights and on provision of a supplemental water supply to the water users be identified and that special permanent committees be established to determine ways and means of solving each problem including possible compromise proposals.

5. That water users begin study of the types of district, districts, or other legally constituted entities necessary to negotiate and enter into an agreement and that

steps necessary to accomplish the formation be ini...
suant to terms of the Memorandum of Understanding o...
cluded as Appendix A to this report.

Title:

Old school vs. new school: status of threadfin shad (*Dorosoma petenense*) five decades after its introduction to the Sacramento-San Joaquin Delta

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Abstract:

Threadfin shad (*Dorosoma petenense*) is a schooling pelagic forage fish native to watersheds of the Gulf Coast of North America. Around 1962 it invaded the Sacramento-San Joaquin Delta from upstream reservoirs, where it was stocked to support sport fisheries. It quickly became, and continues to be, one of the most abundant fishes collected by ongoing monitoring programs in the delta. A substantial portion of the delta provides suitable abiotic habitat and so the species is widely distributed. However, in routine sampling it is most commonly collected and most abundant in the southeastern delta, where suitable abiotic habitat (relatively deep, clear water with low flow) coincides with high prey abundance. Apparent growth rate appears to be relatively fast with summer-spawned age-0 fish attaining fork lengths of 70 to 90 mm by the onset of winter. During fall months (September through December) apparent growth rate of age-0 fish has exhibited no long-term trend but has been negatively related to abundance, suggesting that density-dependent factors may be important to the population. Although abundance has fluctuated since its introduction almost five decades ago, it has recently dropped to persistent near-record lows since 2002, which has been coincident with similar declines for other pelagic species in the delta. The recent decline is apparent in two long-term monitoring programs, fish salvaged from the diversions of the state and federal water projects, and commercial fishing harvest. It appears that the decline is, at least in part, a function of fewer and smaller schools of threadfin shad encountered relative to the past. There was little evidence from the data examined for consistent stock-recruit

or stage-recruit effects on the population. It is likely that a combination of abiotic and biotic factors regionally-focused where threadfin shad are most abundant, which may sometimes be episodic in nature, have a large effect on abundance. Focused studies and sampling of threadfin shad are lacking but are necessary in order to better understand population dynamics in the delta.

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Old school vs. new school: status of threadfin shad (*Dorosoma petenense*) five decades after its introduction to the Sacramento-San Joaquin Delta

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ABSTRACT

Threadfin shad (*Dorosoma petenense*) is a schooling pelagic forage fish native to watersheds of the Gulf Coast of North America. Around 1962 it invaded the Sacramento-San Joaquin Delta from upstream reservoirs, where it was stocked to support sport fisheries. It quickly became, and continues to be, one of the most abundant fishes collected by ongoing monitoring programs in the delta. A substantial portion of the delta provides suitable abiotic habitat and so the species is widely distributed. However, in routine sampling it is most commonly collected and most abundant in the southeastern delta, where suitable abiotic habitat (relatively deep, clear water with low flow) coincides with high prey abundance. Apparent growth rate appears to be relatively fast with summer-spawned age-0 fish attaining fork lengths of 70-90 mm by the onset of winter. During fall months (September-December) the apparent growth rate of age-0 fish is negatively related to abundance, although there is no long-term trend. This suggests that density-dependent factors may be important to the population. Although abundance has fluctuated since its introduction almost five decades ago, it has recently dropped to persistent near-record lows since 2002, which has been coincident with similar declines for other pelagic species in the delta. The recent decline is apparent in two long-term monitoring programs, fish salvaged from the diversions of the State and Federal Water Projects, and commercial fishing harvest. It appears that the decline is, at least in part, a function of fewer and smaller schools of threadfin shad encountered relative to the past. There was little evidence from the data examined for consistent stock-recruit or stage-recruit effects on the population. It is likely that a combination of abiotic and biotic factors have a large effect on abundance. These appear to be regionally-focused where threadfin shad are most abundant, and are episodic in nature. More focused studies and more effective sampling of threadfin shad are necessary in order to better understand population dynamics in the delta.

KEYWORDS

Dorosoma petenense, baitfish, Clupeidae, San Francisco Estuary, pelagic organism decline

SUGGESTED CITATION

Feyrer F, Sommer T, Slater SB. 2009. Old school vs. new school: status of threadfin shad (*Dorosoma petenense*) five decades after its introduction to the Sacramento-San Joaquin Delta. San Francisco Estuary and Watershed Science [Internet]. Available from: http://repositories.cdlib.org/jmie/sfews/vol7/iss1/art3

INTRODUCTION

Threadfin shad (*Dorosoma petenense*) is a key forage fish native to North and Central America in watersheds draining into the Gulf of Mexico. Fisheries managers have commonly manipulated threadfin shad populations in an attempt to enhance sport fisheries, although the results associated with these manipulations have been inconsistent for predator and competitor species (DeVries and Stein 1990). Because of the importance of this species as a forage fish, its biology and interactions with other species have been studied. However, relatively little appears to be known about its long-term population dynamics.

A member of the herring family (Clupeidae) that rarely exceeds 100 mm in length, threadfin shad is typically found in open water habitats of lakes, reservoirs, and backwaters of rivers. It can tolerate low salinities but typically requires freshwater for successful reproduction. Threadfin shad usually spawn from April to August in California (Feyrer 2004; Grimaldo and others 2004). Spawning is typically associated with floating or partially submerged objects, especially submerged aquatic vegetation in the Sacramento-San Joaquin Delta (Grimaldo and others 2004). Threadfin shad at all life stages are typically planktonic feeders (Turner 1966; Feyrer and others 2003), focusing on crustacean zooplankton, although it has the ability to switch feeding modes in response to prey availability (Ingram and Ziebell 1983).

Threadfin shad was intentionally introduced into California in 1953 by the California Department of Fish and Game (CDFG) to provide forage for sport fishes in reservoirs (Dill and Cordone 1997). It was stocked into reservoirs in watersheds of the Sacramento and San Joaquin rivers in 1959, and invaded the Sacramento-San Joaquin Delta by 1962, when it was first detected by the CDFG's Summer Townet Survey. The effect of threadfin shad on the delta ecosystem is largely unknown because there is virtually no pre-invasion fish community data with which to compare. Moreover, there have been relatively few studies on threadfin shad since its introduction almost five decades ago. Nonetheless, it is clear that threadfin shad irreversibly altered the fish community because it quickly became one of the most abundant pelagic fishes in the system. Due to its relatively high abundance, it serves as a primary forage fish for the largest striped bass (*Morone saxatilis*) fishery in western North America and one of the premier largemouth bass (*Micropterus salmoides*) fisheries in the world (Stevens 1966; Feyrer and others 2003; Nobriga and Feyrer 2007).

The abundance of threadfin shad, as measured by indices calculated annually by the CDFG from their Fall Midwater Trawl Survey (FMT), has fluctuated over time but has dropped to persistent near-record lows since 2002 (Feyrer and others 2007; Sommer and others 2007). Although there have been previous periods with similarly low abundance, the current decline has persisted and is coincident with similar declines for several other native and introduced pelagic fishes in the upper San Francisco Estuary over the same time period (Feyrer and others 2007; Sommer and others 2007). This decline in the primary components of the pelagic fish community has prompted unprecedented efforts to compile and synthesize data on the affected species (Sommer and others 2007). The goal of our study was to describe life history aspects of threadfin shad from data available from existing monitoring programs of the Interagency Ecological Program (IEP). The IEP is a cooperative monitoring and research effort led by State and Federal agencies plus university and private partners. It has numerous fish monitoring programs that together take place year-round across the system (Honey and others 2004). Based on extensive previous history working with these data sets (e.g., Feyrer and others 2004; Feyrer and others 2007) and further exploratory analyses, we determined that the IEP data sets would be suitable for a retrospective analysis of abundance, distribution, habitat associations, and apparent growth rate of age-0 fish in the delta.

STUDY AREA

San Francisco Bay (Figure 1) is the entrance to the largest estuary on the Pacific coast of the United States. The estuary is fed by California's two largest rivers – Sacramento (from the north) and San Joaquin (from the south) – which drain a 100,000-km^2 watershed encompassing 40% of California's surface area. The delta is a 3,000-km^2 network of tidal freshwater channels formed by the confluence of the two rivers. From the delta, water flows west into Suisun Bay, through the Carquinez Strait, and enters San Pablo Bay before reaching San Francisco Bay and ultimately the Pacific Ocean. Freshwater flow entering the estuary varies seasonally, with most coming in late winter through spring. Anthropogenic modifications to the estuary include the loss of wetlands, channel modifications for flood control and navigation, and a variety of water reclamation activities including storage, conveyance, and large water diversions by the State Water Project (SWP) and Central Valley Project (CVP) (Nichols and others 1986). Dams on the Sacramento and San Joaquin rivers, including most of their major tributaries, control estuarine inflow. The fish community of the delta is dominated by introduced species (Feyrer and Healey 2003; Nobriga and others 2005; Sommer and others 2007) and has been called the most highly invaded in the world (Cohen and Carlton 1998).

METHODS

Data Sources

The primary data we examined originate from trawl surveys conducted during spring (20-mm Survey) and fall (FMT). We also evaluated data from other sampling programs for this project but ultimately focused on these two data sets because they provided the most comprehensive spatial and temporal coverage for analyses. For example, we excluded the IEP's San Francisco Bay Study because, although it collects threadfin shad, the majority of its samples are collected in saltwater habitats of the lower estuary where threadfin shad are rare or absent. For further information we refer readers to Honey and others (2004), who provide detailed descriptions for all IEP fish monitoring programs.

The 20-mm Survey targets young age-0 fish during spring-summer while the FMT targets older age-0 fish during fall. Although neither of these programs was designed to specifically target threadfin shad, the programs were designed to sample pelagic fishes; threadfin shad is one of the most abundant species encountered in terms of the number of individuals captured (Dege and Brown 2004). The efficiency of these sampling gears for threadfin shad is unknown. However, published studies examining threadfin shad in other systems have used nets with larger mesh sizes, which would presumably be less efficient (e.g., Allen and DeVries 1993; Van Den Avyle and others 1995). Further, data from these programs have been used extensively in prior studies of pelagic fish abundance and distribution in the system (e.g., Stevens and Miller 1983; Moyle and others 1992; Jassby and others 1995; Dege and Brown 2004; Feyrer and others 2007). Both monitoring programs encompass the full distribution of threadfin shad in the system; they extend beyond its downstream distribution into marine-influenced habitats and upstream to the margin of the major freshwater tributaries.

The FMT (Stevens and Miller 1983) has been conducted each year since 1967, except that no sampling was done in 1974 or 1979. Samples (12-minute tows) are collected at 100 sites each month from September to December throughout the upper estuary. Net dimensions are as follows: 17.6-m long with a mouth opening of 13.7 m^2, and nine tapered panels of stretch mesh from 20.3 cm to 1.3 cm in the cod-end. Water temperature (°C), Secchi depth (m), and specific conductance ($\mu s \cdot cm^{-1}$) were measured with each tow.

The 20-mm Survey (Dege and Brown 2004) has been conducted each year since 1995. The survey collects three replicate samples (10-minute tows) at a subset of 48 of the 100 FMT sites. A complete set of samples from each site is termed a survey: five to nine sur-

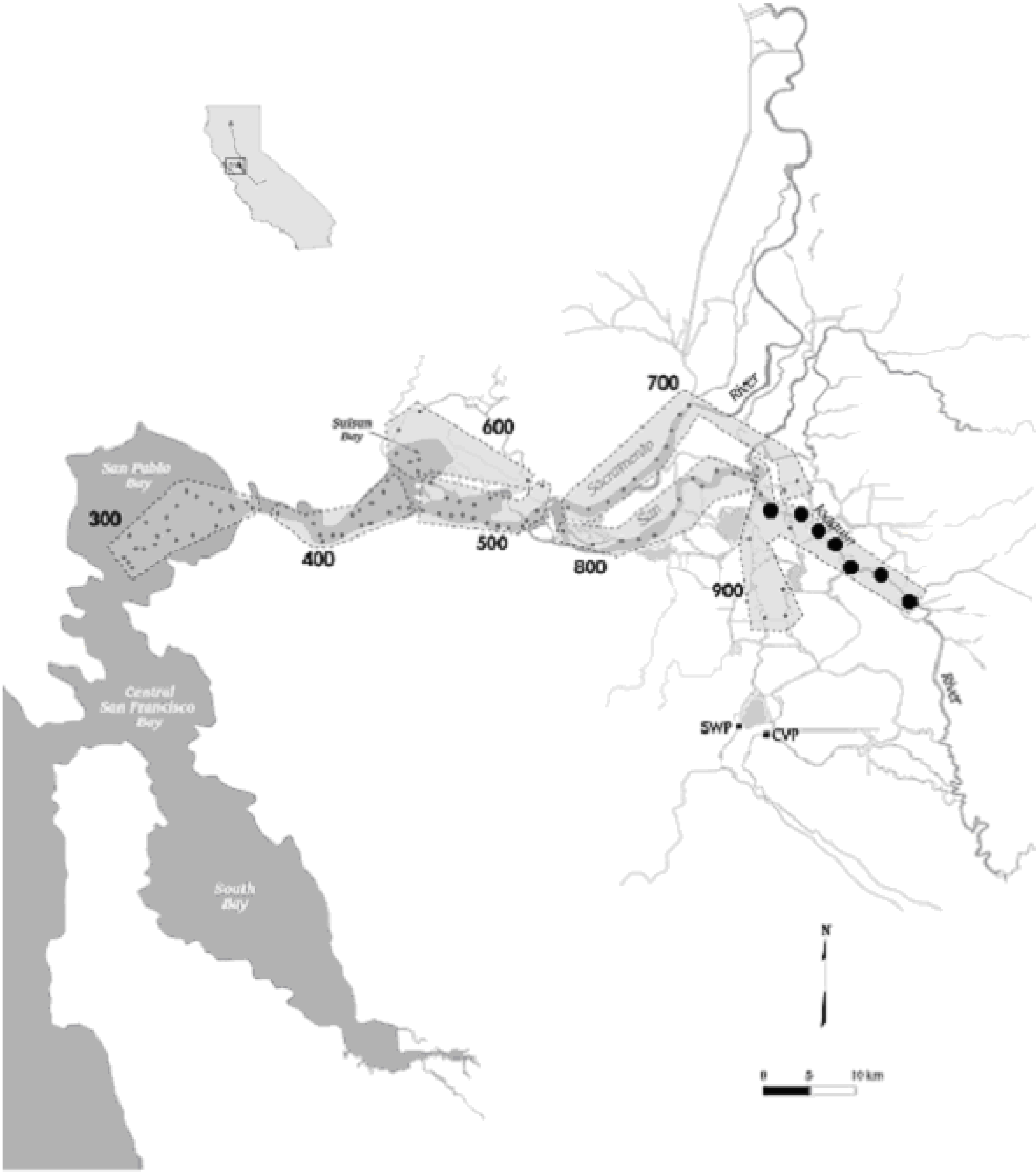

Figure 1 Sampling sites in the Sacramento-San Joaquin Delta. Sites (in bold text) along the San Joaquin River are, from west to east: stations 906, 907, 908, 909, 910, 911, and 912

veys are completed each year from approximately March though June. The conical plankton net used for the survey is 5.1 m long with a mouth opening of 1.5 m^2. The net is constructed of 1,600-µm knotless nylon delta mesh and is mounted on a weighted tow frame with skids. As with the FMT, water temperature, Secchi depth, and specific conductance are measured at each site visit. This survey also simultaneously samples zooplankton during one of the three tows at each site. Zooplankton is sampled with a Clarke-Bumpus net that is attached to the metal frame of the fish net. This net consists of 160 µm knotless nylon mesh and measures 78 cm long with a 12 cm mouth diameter.

We also summarized two other sets of data, salvage of fish at SWP and CVP water projects and harvest by the commercial fishery. The intakes to the south delta diversion facilities of the SWP and CVP (Figure 1) are screened with fish-behavioral louvers designed to separate fish from diverted water before they enter the pumps (Brown and others 1996; Kimmerer 2008). In general, this salvage process consists of fish capture, identification and measurement, transport, and ultimately release at distant locations where the fish are presumed safe from the pumps. However, it is commonly accepted that the majority of threadfin shad probably do not survive the salvage process because of either handling stress or predation at the release sites. Although data from the salvage facilities do not cover the geographic scope of the other surveys, sample size (numbers of fish captured) for the salvage data sets are dramatically larger than the trawl data sets because of the substantial volumes of water diverted, presently more than 6 km^3 per year (Kimmerer 2002). We summarized the salvage data seasonally (spring = March-May, summer = June-August, fall = September-November, winter = December-February) for each year as the total number of threadfin shad combined for both facilities standardized by the total amount of water exported (salvage density). Similar methods have been successfully used to examine abundance trends in other delta fishes (Stevens and Miller 1983; Sommer and others 1997).

Commercial harvest data were provided to us directly from the CDFG. Of the 360 records for threadfin shad from 1977 to 2007, 327 were for the southeast region of the delta ("CDFG's accounting block 306") from approximately Stockton to Franks Tract. The remaining 21 records were for other regions of the delta and were excluded from analyses because they were sparse and represented less than one half of one percent of the total biomass harvested. The data were provided in units of pounds with an associated dollar value ($), which we converted to metric units and then ultimately to an estimated number of individual fish using the length-weight regression from Kimmerer and others (2005) and an average size fish of 80 mm fork length (FL).

Data Analyses

While we examined all of the data sets for interannual trends, the FMT and 20-mm data were the most useful to identify the habitat associations and geographic distribution of threadfin shad. Data from the FMT were also suitable to estimate apparent growth rates.

To identify habitat associations, we used principal components analysis (PCA) to examine distribution along environmental gradients. First, the environmental data from each tow were standardized by subtracting the mean and dividing by the standard deviation, and principal components were extracted from the covariance matrix. Next, we plotted the PCA scores for each sampling station and scaled the size of the points by abundance (average catch per trawl [CPT] for the FMT and average density (fish per 10,000 m^3 for the 20-mm Survey). A key benefit of this approach versus other possible regression-type analyses is that these plots allowed us to interpret how threadfin shad was distributed spatially along environmental gradients in multivariate space coincident with geography as represented by the sampling stations.

We conducted several additional data summaries to better understand patterns of distribution and abundance. First, based upon the results of the PCA, we examined FMT CPT and 20-mm Survey density across stations. Because threadfin shad is a strongly schooling species, we reasoned that simpler measurements of fish presence in trawls might help to reduce the effects of a patchy distribution on the catch data. We plotted time series for the fraction of samples with threadfin shad present, fraction of samples with values above the long-term median and third quartile, and the largest sample. Finally, we constructed several plots - with data from FMT CPT, 20-mm density, and summer salvage density - to examine stock-recruit and stage-recruit effects on the population.

We used a length-frequency method of estimating apparent growth rate. In the FMT, the number of threadfin shad collected during each tow was recorded throughout the survey, but length measurements on individuals were not made until 1975. Initial inspection of the data suggested that most of the fish collected in the FMT were age-0. We systematically identified age-0 cohorts by means of length-frequency histograms created for each month and year from size data based on class intervals of 5.0 mm FL. From the length-frequency histograms, we used the modal progression routine of the FiSAT software program (version 1.2.2; Food and Agriculture Organization–International Center for Living Aquatic Resources Management stock assessment tools; Gayanilo and others 2002) to identify age-0 cohorts. FiSAT applies Bhattacharya's (1967) method to fit normal components to mode means in the length-frequency histograms and then employs NORMSEP (Hasselblad 1966) to refine parameter estimates. This includes an iterative process of the maximum likelihood concept to decompose complex size-frequency distributions into normal curves that represent each cohort within the data set. Modes were accepted as distinct cohorts only when differentiated by a separation index above the critical value of 2 (Gayanilo and others 2002). We estimated the abundance of age-0 threadfin shad in each month from the total number of fish belonging to the age-0 cohort, as determined by FiSAT, divided by the total number of trawls. Apparent growth rates of the age-0 cohort were estimated as the slope of the FiSAT-estimated average fork lengths from September to December. We used regression analysis to determine if apparent growth rate was related to a few key factors that commonly affect bioenergetics: initial abundance (average catch per trawl in September); initial size (average FL in September); overall average water temperature during the sampling period (September-December); or the slope of the average water temperatures for September-December.

RESULTS

Average CPT in the FMT was variable and exhibited no long-term trend (Figure 2). Intra-annual variation in CPT was proportional to average CPT (Pearson correlation coefficient $r = 0.91$, $P < 0.001$). Average CPT peaked at over 80 in 2000 and 2001, and then in 2002 dropped to below 20 and has remained at that level. The CPT time series was significantly correlated with the indices of abundance calculated by CDFG (Figure 2; Pearson correlation coefficient $r = 0.87$, $P < 0.001$).

Average density (number of fish per 10,000 m^3) in the 20-mm Survey was also variable and exhibited no long-term trend (Figure 3). Just as with the FMT, intra-annual variation in density was proportional to average density (Pearson correlation coefficient $r = 0.97$, $P < 0.001$). Average density peaked at over 1,000 from 2001-2003, and then in 2004 dropped to below 500 and has continued to decline.

Salvage density was also variable and has exhibited no long-term trend across seasons (Figure 4). Overall, salvage density in all seasons has been relatively low in recent years. Salvage densities were highest and most variable during summer when spawning occurs and new fish are recruited to the population. Salvage density was lowest during spring, where it has remained relatively low after peaking in the early 1980s. Salvage density during fall was highest in the late 1990s and early 2000s, and has been relatively low since 2003. Winter salvage density peaked in 2003 and has since remained relatively low.

Commercially harvested biomass (kg) and its associated dollar value were also variable over the course of their time series, but exhibited a steady decline after peaking in 2003 (Figure 5). Overall, harvested biomass of threadfin shad ranged from a low of 16 kg in 1977 to a high of 45,067 kg in 2003. The associated dollar values were $45 and $102,810, respectively. By

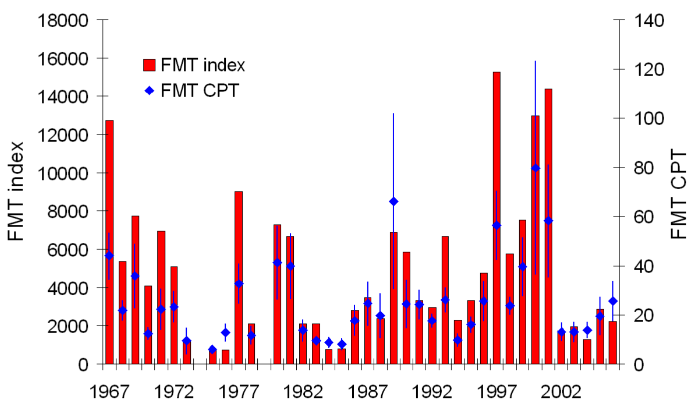

Figure 2 Time series of threadfin shad abundance indices calculated by CDFG and average catch per trawl (+ one standard error; CPT) in the Fall Midwater Trawl Survey (FMT)

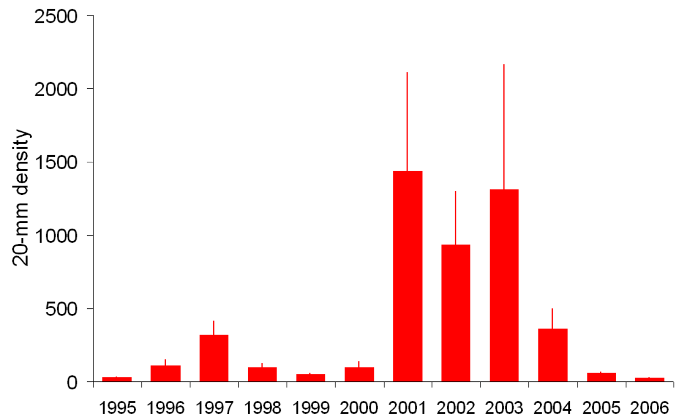

Figure 3 Time series of average (+ one standard error) threadfin shad density (fish per 10,000 m^3) in the 20-mm Survey

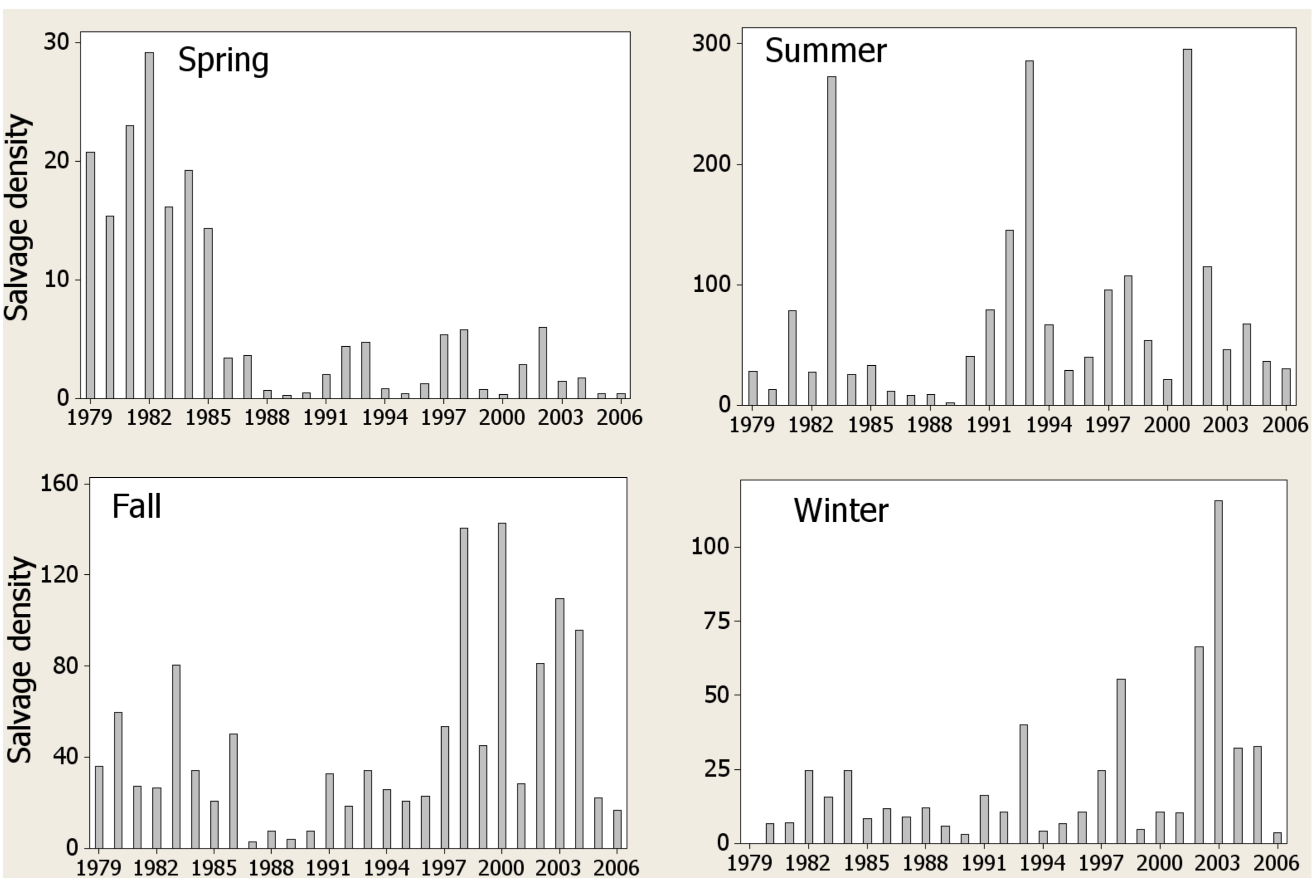

Figure 4 Time series of total combined threadfin salvage density by season. Spring = March – May, Summer = June – August, Fall = September – November, and Winter = December – February.

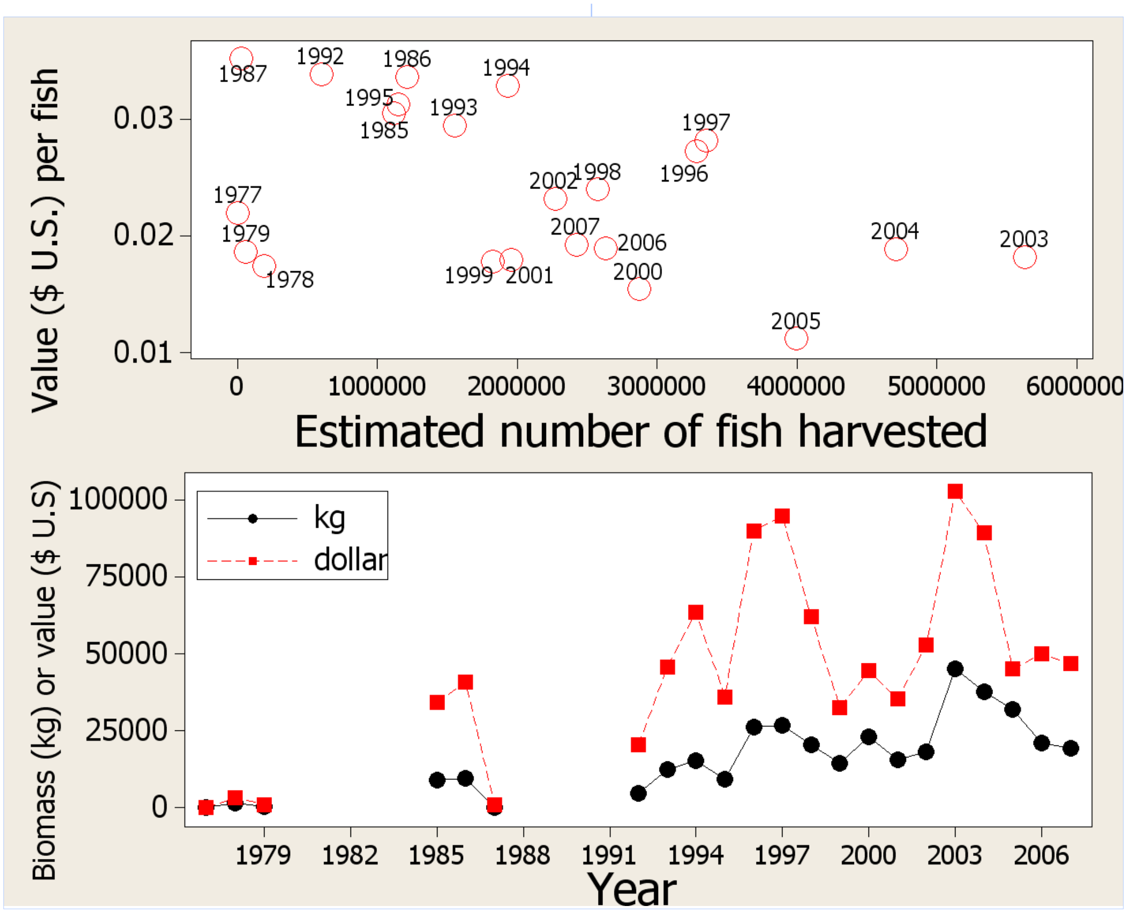

Figure 5 Upper panel: estimated dollar value of commercially harvested individuals plotted against the total number of individuals harvested. Lower panel: time series of commercially harvested biomass (kg) and its associated dollar value of threadfin shad.

2007 harvested biomass and its dollar value dropped to 19,377 kg and $46,816, respectively. Data were not available to determine if this was a function of smaller catches, decreasing effort, or a combination of both. The approximated dollar value per individual fish typically centered around $0.02, but hovered near or above $0.03 for a period from the late 1980s to the mid 1990s (Figure 5). Seasonally, commercially harvested biomass (kg) was highest during fall and winter and lowest in spring and summer (Figure 6).

The results of the PCAs with the FMT and 20-mm data sets showed that both younger and older age-0 threadfin shad was primarily distributed in the southeastern region of the delta under similar environmental conditions (Figure 7). The first two axes of the PCA on the FMT data set were significant eigenvectors as indicated by values > 1.0 (1.19 and 1.05, respectively), which explained 57.6% (30.7 and 26.9, respectively) of the variation (see Figure 2). Axis one was characterized by a strong positive loading for water depth and a negative loading for specific conductance. Axis two was characterized by strong positive loadings for water depth and Secchi depth. The plot of scores on these two axes, scaled by average CPT, demonstrated that threadfin shad were most abundant at sites along the San Joaquin River and the south delta in association with deep, clear, fresh water.

The first two axes of the PCA on the 20-mm data set were significant eigenvectors as indicated by values > 1.0 (1.40 and 1.06, respectively), which explained 49.3% (28.0 and 21.3, respectively) of the variation in the data set (Figure 7). Axis one was characterized by strong positive loadings for water depth and Secchi depth, and a negative loading for specific conductance. Axis two was characterized by strong positive loadings for water temperature, Secchi depth, and zooplankton abundance. The plot of site scores on these two axes scaled by average threadfin shad density demonstrated that younger age-0 threadfin shad were also most abundant at sites along the San Joaquin River and the south delta in association with deep, clear, fresh water with high zooplankton abundance.

As suggested by the variability in the time series data and the distribution patterns in the PCAs, we found that threadfin shad exhibited a contagious distribution such that the majority of the catch occurred in a small geographic area and interannual variation in abundance was highly influenced by large individual catches. In the FMT, a suite of seven adjacent stations (906, 907, 908, 909, 910, 911, and 912; see bold text in Figure 1) in the San Joaquin River dominated the catch relative to all other stations, including average catch per trawl (140 versus 11) and the fraction of samples with threadfin shad present (0.76 vs. 0.27). The average CPT across these stations was highly correlated with the annual abundance indices calculated by CDFG (Pearson correlation coefficient r = 0.84, $P < 0.001$), suggesting these stations have

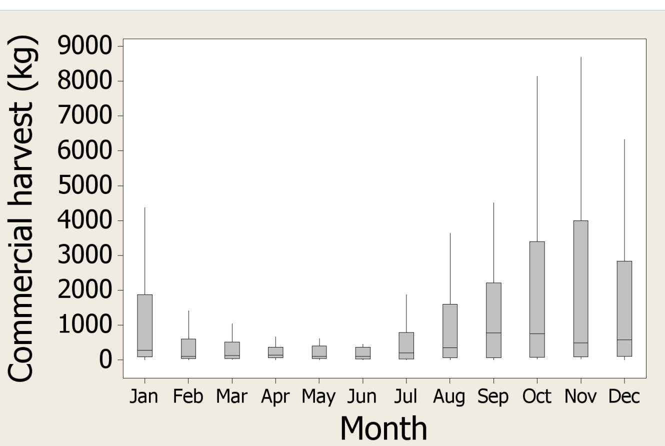

Figure 6 Box plot representation of commercially harvested biomass (kg) of threadfin shad by month

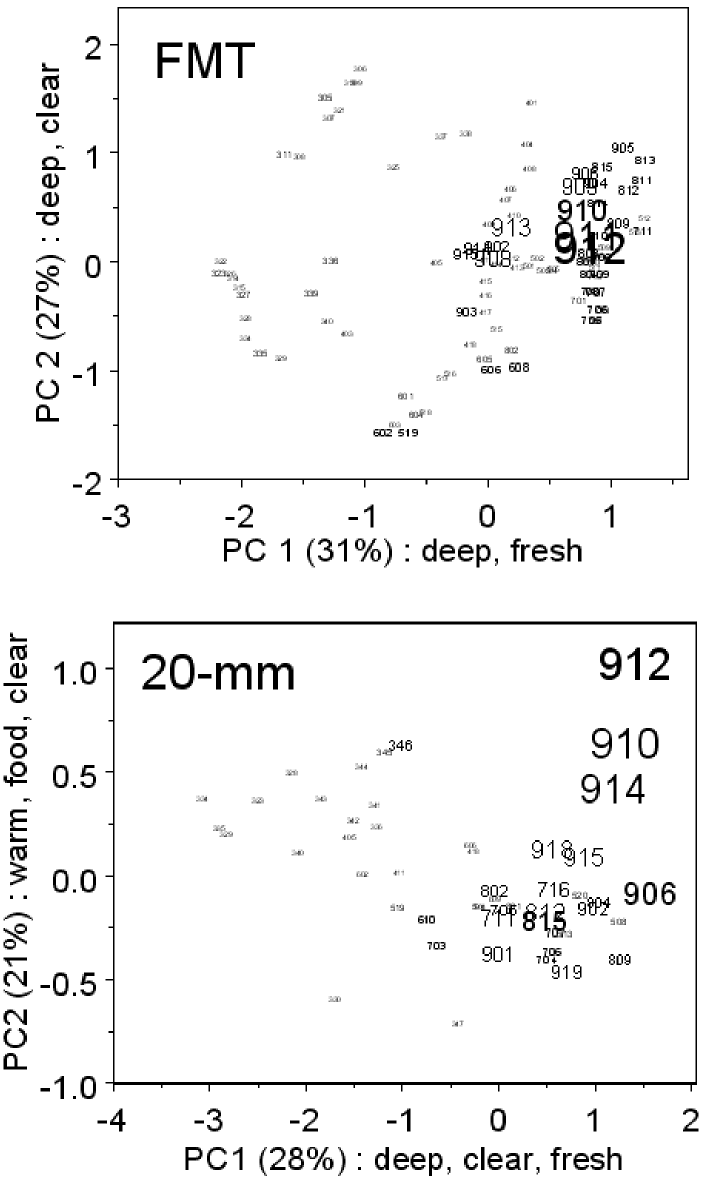

Figure 7 Plots of scores for the first two axes of principal components analyses conducted with data from the Fall Midwater Trawl Survey (top panel) and the 20-mm Survey (lower panel). Sample scores are labeled for the sampling stations and are scaled by average abundance. The general location of the stations is given in Figure 1. Values in parentheses in the axis labels indicate the explained amount of variance.

been driving the long-term trends observed in the abundance indices. At these stations there has been a substantial recent decline in the fraction of samples with threadfin shad present, the fraction of samples with counts of threadfin shad above the long-term median and third quartile, and the maximum count of threadfin shad in a sample (Figure 8).

The 20-mm Survey data set is also dominated by catches from the same geographic region (stations 910 and 912) in terms of the fraction of samples with threadfin shad present (0.61 vs. 0.30) and average density of threadfin shad (2,275 vs. 107 fish per 10,000 m^3). However, unlike the FMT, there were no trends across these stations in the fraction of samples with threadfin shad present, fraction of samples with densities above the long-term median and third quartile, and the maximum density (Figure 9).

We constructed three candidate stock-recruit relationships and two candidate stage-recruit relationships (Figure 10). The stock-recruit models were FMT CPT, 20-mm density, and summer salvage density all plotted against the previous year's FMT CPT. The stage-recruit models were summer salvage density plotted against 20-mm density and FMT CPT plotted against summer salvage density. Although none of the models provided particularly strong evidence of consistent stock- or stage-recruit effects, all response variables exhibited at least some positive response to the prediction variables, with the exception of the FMT CPT-summer salvage density model which had no response.

Using the FiSAT software we were able to identify an age-0 cohort for each month (September-December) in 24 of the 28 years; data were insufficient in 1984, 1986, 1991, and 1997. In total, 85% of the fish mea-

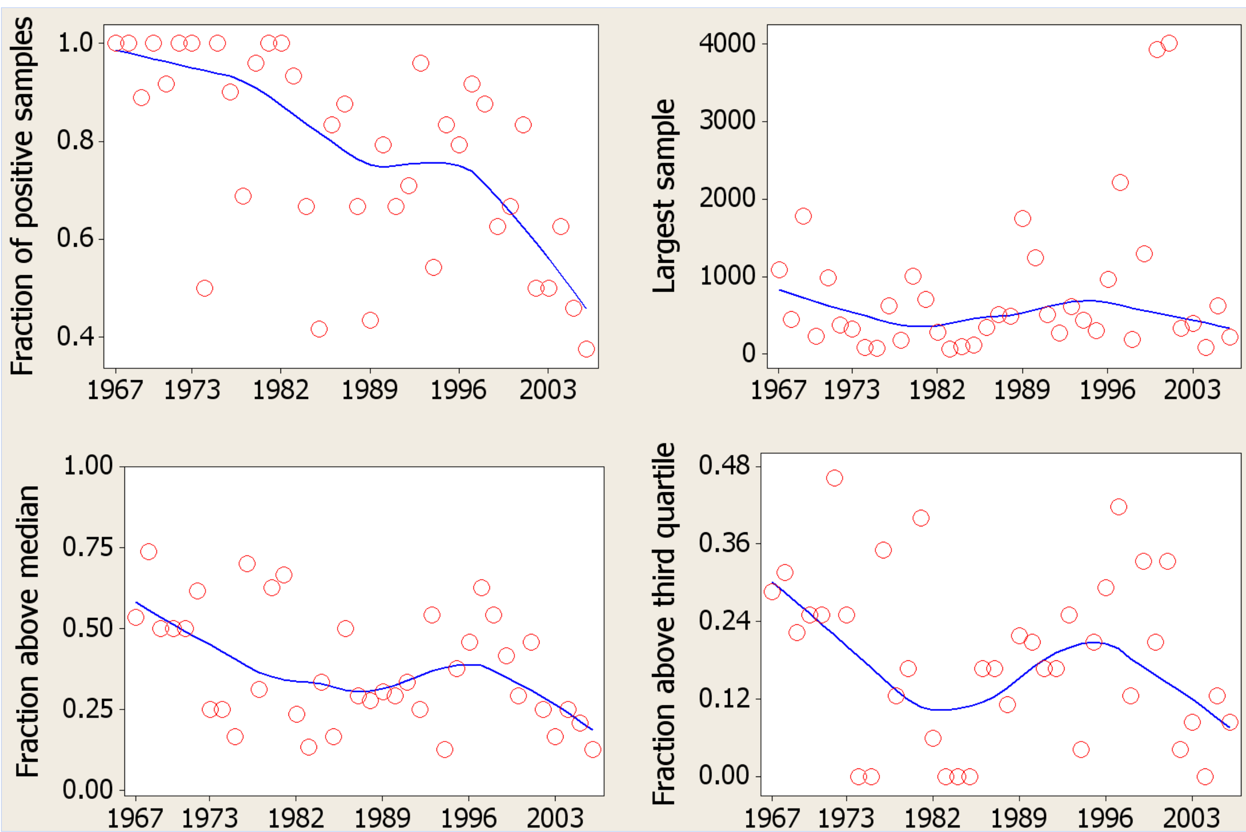

Figure 8 Time series for various factors summarized across key stations (906-912) of the Fall Midwater Trawl Survey. Curves are LOESS smooths.

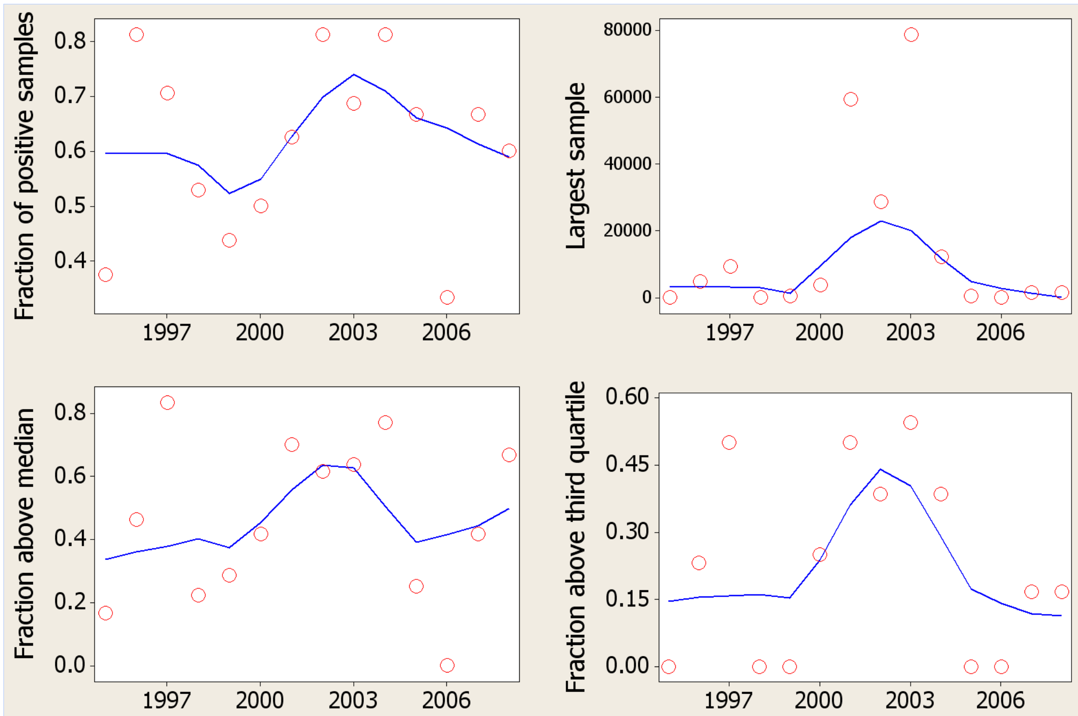

Figure 9 Time series for various factors summarized across key stations (910 and 912) of the 20-mm Survey. Curves are LOESS smooths.

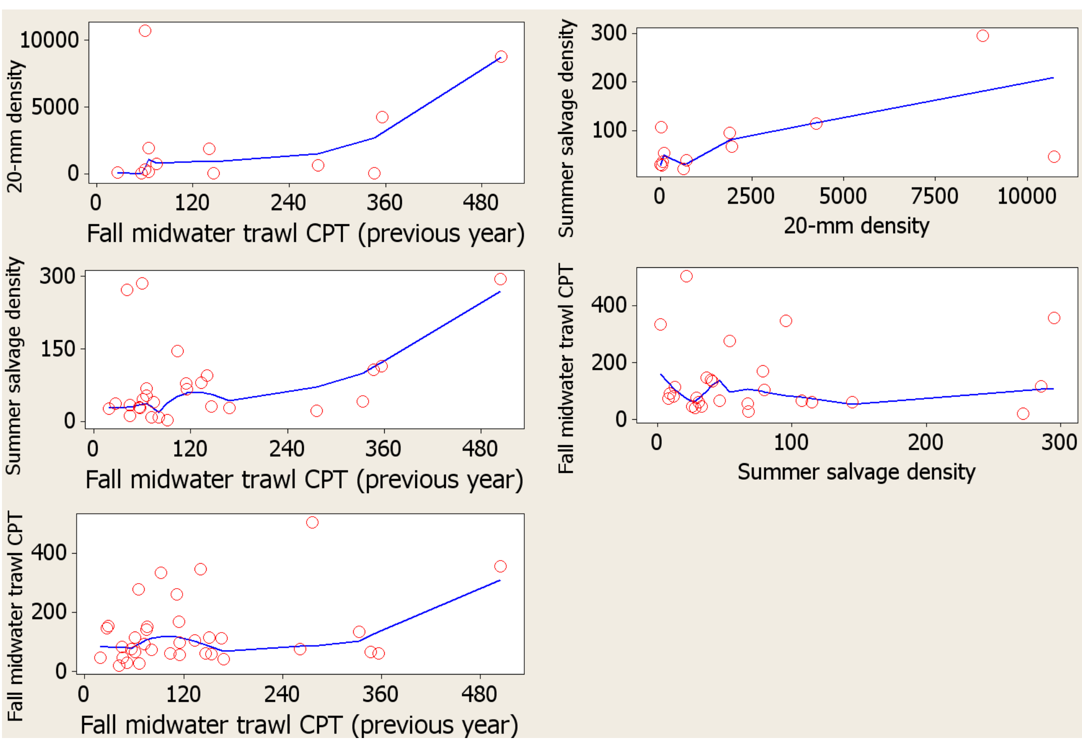

Figure 10 Candidate stock-recruit and stage-recruit plots for threadfin shad. Curves are LOESS smooths.

sured during the FMT belonged to an age-0 cohort as estimated by FiSAT. Across the full 24 years, average catch per trawl of threadfin shad estimated to belong to the age-0 cohort was significantly correlated with total threadfin shad catch per trawl, suggesting age-0 fish indeed dominate the FMT samples (Pearson correlation coefficient $r = 0.99$; $P < 0.001$).

Average apparent growth rate of the age-0 cohorts during September-December was 8.5 mm FL/month (standard deviation = 2.3, minimum = 5.4, maximum = 13.5), and exhibited no apparent long-term trend. Apparent growth rate was only significantly related, and negatively so, to initial abundance (apparent growth rate = 10.3 – 0.207 (initial abundance); r^2 = 26%; P = 0.036).

DISCUSSION

Since most aquatic species introductions generally fail (Moyle and Light 1996), why has threadfin shad persisted during the many decades since its initial introduction? Moyle and Light (1996) propose that several attributes can contribute to the success or population growth of introduced species. Of particular relevance for this case are that success usually comes in disturbed environments, disturbed (e.g., non co-evolved) communities, and where existing species numbers are low. Relative to other fish species in the delta, threadfin shad exhibits traits that conform to an opportunistic life history strategy (Winemiller and Rose 1992; Nobriga and others 2005). These general traits (small, short-lived, high reproductive effort) combined with favorable conditions to foster the successful integration of threadfin shad into the delta fish community. The physical environment of the delta is suitable for threadfin shad across the entire system based on salinity, water temperature, and water clarity (Feyrer and others 2007). Thus, while we observed substantial variability in the abundance of different life stages, the fish is found throughout this tidal freshwater system. This suggests that the delta has been physiologically accommodating for threadfin shad. However, the availability of resources (food abundance) appears to have a particularly strong effect on where threadfin shad are most abundant. Thus, the invasion success of threadfin shad in the delta could be a model for the 'niche opportunity' concept (Shea and Chesson 2002), and conforms to many of the empirical rules of biological invasions proposed by Moyle and Light (1996).

In the delta threadfin shad is widely distributed. However it is most commonly encountered and abundant in the southeastern region where suitable abiotic habitat coincides with high prey abundance. These regions also have a relatively high density of submerged aquatic vegetation in shallow flooded islands and littoral zones (Brown and Michniuk 2007), which provides important spawning and larval rearing habitat (Grimaldo and others 2004). Historic studies conducted in 1963-1964 (Turner 1966), and those more recently (Feyrer 2004; Grimaldo and others 2004), identified a similar distribution for threadfin shad. Turner (1966) also found that threadfin shad was relatively abundant in dead-end sloughs of the northeast delta, areas which are not sampled by the current monitoring programs but provide functionally similar habitat.

Threadfin shad appear to grow relatively fast in the delta and reach 70-90 mm by the onset of winter. This growth rate is generally consistent with that reported for Lake Powell, Utah and Arizona, U.S.A. (Blommer and Gustaveson 2002). However, it is faster than that observed in central Arizona, U.S.A., reservoirs (Johnson 1970). Sources of growth rate variation in fish populations can often be difficult to detect. Our results indicated that apparent growth rate during fall declined with increasing abundance. The negative relationship with abundance suggests density-dependent effects may be important. Density dependence is consistent with previous research indicating that intraspecific competition for food can be a major factor limiting growth of threadfin shad in reservoirs (Johnson 1970). Other studies have also found that the condition of young shad is sensitive to prey abundance (Kashuba and Matthews 1984). We could not detect an effect of overall average temperature or the rate at which temperatures decrease into winter. However, Betsill and Van Den Avyle (1997) found that interactions between food availability and water temperature explained a substantial portion of the variability in growth rates and cohort survival of young threadfin shad.

Catches at just seven of the 100 sampling sites have driven long-term patterns in the CDFG-calculated abundance indices. The general pattern at these stations can be characterized as having variable periods of high and low abundance with no overall long-term trend. The recent period of near-record low abundance in the FMT is not unprecedented but is especially noteworthy because it has persisted. Low abundance is also apparent in the 20-mm Survey, in salvage density during all seasons, and also in commercially harvested biomass trends. It is coincident with similar declines for other pelagic fishes (Feyrer and others 2007; Sommer and others 2007). The persistence of low abundance is also noteworthy because of the documented ability of threadfin shad to rapidly recover from low abundance levels. These so-called population explosions occur in part because of synchronous spawning behavior, which maximizes reproductive fitness (Kimsey and others 1957; McLean and others 1982). The contagious distribution of threadfin shad necessitates examining factors other than simple abundance to better understand the context of the current period. The observed lower fraction of samples with threadfin shad present and smaller-sized catches suggest that the recent decline in abundance may be driven by the FMT encountering fewer and smaller-sized schools of threadfin shad. There have been similar periods of smaller-sized catches in the past, especially around the mid 1980s. However, the persistently low fraction of samples with fish present is unprecedented in the time series.

There may be a number of factors affecting threadfin shad abundance in the delta. Recent studies suggest that there are no measurable effects of disease on the population (Baxter and others 2008). There is also no evidence that abiotic habitat – measured as the combination of water temperature, clarity, and salinity – has declined in recent years (Feyrer and others 2007). Traditional stock-recruit relationships are generally poor for opportunistic-type fishes such as threadfin shad (Winemiller 2005). It is therefore not surprising that we found little evidence for consistent stock-recruit or stage-recruit effects on the population. However, there did appear to be a complete "disconnect" between summer salvage density and FMT CPT, suggesting that factors occurring during the summer-to-fall transition might be one possible critical period. There are two factors in particular that are of concern for threadfin shad during this time period, dissolved oxygen and the toxic algae *Microcystis aeruginosa*, both of which occur in the center of threadfin shad distribution. Episodes of low dissolved oxygen concentration commonly occur in the San Joaquin River and have been known to cause die-offs of threadfin shad. Such events are difficult to characterize and quantify but might be responsible in part for the sudden declines in abundance sometimes observed from one year to the next. In recent years there have been dense blooms of *M. aeruginosa* geographically centered where threadfin shad are most abundant (Lehman and others 2008). The blooms also occur during the critical late summer/early fall when newly spawned fish are recruiting to the population (Lehman and others 2007). The effects of *M. aeruginosa* on threadfin shad could be direct by inhibiting feeding or indirect by affecting food availability. For a variety of herbivorous crustacean zooplankton, *M. aeruginosa* can be toxic, non-nutritious, or inhibit feeding on co-occurring nutritious food (Fulton and Paerl 1987). Further, several *M. aeruginosa* strains have been shown to increase toxin production when exposed to fish (Jang and others 2004). Other factors such as predation and low water temperatures are also known to affect threadfin shad populations in other systems (Parsons and Kimsey 1954; Griffith 1978; Blommer and Gustaveson 2002; McLean and others 2006). In the delta winter temperatures occasionally approach minimum tolerances of threadfin shad and predators such as striped bass and largemouth bass can be highly abundant (Feyrer and Healey 2003; Nobriga and Feyrer 2007).

One general limitation of our study is the dependence on correlations with limited data. We acknowledge that infrequent regionally-focused events, such as those suggested above, can be difficult to detect with such methods and therefore may incorrectly be assumed to be unimportant (Rose 2000). Further, non-linear effects and interactions between factors are likely to be important, but are rarely detected with such methods. Improved field observations and controlled laboratory studies designed specifically for threadfin shad, which can then inform modeling studies, are desperately needed to better understand the factors that affect threadfin shad population dynamics in the delta.

In summary, threadfin shad has had exceptional success in the Sacramento-San Joaquin Delta. In particular, channels of the south delta with deep, clear, fresh water and high zooplankton densities support high fish abundance and growth rates. Like other regions where this species occurs, population trends have been highly variable without clear stock-recruitment relationships. While there have been similar periods of low abundance in the past, the persistently low fraction of samples with shad present is unprecedented and coincides with declines in several other pelagic fishes. Hence, there is reason to believe that threadfin shad currently may not be thriving in the delta. However, the future of the delta likely includes warmer temperatures and increases in the amount of open water habitat from the flooding of islands, which may work to the advantage of this introduced species (Lund and others 2007).

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A method for physically based model analysis of conjunctive use in response to potential climate changes

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[1] Potential climate change effects on aspects of conjunctive management of water resources can be evaluated by linking climate models with fully integrated groundwater–surface water models. The objective of this study is to develop a modeling system that links global climate models with regional hydrologic models, using the California Central Valley as a case study. The new method is a supply and demand modeling framework that can be used to simulate and analyze potential climate change and conjunctive use. Supply-constrained and demand-driven linkages in the water system in the Central Valley are represented with the linked climate models, precipitation-runoff models, agricultural and native vegetation water use, and hydrologic flow models to demonstrate the feasibility of this method. Simulated precipitation and temperature were used from the GFDL-A2 climate change scenario through the 21st century to drive a regional water balance mountain hydrologic watershed model (MHWM) for the surrounding watersheds in combination with a regional integrated hydrologic model of the Central Valley (CVHM). Application of this method demonstrates the potential transition from predominantly surface water to groundwater supply for agriculture with secondary effects that may limit this transition of conjunctive use. The particular scenario considered includes intermittent climatic droughts in the first half of the 21st century followed by severe persistent droughts in the second half of the 21st century. These climatic droughts do not yield a valley-wide operational drought but do cause reduced surface water deliveries and increased groundwater abstractions that may cause additional land subsidence, reduced water for riparian habitat, or changes in flows at the Sacramento–San Joaquin River Delta. The method developed here can be used to explore conjunctive use adaptation options and hydrologic risk assessments in regional hydrologic systems throughout the world.

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1. Introduction

[2] Climate change is likely to have important influences on water-resources management options that will be needed to sustain groundwater by conjunctive use strategies [*Alley et al.*, 1999; *Alley*, 2001]. In most watersheds, groundwater resources are really part of a single resource comprising precipitation, surface water, and groundwater resources that require combined simulation and analysis. Influences of climate change may be manifested as changes in streamflow in regions suitable for agriculture, and in the fundamental interplay between natural and societal water supplies and demands. With respect to groundwater, these climate-related changes may include significant variations in recharge, discharge, and groundwater withdrawals in concert with, and independently from, climatic influences on surface water resources. Many representations and considerations of these influences may have neglected the variations in near-term policy and operational decision making on seasonal to interannual time scales, and ignored the effects of climate changes on long-term policy and capital investment decisions on interdecadal time scales [*Gleick and Adams*, 2000; *Gleick et al.*, 2006; *Aerts and Droogers*, 2004; *Intergovernmental Panel on Climate Change* (*IPCC*), 2008; *California Natural Resources Agency*, 2009]. Some effects of climate change on agriculture have been addressed by previous studies [*Frederick et al.*, 1997; California Department of Water Resources (*CADWR*), 2005, 2008a; *U.S. Climate Change Science Program*, 2008; *Lettenmaier et al.*, 2008; *Karhl and Roland-Holst*, 2008]. Others have included these features but have not completely represented both components (surface water and groundwater) of conjunctive use and,

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especially, the role or effects of groundwater resources [*IPCC*, 1996; *Aerts and Droogers*, 2004; *Gleick et al.*, 2006; *Hanak and Lund*, 2008; *Chung et al.*, 2009]. Thus, a method to assess the short- and long-term perspectives is needed to understand how climate change may effect conjunctive use in a supply and demand framework to assess development, management, and sustainability of water resources [*Alley et al.*, 1999; *Alley*, 2001; *Alley and Leake*, 2004; *Gurdak et al.*, 2009; *Hanson et al.*, 2010b].

[3] Both climate change and variability along with increased human demand with potential land use changes will affect the distributions of supply and demand components [*Vörösmarty et al.*, 2010; *Aerts and Droogers*, 2004] and sustainable water development [*Scanlon et al.*, 2006] throughout the world's regional aquifers. Recent studies [*Hanson et al.*, 2002, 2004, 2006, 2009; *Gurdak et al.*, 2007, 2009; *Kumar and Duffy*, 2009] have identified quasiperiodic cycles in hydrologic time series of precipitation, groundwater, and streamflow that appear to correspond to quasiperiodic climatic forcings such as ENSO, NAMS, PDO, and AMO [*Dettinger et al.*, 1998; *Gurdak et al.*, 2009]. Additional recent studies also have indicated that climate change has started to affect the streamflow in regional watersheds of North America such as the Sierra Nevada and the Rocky Mountains [*Stewart et al.*, 2004, 2005; *Milly et al.*, 2005; *Barnett et al.*, 2008; *Das et al.*, 2009; *Gray and McCabe*, 2010], and has affected groundwater recharge such as in Sierra Nevada watersheds [*Earman and Dettinger*, 2008; J. L. Huntington and R. G. Niswonger, Role of surface and groundwater interactions on projected base flows in snow dominated regions: An integrated modeling approach, submitted to *Water Resources Research*, 2011] that provide runoff and recharge to the regional aquifers of the Central Valley, California.

[4] A method is needed to assess how climate change could affect surface water and groundwater use in highly developed agrourban watersheds. An emerging approach to providing this method is holistic modeling with conjunctive use analysis using linked and physically based hydrologic models that combine the natural and human components of use and movement of water. Some previous climate change studies have linked GCMs and regional hydrologic models at watershed scales with land uses such as agriculture [*Aerts and Droogers*, 2004; *Chung et al.*, 2009]. A few other studies linking GCMs to regional hydrologic models in historical contexts have included groundwater, surface water, and the demands of agriculture [e.g., *Hanson and Dettinger*, 2005]. However, there has not been a model linkage that has propagated potential forcings of climate change from the GCM global scale through the precipitation-runoff modeling of surrounding mountains and then to demand-driven and resource-constrained conjunctive uses of groundwater and surface water in an agricultural system such as the Central Valley of California. Previous studies have investigated portions of agricultural watersheds, such as the northern half of the Central Valley (Sacramento Valley), and investigated the demand from climate change on the regional surface water resources [*Aerts and Droogers*, 2004; *Chung et al.*, 2009] throughout the Central Valley. In contrast, this method employs a suite of models to obtain a physically based and realistically complex depiction of the whole conjunctive use system within a supply and demand modeling framework.

[5] Competing demands on water resources by urban, agricultural, and environmental stakeholders continue throughout the world [*Vorosmarty et al.*, 2010] and are especially exemplified by the history of water use and resource development in the Central Valley. California's water delivery system and agricultural practices have been designed and operated on the basis of the climate of the 20th century, yet the Central Valley's population has nearly doubled to 3.8 million people since the 1980s and is expected to increase to 6 million by 2020 [*Faunt et al.*, 2009d]. Regionally, urban growth has intensified demands for water that are exacerbated by expected reductions in Colorado River water deliveries to Southern California [*Faunt et al.*, 2009d], Statewide drought [*CADWR*, 2008b, 2008c], and the San Joaquin–Sacramento Bay Delta ecological crisis [*Faunt et al.*, 2009d]. During the historical period (1961–2003), surface water generally has been available with the major storage and supply systems in place, except during extreme droughts [*Faunt et al.*, 2009b]. The historical delivery of surface water represents 53% of the total water delivered for irrigation and municipal and industrial use, with groundwater pumpage making up the rest. Historical simulations [*Faunt et al.*, 2009a, 2009b, 2009c, 2009d] indicate that the full capacity for delivering groundwater has not been tapped since no more than about 61% of the potential simulated total in-place well-pumping capacity was required to supply the demand for water during the driest years of recent decades.

[6] As part of the ongoing U.S. Geological Survey Climate Change Program (http://www.usgs.gov/global_change/), the purpose of this study is to develop simulation and analysis methods. The assessment of the feasibility of these methods is demonstrated with the analysis of the effects of climate change on the Central Valley hydrologic system. This supply and demand modeling framework provides a method to evaluate a suite of linked models as part of the sort of decision support system that will be required for the analysis of conjunctive use in regional flow systems throughout the world. While the Central Valley example is used to demonstrate the capabilities of this method, this methodology is applicable to a wide variety of regional settings from the North China Plains, Indo-Gangetic basins [*Briscoe*, 2005] or Mediterranean basins, to the Blue Nile of Africa [*Jeuland*, 2010] and the Guranai of South America [*Foster et al.*, 2006].

[7] In general, the present study is a step toward addressing several basic questions about the influence of climate change on conjunctive use of water resources: First, how does climate change and variability affect the availability and proportions of supply and demand components of agriculture? How do recharge, discharge, and change in storage in principal aquifers in the United States such as the Central Valley respond to climate variability on interannual to multidecadal timescales and to climate change from human activities? How much hydrologic response is caused by natural variability and how much is caused by human activities [*Gurdak et al.*, 2009]? Can the hydrologic responses projected by a series of linked physically based hydrologic models provide a tool for the management of demand-driven and supply-constrained conjunctive use?

[8] In this paper, we present the approach of this method by briefly describing the major components, including the downscaling of the climate change scenarios and the linkage

of the models. We demonstrate feasibility of the conjunctive use analysis from this method by presenting results from a GCM linked to a regional mountain hydrologic watershed model (MHWM) that provides inflow boundary conditions for an integrated hydrologic model of the Central Valley (CVHM) (Figure 1). The features available for simulation and analysis of the uses and movements of water include runoff from the surrounding mountains, the demands, uses and movements of water for irrigation and natural vegetation, and the response of supply from groundwater and streamflow under a climate change scenario. The potential effects of climate change simulated here include changes in diversions used to supply surface water for irrigation, streamflow and streamflow infiltration, groundwater storage, and related effects such as land subsidence and groundwater/surface water relations in the delta. Thus, groundwater, surface water, and agricultural components simulated by CVHM within the valley are inherently connected to the surrounding watersheds through runoff simulated by MHWM, therefore providing for a quantitative analysis of impacts on conjunctive use throughout the entire hydrologic system.

2. Approach to Regional Modeling

[9] GCM results were downscaled to a spatial resolution that is more commensurate with the complex terrain of

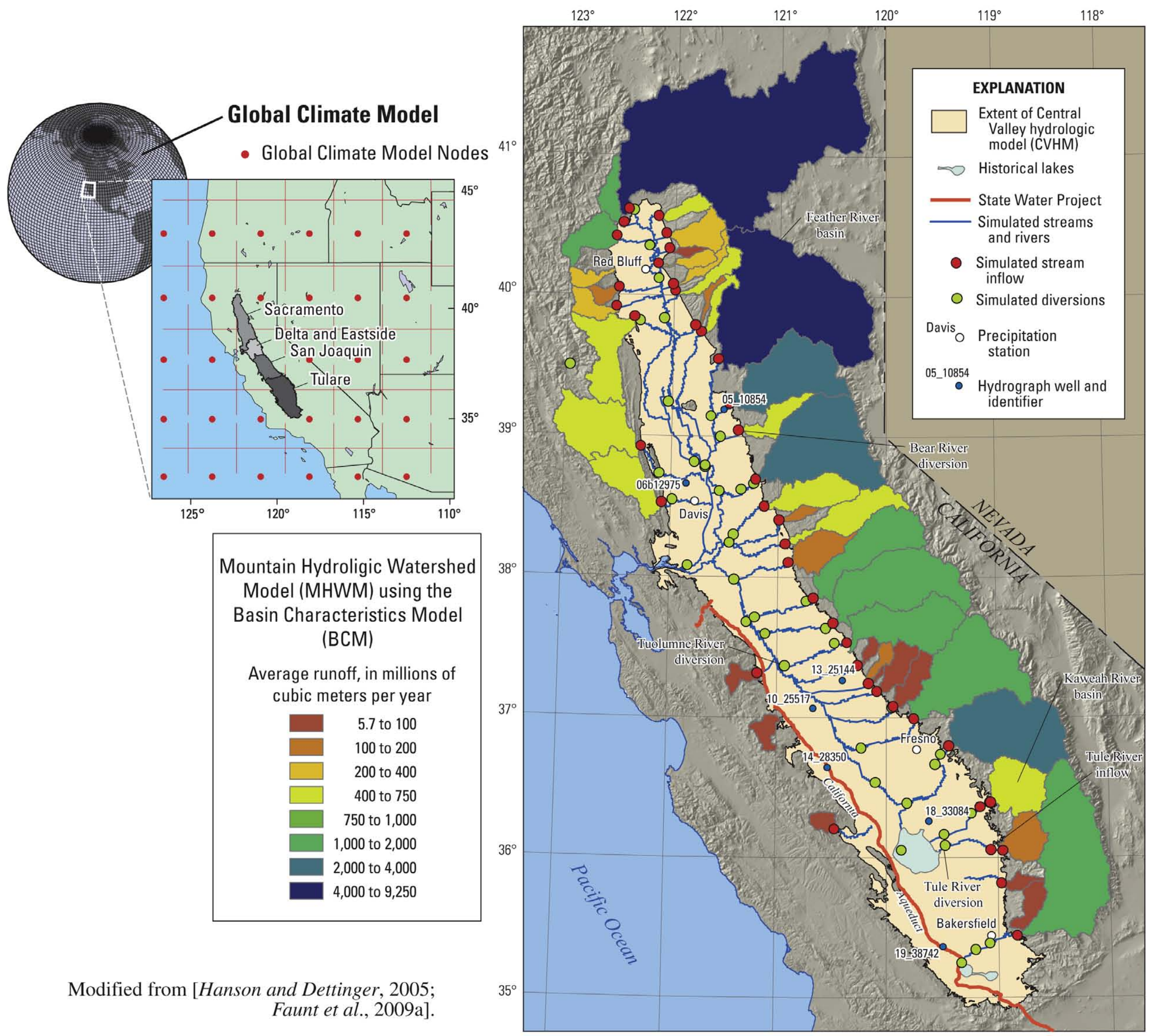


Figure 1. Map showing relation of global climate model (GCM) grid to areas of regional hydrologic models, to California, and to the Central Valley, California. Also shown are watersheds modeled with the mountain hydrologic watershed model (MHWM) by the basin characterization model (BCM) model and the active model grid for the valley-wide Central Valley hydrologic model (CVHM) with stream inflow that represents the linkage between the BCM and the CVHM models and diversion locations, selected precipitation and streamflow gaging stations, and wells. Modified from *Hanson and Dettinger* [2005] and *Faunt et al.* [2009a].

the CV watersheds and linked with regional hydrologic models. In so doing, it is possible to assess whether this methodology is a feasible approach to investigate potential effects of climate change on conjunctive use, not only in CV, but in other regional hydrologic systems. The order of modeling and linkage is (1) GCM simulation, (2) statistical downscaling over the extent of the regional hydrologic models (RHMs), (3) precipitation-runoff simulation of the regional watersheds surrounding the valley, (4) integrated hydrologic modeling of the valley, and (5) analysis of the multimodel output (Figure 2).

[10] The future climate projection used to demonstrate the method is the climatic response of a particularly greenhouse sensitive GCM, the Geophysical Fluid Dynamics Laboratory Climate model 2.1 (GFDL) [*Delworth et al.*, 2006], to a scenario of rapidly increasing greenhouse gas emissions (A2) [*Cayan et al.*, 2009; *IPCC*, 2007]. This particular climate scenario is generally characterized over California as quite warm and substantially drier than historical conditions. Climate projections such as the GFDL-A2 and related seasonal changes in precipitation and temperature in any given climate simulation only represent an example of the potential outcomes. Therefore, the MHWM and CVHM responses simulated here demonstrate the use of the method and do not represent particular events in the future; rather this example is a single sample from a distribution of possible hydrologic outcomes that, with consideration of additional scenarios (to come in future studies), could provide useful guidance for water resource management decisions.

[11] The MHWM model here is an implementation of the basin characterization model (BCM) [*A. L. Flint and Flint*, 2007; *L. E. Flint and Flint*, 2007a, 2007b], which is a grid-based distributed-parameter water balance model used to simulate evapotranspiration, changes in soil water storage, recharge, and runoff from precipitation in the surrounding watersheds of the Sierra Nevada on the eastern side of the Central Valley and selected parts of the Coast Ranges on the western side. The MHWM (BCM) was calibrated to reproduce historical streamflows for the period 1950–2000. The GCM predicted precipitation and temperature were used as input to MHWM (Figure 2). While other grid-based precipitation-runoff models could be employed for this part of the method such as the VIC [*Lettenmaier and Gan*, 1990; *Lettenmaier et al.*, 2008] or PRMS [*Leavesley et al.*, 1992; *Hay et al.*, 2000] models, the BCM

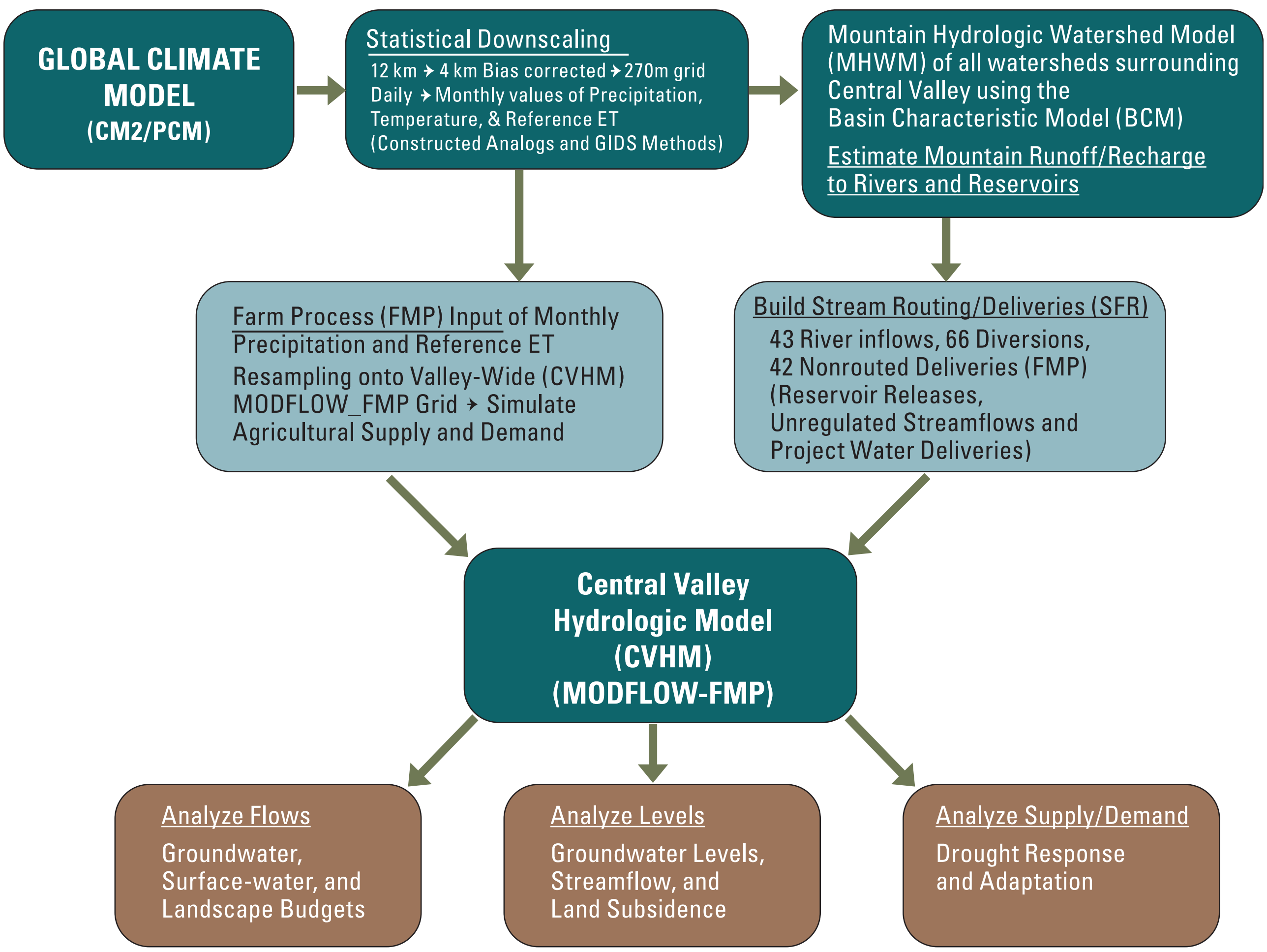


Figure 2. Diagram showing architecture of model linkages and data flow, used to simulate and analyze climate change, that constitute components of a decision support system for conjunctive use in the Central Valley, California.

provided adequate temporal detail and enhanced spatial detail that was efficiently computed for the large number of watersheds surrounding a large regional aquifer system such as the Central Valley.

[12] The CVHM is based on the integrated hydrologic flow model MODFLOW [*Harbaugh*, 2005] with the Farm Process (MF-FMP2) [*Schmid et al.*, 2006; *Schmid and Hanson*, 2009], and simulates integrated uses and movements of water throughout the landscape, surface water, and groundwater flow systems (Figure 1) [*Faunt et al.*, 2009a, 2009b, 2009c, 2009d]. The CVHM model was calibrated to historical hydrologic conditions for the period 1961–2003, to reproduce observed time series of streamflows, streamflow losses and gains, diversions of streamflow, land subsidence, and groundwater levels throughout the valley. CVHM is discretized with 10 layers of 2.59 km^2 square model cells and monthly stress periods and biweekly time steps [*Faunt et al.*, 2009c]. In this linked model methodology, the simulated reference ET, runoff and recharge from the MHWM, along with downscaled precipitation and reference ET derived from the GCM output, were then used as input to the Central Valley regional hydrologic model (CVHM) (Figure 2).

2.1. Linking Regional Hydrologic Models to a GCM

[13] The linkage of regional models to the GCM was a multistep and multipath process (Figure 2) that only used precipitation and temperatures from the GCM to describe climate change and represent the movement and use of water. Multiple steps were used to transform the GCM data to provide a feasible linkage through multiple paths to the RHMs (MHWM and CVHM) as regional monthly input that helps maintain separation between the supply and demand components of water use and groundwater/surface water responses to climate change. This method of linkage was unidirectional, in the sense that the larger scale models provide input to their finer-scale model partners, but are not affected by any feedback from the output of the finer-scale models. The methods and issues of linkage were discussed and analyzed for a historical period [*Hanson and Dettinger*, 2005] and for multiple watersheds with different hydrologic settings [*Aerts and Droogers*, 2004]. This method connects a GCM, which is globally energy and water balanced but not constrained through calibration by water transport to observed water transport, with the RHMs that represent more localized inflows and outflows that are both balanced and constrained through the calibration process with numerous local historical observations and observation types. Because the GCM is not specifically calibrated or adjusted for the detail of a regional watershed, downscaling with bias corrections are necessary to effectively transmit the GCM output to the RHM as input.

[14] The downscaling of GCM output is accumulated to monthly values from the constructed analogues [*Hidalgo et al.*, 2008] and gradient and inverse distance squared weighting (GIDS) methods [*Flint and Flint*, 2011]. The downscaling of precipitation and temperature data was a three-step statistical process (Figure 2) that started with the constructed analogues method [*Hidalgo et al.*, 2008]. First, the constructed analogues method is used to downscale GCM-simulated weather, day by day, from the GCM grid cells to a 12 km grid on the basis of the combinations of GCM scale observed, historical weather patterns that best reproduce the GCM-simulated weather for a given simulated day. The statistical downscaling method skillfully reproduces daily and, especially, monthly variations of precipitation and temperature deviations from long-term normals during the historical period, when applied to geographically smoothed (GCM-scaled) versions of the historical record [*Hidalgo et al.*, 2008; *Maurer and Hidalgo*, 2008]. The (RMSE) skill with which GCM patterns are reconstructed by constructed analogues during applications to GCM projections of future precipitation and temperature variations and changes does not decline as the 21st century proceeds, giving the primary basis for believing that the method continues to be skillfully applicable even under changing climatic conditions. Once this best fit combination of historical weather patterns is identified, the same combination of more finely resolved weather maps (for the same historical days) is constructed to obtain the downscaled (highly resolved) weather pattern corresponding to the GCM weather. Second, these constructed-analogues weather maps were then further downscaled to a 4 km grid using the GIDS method and bias corrected for long-term average and standard deviation differences between downscaled and observed statistics [*Flint and Flint*, 2011], which is an update to approaches used previously by *Aerts and Droogers* [2004] and *Hanson and Dettinger* [2005]. This downscaling step used a statistical interpolation approach developed by *Nalder and Wein* [1998] that was modified with a nugget effect specified as the length of the coarse resolution grid, in this case 12 km grid cell [*Flint and Flint*, 2011]. The model combines a spatial weighting with GIDS to monthly grid data by using multiple regressions developed for each month at each grid cell. Parameter weighting is based on location and elevation of the new fine-resolution grid (4 km) relative to existing coarse-resolution (12 km) grid cells [*Flint and Flint*, 2011]. The bias correction was then completed on a cell-by-cell basis for each month of the 100 year future climate scenario by matching means and standard deviations from the PRISM regional precipitation and temperature fields [*Daly et al.*, 1994] at each 4 km cell for the base period 1950–2000. This base period includes the IPCC base historical period 1970–2000 [*IPCC*, 2007, 2008].

[15] The third step is statistical downscaling to a finer spatial resolution that captures the resolution of the surrounding mountain watersheds and water balance subregions of the Central Valley example. This step uses the bias-corrected 4 km precipitation and air temperature data to downscale further to a 270 m grid for input to the MHWM with this same discretization using the GIDS approach. Downscaled precipitation and air temperatures at 270 m are used as the climate drivers to simulate runoff, recharge, and ET for the BCM in MHWM in the surrounding mountain watersheds, and then downscaled precipitation and reference ET are directly used as inputs for MF-FMP2 in CVHM to simulate water consumption of natural vegetation and crops, runoff back to streamflow networks, and deep percolation as groundwater recharge (Figure 2).

[16] It is important to recognize that this is a scenario, not a forecast and is used here to illustrate a plausible outcome and demonstrate the method of model linkage, feasibility of the supply and demand modeling framework, and

utility of conjunctive use analysis. The GCMs used in current climate change projections or even historical climate simulations are not constrained nor expected to reproduce the historical sequence of climatic events on any time scale short of the slow, specified time scale of the externally imposed greenhouse gas buildup. Given a large enough ensemble of such simulations (differing only in their initial conditions), the range of simulations may reflect (imprecisely) the range of possible alternative pathways along which historical climate could have evolved or, more practically, the range of uncertainties associated with the sensitive dependence of the climate (and climate model) on uncertain initial conditions, GCM to GCM differences, and continuing uncertainties about which emissions pathway society will choose to follow [*Dettinger*, 2005]. Particular components of the linked system also may have inherent uncertainties, such as those contained in streamflow projections [*Maurer and Duffy*, 2005], attributes of agricultural practices [*Ficklin et al.*, 2009], or assessment of risk in planning reservoir operations [*Brekke et al.*, 2009]. Therefore, the single (GFDL-A2) projection evaluated here can only be interpreted as one example from among a wide range of possible climate futures. The GFDL-A2 GCM simulation selected is one of the more extreme climate change scenarios among those available at the time of analysis [*Cayan et al.*, 2008], and can be considered a conservative estimate of the potential changes to the supply and demand components of a hydrologic system.

[17] In contrast, CVHM is an RHM that is tightly constrained by specified boundary forcings and conditions that require a constrained and calibrated regional water balance based on the match between historical observed and simulated water transport. Because of these strong constraints, historical simulations by RHMs, such as CVHM, can be calibrated to reproduce the historically observed fluctuations and magnitudes in groundwater levels, streamflow, land subsidence, and related water flow as closely as possible within the level of detail of the modeling framework [*Faunt et al.*, 2009c]. Even though RHMs, such as CVHM, are typically designed to be capable of being accurate at temporal and spatial scales relevant to the conjunctive use issues, uncertainties in measured inflows and outflows can typically range from 5% to more than 20% [*Hanson et al.*, 2002]. In turn, these uncertainties can result in several meters of model error in groundwater levels and related errors in estimates of changes in groundwater storage. When this is compounded with other local uncertainties driven by other climatic forcings such as tidal fluctuations at the delta, the resulting errors, even for calibrated models, can easily exceed a meter for groundwater levels at any given time or location. Even with these uncertainties, the CVHM model adequately reproduces the flow system, the long-term historical changes in flows and groundwater levels on a regional scale (root-mean-square error of groundwater heads of 0.24 m [*Faunt et al.*, 2009c]), and seasonal dynamic interactions in the conjunctive use and movement of water throughout the Central Valley [*Faunt et al.*, 2009c; *Hanson et al.*, 2010b].

2.2. Using the MHWM Model With GCMs

[18] The MHWM model used here is based on deterministic water balances that estimate in-place recharge, actual ET, and runoff according to the underlying BCM model [*A. L. Flint and Flint*, 2007; *L. E. Flint and Flint*, 2007a, 2007b]. The BCM model is grid based at 270 m and relies on gridded inputs of monthly precipitation, maximum and minimum air temperature. The model uses the distribution of precipitation, snow accumulation and melt, potential evapotranspiration, soil water storage, and bedrock permeability to calculate monthly water balances for the model area, including basin recharge and runoff over current and future climatic conditions. In this study, the MHWM application of BCM was driven by the downscaled GCM climate data to simulate actual ET, runoff, and recharge from the watersheds in the Coast Ranges and Sierra Nevada that provide inflows to the Central Valley (Figure 1).

[19] BCM computes potential evapotranspiration on an hourly time step on the basis of solar radiation that is modeled on the basis of percent of visible sky, accounting for topographic shading of each 270 m grid cell. Computed solar radiation, combined with maximum and minimum air temperatures, is converted to net radiation and soil heat flux [*Shuttleworth*, 1993]. The result is input into the Priestley-Taylor equation (equation (1)) [*Priestley and Taylor*, 1972] to estimate potential evapotranspiration (ET_p), taking into account vegetated and bare soil areas based on vegetation cover on a cell-by-cell basis [*A. L. Flint and Flint*, 2007].

$$\mathrm{ET}_P = \frac{S}{(S+\gamma)}(R_n - G)\lambda \tag{1}$$

where s is the slope of the vapor deficit curve, γ is the psychrometric constant, R_n is net radiation, G is soil heat flux, and λ is the heat of vaporization. The component $\frac{S}{(S+\gamma)}$ is a temperature-dependent function of the form

$$SSG = \frac{S}{(S+\gamma)} = -13.281 + 0.083864\,(T_a) - 0.00012375\,(T_a)^2 \tag{2}$$

where T_a = average monthly air temperature in degrees Kelvin.

[20] The projected (future) potential evapotranspiration (ET_p) relies on projected air temperature to scale the driving forces to current ET_p:

$$\mathrm{ET}_{p(\mathrm{future})} = (SSG_\mathrm{f}/SSG_\mathrm{c})(\mathrm{ET}_{p\,\mathrm{current}}) \tag{3}$$

where SSG_c and SSG_f are $\frac{S}{(S+\gamma)}$ for current climate and future climate, respectively, on the basis of mean monthly air temperature, T_a, for current climate or future projections. This ET_p is aggregated to monthly totals and used with precipitation, soil water storage, and bedrock permeability to determine areas where excess water is available. If available, the model determines whether the water can be stored in the soil, infiltrated into the underlying bedrock (at an estimated rate equivalent to the bedrock permeability), or routed away as runoff.

[21] In general, if a future month is warmer than the 1971–2000 "normal" month, then ET_p increases; if it is colder then ET_p decreases. This approach to estimating future ET_p assumes that R_n and G are the same in the

future as they are now, for which we have no reliable information at this time. Because *SSG* is nonlinear with temperature, areas with colder climates (e.g., northern Central Valley and Sierra Nevada) that increase in temperature with future climate have a greater increase in ET_p than warmer areas because the slope of equation (2) continually flattens out with increasing temperature.

[22] Snow accumulation and ablation are simulated by using an adaptation of the operational National Weather Service (NWS) energy and mass balance model; specifically, by using the Snow-17 model described by *Anderson* [1976] and *Shamir and Georgakakos* [2007]. The model calculates the potential for melt as a function of air temperature and an empirical snowmelt factor that varies with day of year [*Lundquist and Flint*, 2006]. The accumulated snow depth is calculated for areas where precipitation occurs and air temperature is less than or equal to 1.5°C (34.7°F). Sublimation of snow is calculated as a percentage of potential evapotranspiration on a monthly basis analogous to snow course data.

[23] In the historical (1962–2003) period, observed precipitation and temperatures were input to the BCM to simulate the potential runoff and recharge from the mountain watersheds that surround the Central Valley (Figure 1). Although the model is monthly, because of the disruption of the natural seasonal signal by reservoir operations, the model was calibrated to approximately reproduce annual measured runoff totals from below reservoirs at 43 stream inflow points. This calibration was a manual, iterative process that began by modeling small gauged upper watershed subbasins with no regulated flows owing to management or diversions to establish appropriate bedrock permeabilities for each of the bedrock types in the model. Bedrock permeability is the parameter that partitions excess water into runoff and recharge, with higher permeabilities resulting in greater recharge, and lower permeabilities resulting in greater runoff. Details and results of this calibration for the Great Basin Carbonate and Alluvial Aquifer System are discussed at length by *Flint et al.* [2011], along with model limitations and uncertainties. Upper watershed subbasin outflows were assumed to reflect only runoff conditions that have insignificant base flow. Recharge and runoff were then simulated for all 43 watersheds.

[24] Because the different basins have varying amounts of base flow because of the different geologic environments and alluvial deposits, further calibration was performed by adding in-place recharge to runoff estimates until observed yearly outflows were matched. For example, the Sacramento River basin is bounded by volcanic rocks that produce large amounts of groundwater-fed base flow, and as a result, all of the recharge calculated for that basin was added to the runoff in the final calibration. In contrast, the basins in the granitic terrains of the central Sierra Nevada are runoff dominated, and no estimated recharge was added to the basin outflow to match the measured streamflow data. The calibration was done by using annual data, without regard to the timing differences owing to seasonal management operations that are reflected in the monthly observations. The calibration results for the 43 basins, when comparing measured and simulated annual basin discharge for 1962–2003 are reasonable and provide confidence in the calibration. The average ratio of the total measured discharge to simulated discharge was 1.00, and the average ratio of the log of the total measured discharge to simulated discharge was 0.991. The Nash-Sutcliffe efficiency statistic [*Nash and Sutcliffe*, 1970] (1 minus average mean square error divided by variance) was 1.00 and the average r^2 of the measured versus the simulated annual discharge was 0.746.

[25] A final step was taken that scaled the simulated basin discharge to better match the reservoir outflows, accounting for losses in the system owing to diversions or agriculture, or gains to the system owing to subsurface flows from larger, higher-elevation basins to adjacent smaller basins that are downslope. A potential uncertainty in the impacts of climate change on conjunctive use is with regard to the future reservoir operations that are the linkage point between the outflows from the mountain hydrology simulated with MWHM and stream inflows in the Central Valley simulated with CVHM. The MHWM currently does not explicitly simulate rules for reservoir operations but instead uses a scaling approach to match current flows below the reservoirs that approximate annual influences of the reservoir on the water delivered from the mountain watershed to the valley. These same scaling factors are applied to the future climate flows as well, making the assumption that reservoir operations will not significantly change with changes in climate. No water allocation models adequate to providing the linkages and operating rules for all of the reservoirs around the Central Valley were available for this study. However, where regulated flows from reservoir operations provide a significant influence over inflows, this additional linkage may be required to improve the skill of the projections.

[26] Monthly runoff and recharge were simulated for 2000–2100 for all watersheds surrounding the Central Valley and accumulated for drainage areas above each of the stream inflow locations. The monthly accumulated runoff and recharge simulated with MHWM from the watersheds surrounding the Central Valley become the inflows to the CVHM simulation of streamflow routing throughout the Central Valley (Figure 1).

2.3. Using the CVHM Model With GCM and MHWM

[27] To demonstrate the linkage with the GCM and MHWM to CVHM simply requires monthly downscaled GCM climate data over the valley floor and simulated stream inflows from the MHWM model. The downscaled monthly precipitation and potential reference evapotranspiration (Priestley-Taylor approximation, equation (3)) are used as inputs for the Farm Process within MF-FMP2 [*Schmid and Hanson*, 2009] on a cell-by-cell basis to drive consumption of water and runoff across the modeled landscape of the Central Valley from irrigated agriculture as well as from natural and urban vegetation (Figure 2). The CVHM simulates the streamflow, consumption of water as well as runoff and return flows across the landscape, the pumpage of groundwater to supplement surface water deliveries for irrigation, urban water supply pumpage and the effects of groundwater pumpage as land subsidence. Potential effects of increased CO_2 concentrations in the atmosphere on crop water demand coefficients are not included in this study. Similarly, agricultural and urban land uses were held fixed at year 2000 conditions [*Faunt et al.*, 2009a,

2009b, 2009c, 2009d]. Thus, only the direct effects of climate on agricultural and water resources are demonstrated with this example of the supply and demand modeling framework.

[28] The monthly runoff from the surrounding watersheds simulated by the MHWM became stream inflows at 43 locations in the CVHM, where it was routed through the streamflow network throughout all of the major rivers and related conveyance of water to the 66 diversions and exits the valley at the delta (Figure 1). The downscaled precipitation over the valley floor from the GFDL-A2 scenario was used to classify wet, variable-to-dry, and dry year periods from the cumulative departure of future precipitation at Davis, California (Figure 1) and are shown in time series graphs as background shading (Figure 3). As in the work by *Hanson and Dettinger* [2005], each potential future diversion and nonrouted delivery (NRD) was specified for each month on a potential delivery based on future climatic periods and the historical monthly climate-based deliveries. The CVHM simulates supply-constrained demand because these assigned diversions are also dependent on whether the amount of water that enters from the upstream watershed provides enough water to satisfy any or all of the specified diversion after routing the water from the mountain watershed. The diversions take any water that is available up to the specified amount, and the FMP then demands water from the point of diversions to be delivered from one or more diversions to each water balance subregion on the basis of the demand for irrigation from local agriculture in 21 water balance subregions. The NRDs are delivering the full amount specified and their conveyance is not simulated.

[29] The conjunctive use of surface water deliveries and groundwater within CVHM are demand driven and supply constrained on the basis of the physical movement and use

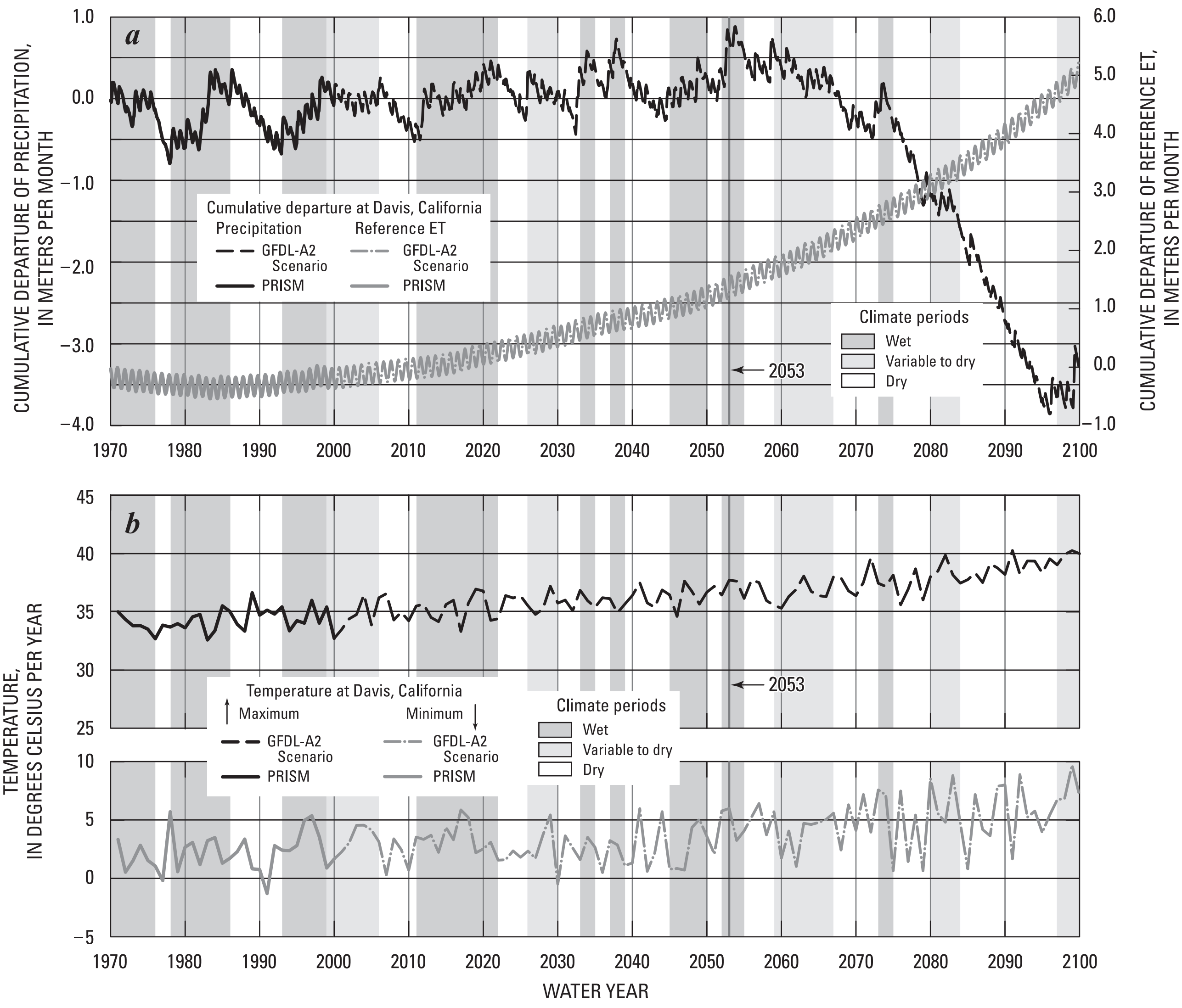


Figure 3. Graphs showing (a) historical and future cumulative departure of monthly precipitation and evapotranspiration (ET) and (b) monthly historical and future cumulative departure of temperature, (c) historical and selected future streamflow percentages, (d) selected historical and future streamflow, and (e) discharge, for selected decades, from the principal surrounding watersheds of the Central Valley, California.

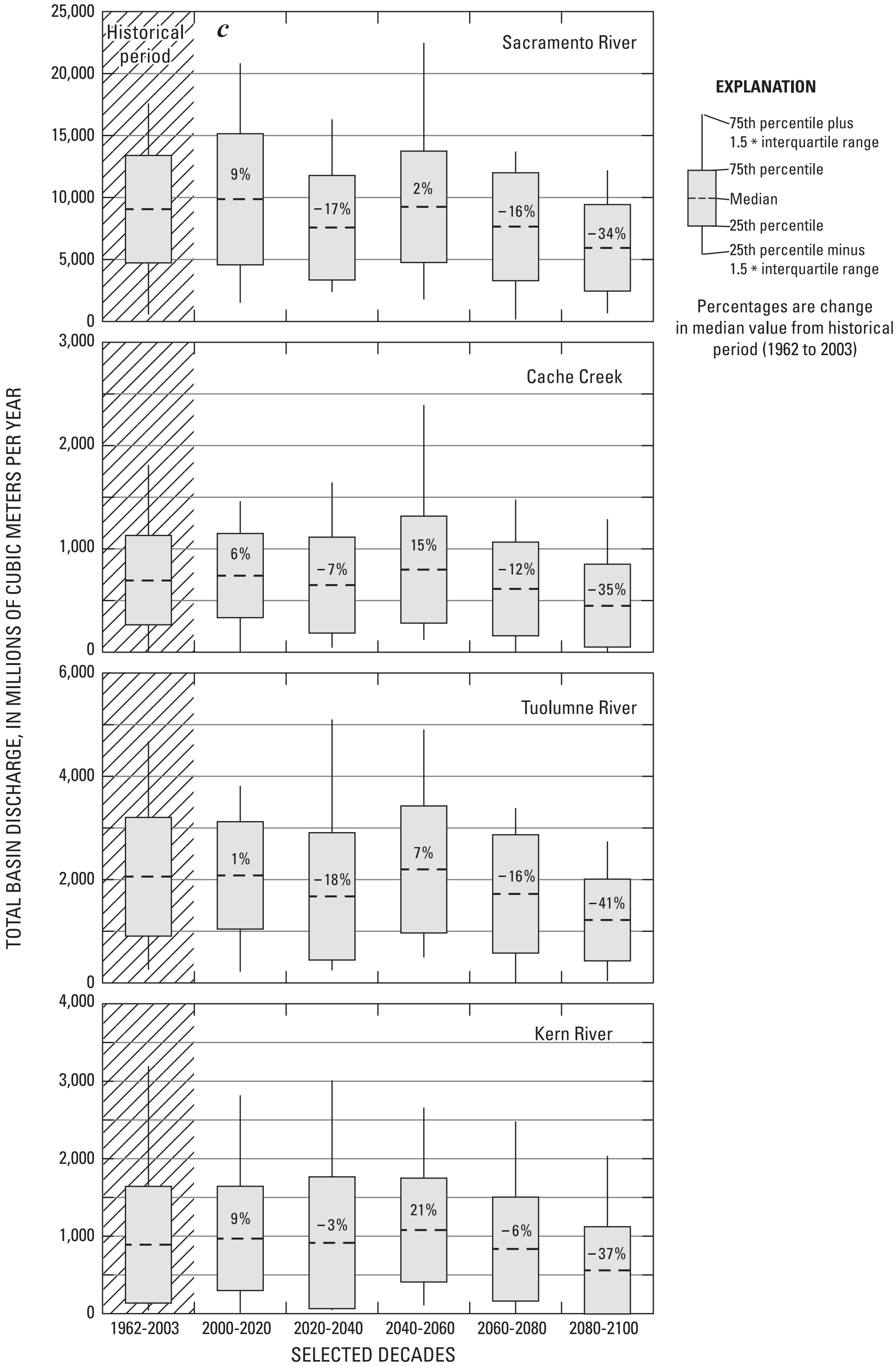


Figure 3. (continued)

of water simulated with MF-FMP2. The supply and demand framework starts with estimation of demand for water as the actual ET from irrigated agriculture and natural vegetation throughout the valley floor. Actual ET is the product of the downscaled reference ET (ET_p) and crop coefficients on a cell-by-cell basis that are scaled by fractions of land exposed to bare soil evaporation and to transpiration for each crop type. The crop irrigation requirement (CIR) is the demand for water that is needed to satisfy the actual ET after potential consumption of precipitation and direct uptake from groundwater. The crop irrigation requirement (CIR), deep percolation to groundwater, and runoff back to streams is then simulated with the additional use of irrigation efficiencies and fractions of inefficient loss of water to runoff on a cell-by-cell basis. Thus the CIR and irrigation efficiencies on a cell-by-cell basis

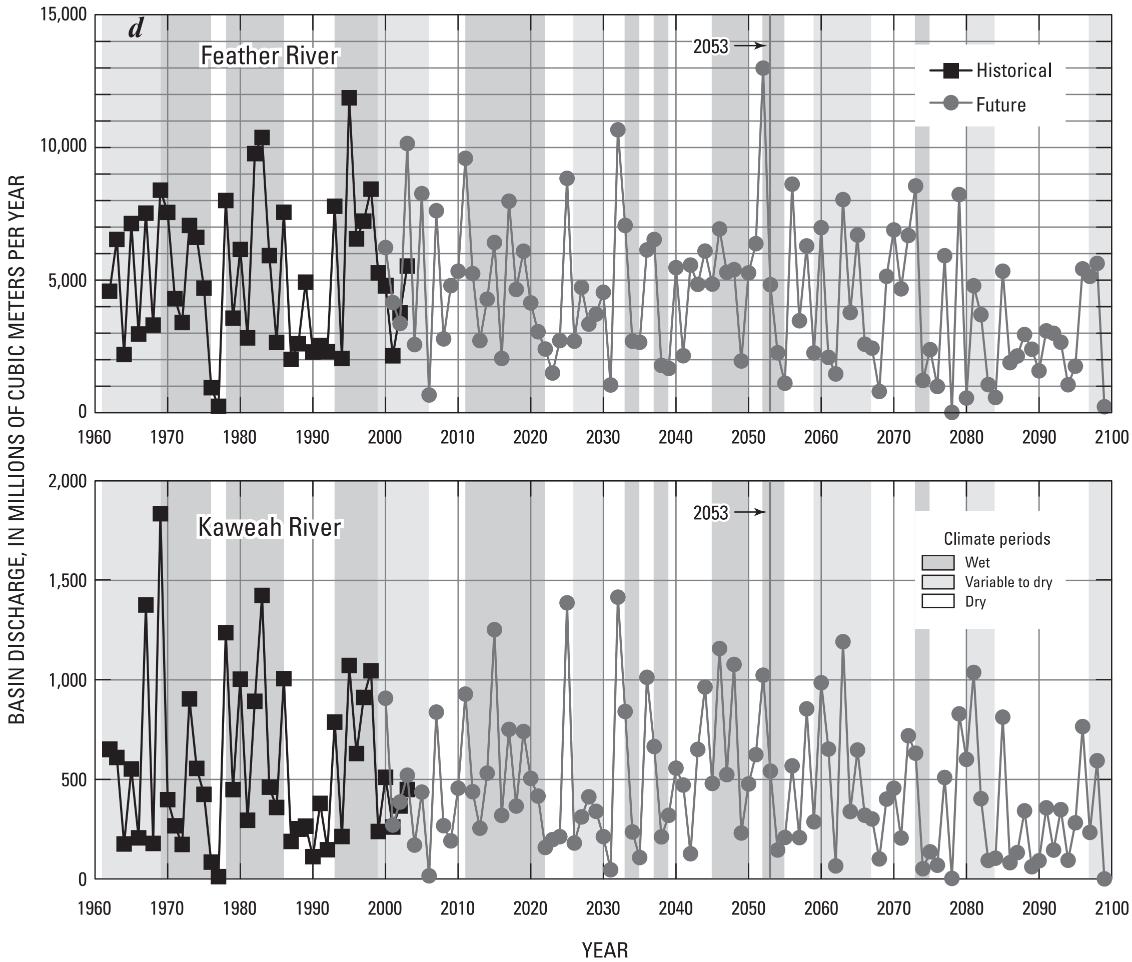


Figure 3. (continued)

dictate the collective Total Farm Delivery Requirement (TFDR) that is needed to satisfy the irrigation demand for each of the water balance accounting subregions. Groundwater recharge and runoff to streams is then computed as fractions of the inefficient losses from precipitation and irrigation. The irrigation demand for surface water is the first supply component of the TFDR. These demands are constrained by the potential climate-based diversions and by the actual amount of water routed through the streamflow network that is available to achieve the potential diversions. If surface water deliveries do not satisfy irrigation demand, then the TFDR demand is supplemented with additional supply from groundwater pumpage. The future scenario demonstrated here used deficit irrigation that would reduce demand to the available supply if demands exceed the capacity to supply irrigation. However, an operational drought, where demand exceeds the collective capacity of surface water deliveries supplemented with groundwater pumpage, was never achieved in this future scenario because of the excessive capacity to pump groundwater.

[30] To complete the linkage with climate, the model also simulates the potential groundwater outflow or inflow as well as river outflow at the delta. Boundary groundwater levels that control the groundwater outflow at the delta were changed on a monthly basis to reflect the rising sea level. The overall rise in sea level for San Francisco Bay was estimated to be as much as 0.86 m (3.1 feet) for the GFDL-A2 scenario [*Cayan et al.*, 2008].

[31] Increase in urban water demand for this example was an assumed linear 1.2% annual increase in urban water use based on a statewide projection for the period 2008–2025 [*Johnson*, 2009]. This increase was imposed directly onto the distribution of urban wells from the year 2000 and reflects an increase in urban water use without a change in urban land use. This projected increase in urban demand is less than half of the 4% increase from the recent past (1983–2003) used for the historical calibration of CVHM [*Faunt et al.*, 2009a, 2009b, 2009c].

3. Results

[32] The feasibility of the supply and demand modeling framework and how this method can provide insight into primary and secondary effects of climate change on conjunctive use within regional hydrologic systems is demonstrated through the linked models of the Central Valley, California. Given a set of linked global climate, regional downscaled climate and regional and local hydrologic models such as described here, the response and sensitivity of a given regional hydrologic system to possible climate changes can be used to evaluate the conjunctive use of

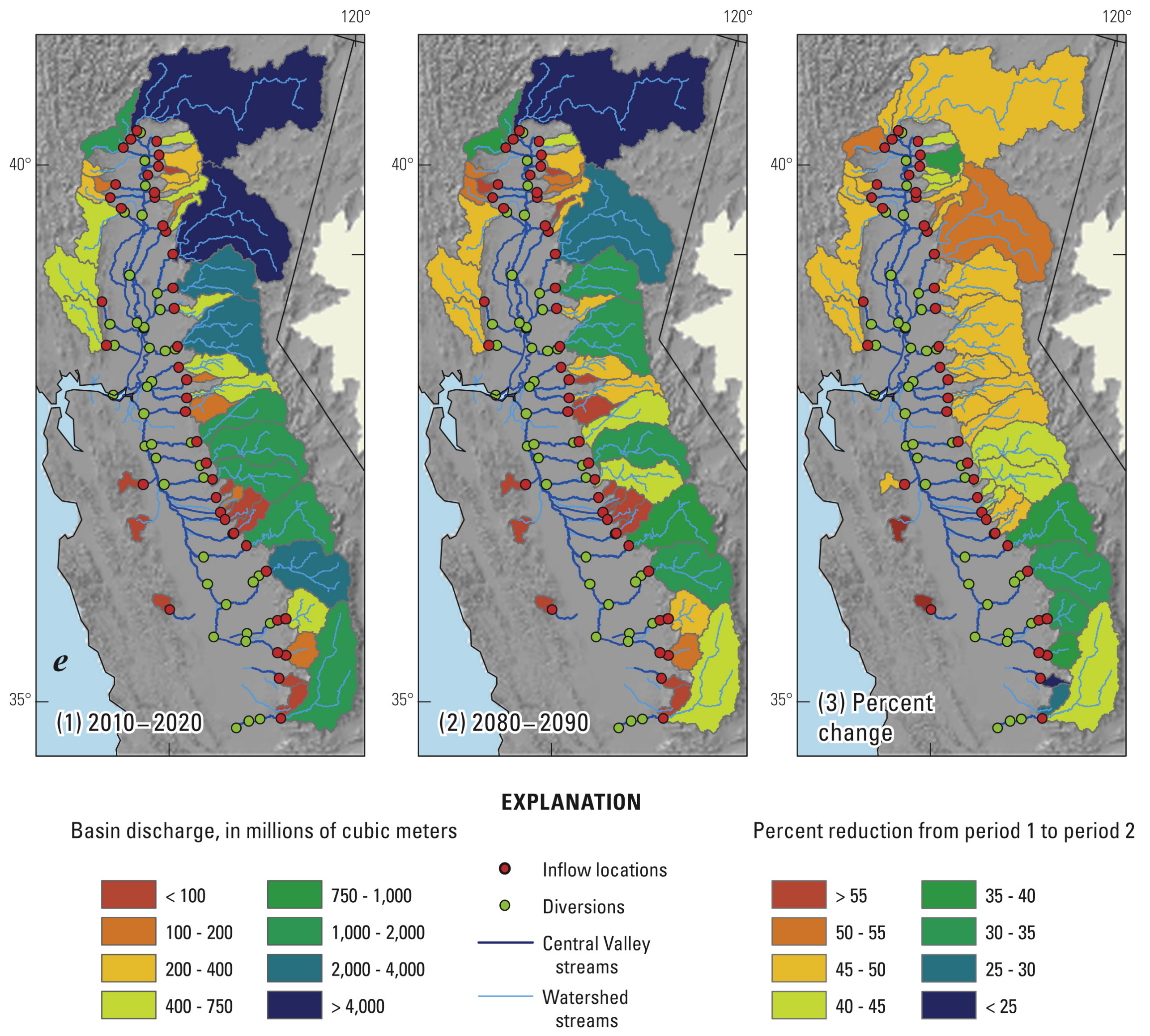


Figure 3. (continued)

water where complex hydrologic and agricultural supply and demand interact.

[33] The downscaled GCM precipitation and temperatures from the GFDL-A2 climate change scenario drive the supply and demand components of this modeling system. The models react to the reduced supply of water with reduced precipitation and related runoff to streamflow, as well as increased demand for irrigation and water available for runoff through reduced precipitation and increased ET*p* from increased temperatures. Overall the precipitation includes intermittent climatic droughts in the first half of the century and sustained droughts in the second half (Figure 3a). Over the 2000–2100 simulation, 57 years are below average precipitation, with 15 years less than and 15 years more than one standard deviation from the mean, respectively. Twelve of these pronounced dry years occur in the second half the 21st century GFDL-A2 scenario, with some average to dry periods lasting more than a decade. Minimum and maximum temperatures from the GFDL-A2 mean increase by approximately 5.4°C and 7.3°C, respectively, from 2000 to 2100 (Figure 3b). Accordingly, cumulative departures of ET_p that historically lack any significant trend [*Hidalgo et al.*, 2005], increase at an accelerating pace through the 21st century driven by increasing temperatures (equation (2) and Figure 3a).

[34] The supply and demand framework reacts to reductions in runoff from the MHWM model and significantly reduces the surface water supply linkage to CVHM that, in turn, shifts the agricultural system into substantial reliance on groundwater pumpage. The simulated changes in climate result in substantial declines in the flows draining into the Central Valley from surrounding mountain watersheds simulated with MHWM, with up to 40% declines in discharge at many of the CVHM inflow points by the end of the 21st century (Figure 3c). This scenario is consistent with recent climate change effect estimates of reduced discharge of 16%–34% during droughts in the 21st century for the Rocky Mountains [*Gray and McCabe*, 2010] but is

higher than most previous estimates for the Sierra Nevada [*Gleick*, 1987; *Lettenmaier and Gan*, 1990; *Jeton et al.*, 1996; *Knowles and Cayan*, 2002]. Annual time series of discharges from the Feather and Kaweah River uplands illustrates the generally prevailing trend in this scenario toward a moderate decline by the end of the century, but more notable increases in frequency of lower streamflows and related dry years in the latter half of the 21st century (Figure 3d).

[35] The linked models yield overall reductions in surface water deliveries for irrigation to the regions adjacent to the Sierra Nevada that show the greatest impact of the simulated transition in sources of supply to meet climate-driven increases in agricultural demand. The projected spatial distribution of mean basin discharge for two selected decades (2010–2020 and 2080–2090) indicates reduction of the inflows to CVHM by 20% to 65% with the largest reductions in the northern Sierra Nevada (Figure 3e). This is consistent with previous studies that showed the largest decrease in snow-water equivalent in the north [*Knowles and Cayan*, 2002] because the northern Sierra Nevada is lower and warmer and thus is more susceptible to warming in the near term future (most of this century, at least). The cooler colors indicate more total basin discharge (Figure 3e, maps 1 and 2), correlating in most cases with the size of the basin, and indicating that most of the discharge comes from the northern basins. Near the end of the 21st century, the potential total basin discharge contributing to the Central Valley water supply has declined by over 45%. Thus, the detail of MHWM allows delineation of all of the mountain watersheds and related reductions that affect the large northern watersheds that feed into the Sacramento Valley, which is historically a larger user of surface water [*Faunt et al.*, 2009a, 2009b, 2009c].

[36] The modeling framework exemplifies the types of conjunctive use relations that are a direct outcome of separation of the supply and demand components from cell-by-cell estimation of crop and native vegetation consumption combined with regional, physically based supply within a fully integrated hydrologic simulation. For example, the GFDL-A2 climate projection drives changes in the MHWM runoff and recharge that result in reductions in water supply to the Central Valley as streamflow for irrigation, water supply, and ecological uses, as well as reductions in groundwater recharge. This decline results in reduced streamflow diversions for irrigation and riparian habitat uses (as indicated by the potential for reduced inflows and more intermittent diversions on the Tule River; Figure 4a) in the Tulare Basin, reduced diversions on the Tuolumne River (Figure 4b) in the San Joaquin Basin, and reduced diversions on the Bear River (Figure 4c) in the Sacramento Valley. As surface water diversions are reduced, demands for groundwater pumpage increase to compensate, and groundwater levels are affected. A 50% reduction in recharge from streamflow infiltration (Figure 4c) on the Central Valley also adversely reduces groundwater levels. Relative to the historical period (1961–2003), deep percolation from precipitation and irrigation increases by about 4%, but this is a small component of the 3.5 times increase in storage depletion from increased pumpage. The small increase in net recharge is caused by a combination of increased irrigation and reduced ET uptake directly from groundwater.

[37] Climate and agriculture are linked through increased irrigation demand. This is exemplified by the GFDL-A2 scenario where the amount of actual ET increases with increased ETp and decreases in precipitation. For the historical period 1961–2003, total delivery requirements for agriculture ranged between 18,500 and 28,400 $hm^3\ yr^{-1}$ (15–23 MAF yr^{-1}, where MAF is million acre-feet, 1.233 $\times$ 10 m^3), with a modest decline through time that may have reflected increasing irrigation efficiencies. Under the first 50 years of the GFDL-A2 scenario, total delivery requirements continued to decline generally, with increases during intermittent droughts, ranging from 21,500 $Hm^3\ yr^{-1}$ (17.4 MAF yr^{-1}) to 17,800–25,300 $Hm^3\ yr^{-1}$ (14.4–20.5 MAF yr^{-1}) (Figure 5a). This is comparable to the historical average and range, and is about 9% less than the average TFDR for the entire 21st century projection. However, in the second half of the 21st century under the GFDL-A2 scenario, sustained droughts and more persistent dry conditions drive demand to about 50% larger increases than the range of historical demand fluctuations, increasing to as much as 30,800 $Hm^3\ yr^{-1}$ (25 MAF yr^{-1}) by the end of the 21st century (Figure 5a). Thus, the supply and demand method quantifies the total water delivery requirements (TFDR) for agriculture and the proportions of surface and groundwater supplies used to meet them.

[38] The modeling framework allows us to simulate the temporal and spatial transition of conjunctive use from predominantly surface water to groundwater deliveries for its irrigation supplies during persistent droughts driven by climate change. The historical modeled proportion of surface water to groundwater deliveries was about 2 to 1 for wet periods and about 1 to 3 during persistent dry periods, averaging about 1.33 to 1 overall. In contrast, the GFDL-A2 scenario yields modeled ratios of surface water to groundwater deliveries that average about 1 to 2.75, and ranging from 1 to 1 during wetter periods to about 1 to 3 during dry epochs. This partitioning between supply sources drastically changes under the effects of the persistent droughts and warm temperatures of the second half of the 21st century. By the end of the century, the fractions are consistently 1 to 3 or lower in favor of predominantly groundwater supplies (Figure 5a). The overall delivery requirements also increase to annual volumes that are more than the demand prior to the regular delivery of State and Federal project water. Combined with this change in sources is a 20% increase in actual ET from applied water that also reflects an overall 3.3% increase in overall actual ET combined with a 10% reduction in actual ET from reduced precipitation and a 61% reduction in actual ET directly from groundwater between the first and second half of the 21st century.

[39] The modeling framework also facilitates the analysis of changes in streamflow gains and losses through river beds into the Central Valley's groundwater system that are altered with climate change. The GFDL-A2 scenario yields decreases in net riverbed infiltration all over the Central Valley (Figure 5b). The streamflow base flows in the Sacramento Valley are diminished and then stop, and the rates of infiltration from the rivers of the San Joaquin Valley increase during the second half of the 21st century (Figure 5b). Overall the nature of net riverbed infiltration has changed from the simulated historical distribution for the period 1961–2003, and may result in reduced and more variable surface water flows in the delta.

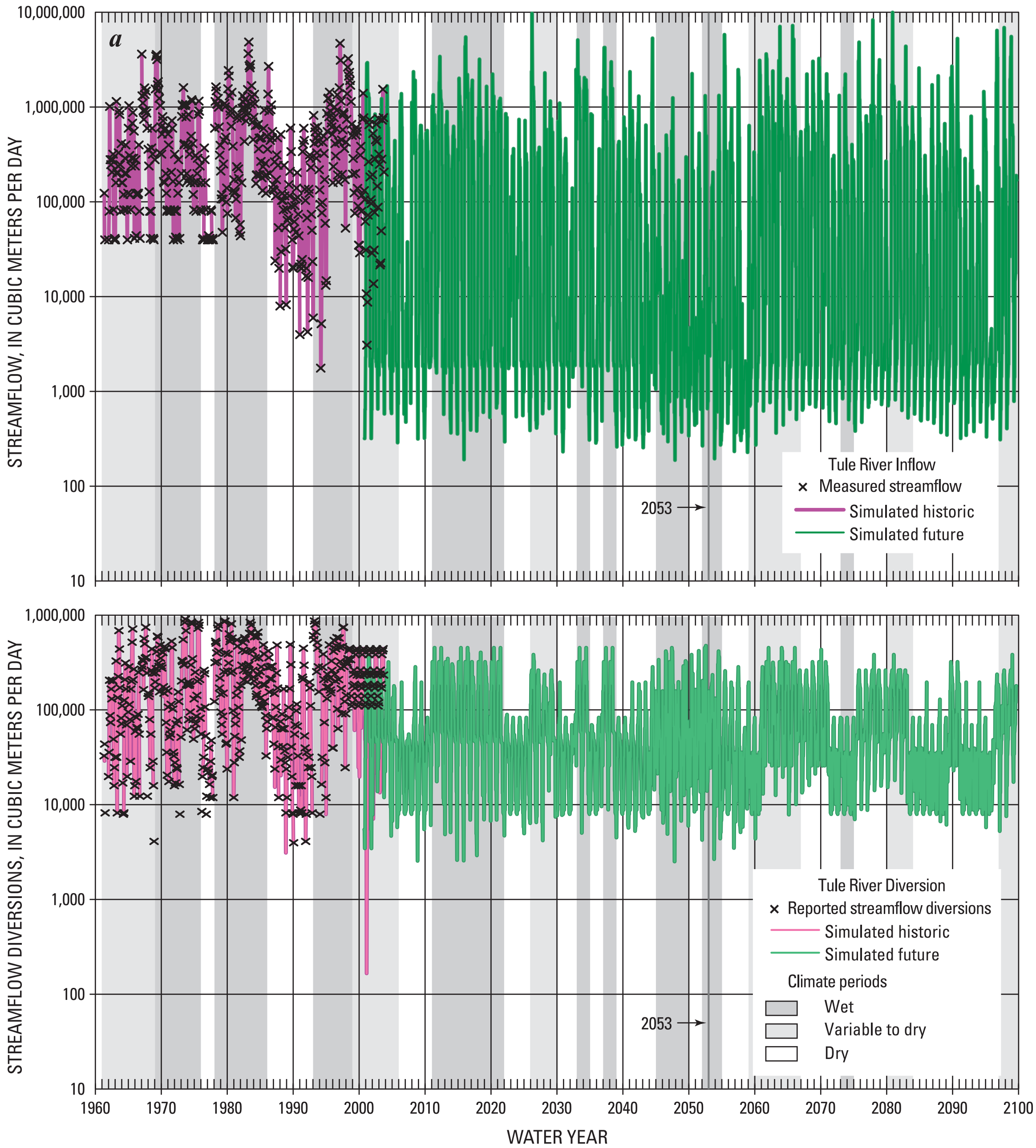


Figure 4. Graphs showing historical and future hydrologic response with the GFDL-A2 scenario of (a) stream inflow and diversions for riparian habitat along the Tule River in the Tulare Basin, (b) diversion along the Tuolumne River for riparian habitat streamflows in the San Joaquin River Basin, and (c) diversion from the Bear River in the Sacramento Valley, Central Valley, California.

[40] The integrated approach to supply and demand demonstrates the transition to a groundwater-based agricultural system with some of the largest effects from the change in climate related to the changes in groundwater storage. Future accelerated storage depletions are driven by climate-induced increases in groundwater demands by agriculture (with no change in land use or land cover) and municipal needs (with an assumed 1.2% urban growth) and the persistent droughts at the end of the century (Figure 5c). The historical simulation of 1961–2003 yielded substantial groundwater storage depletions of almost 86,300 Hm^3 (70MAF) that was especially large in the southern part of the valley called the Tulare Basin [*Faunt et al.*, 2009a, 2009b, 2009c]. In contrast, the future GFDL-A2 scenario yields additional storage depletions of about 113,500 Hm^3 (92 MAF) in the first half of the century followed by depletions of 235,600 Hm^3 (191 MAF) in the latter half.

[41] The simulation of agricultural irrigation from multiple aquifers within an integrated hydrologic model demonstrates that groundwater level declines do not occur everywhere, and occur differently depending on locations and depths below land surface of the pumped aquifers and distribution of multiaquifer wells (Figures 4c and 6). Simulation of conjunctive use shows how water level declines in

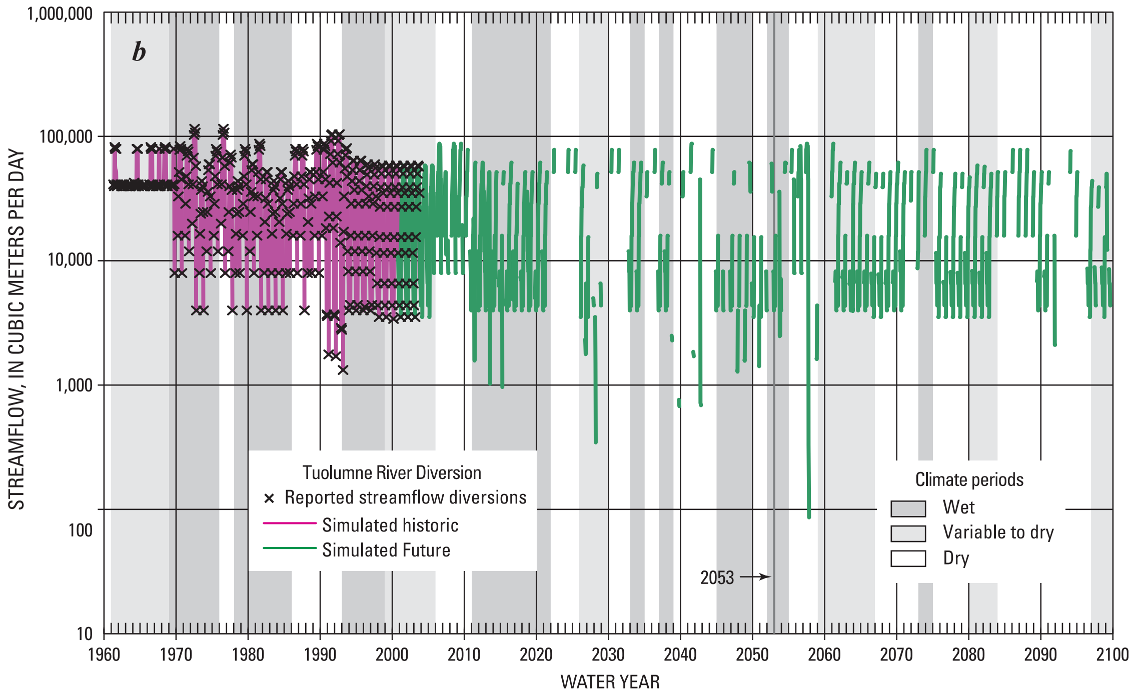
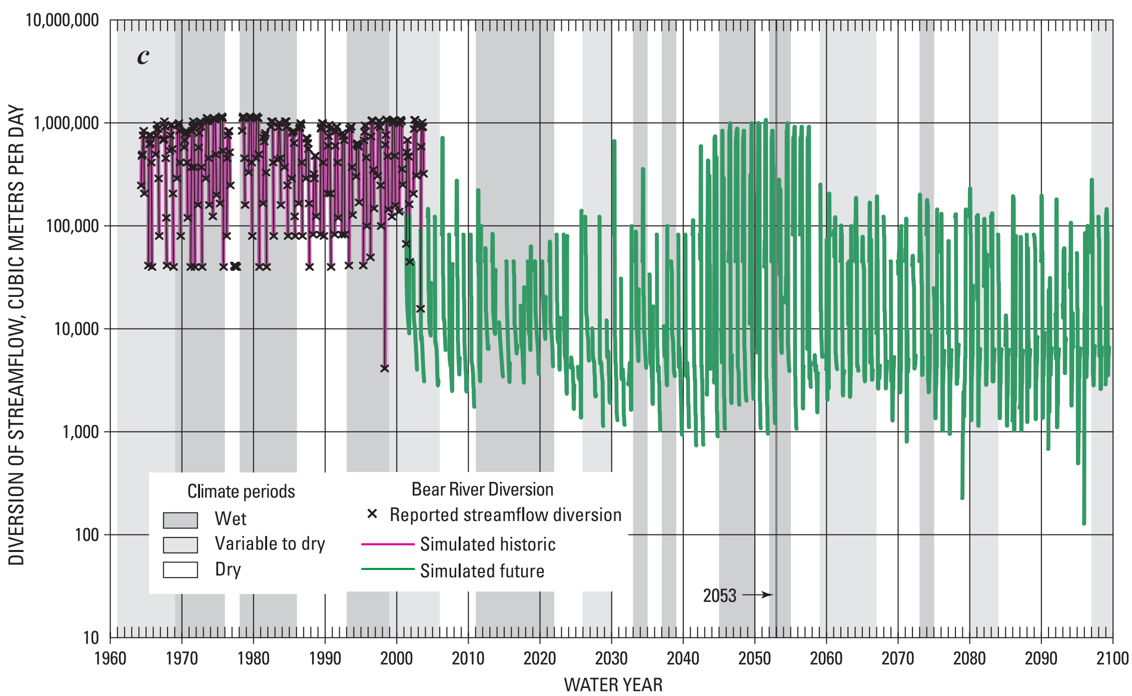


Figure 4. (continued)

the shallower aquifers of the Sacramento Valley are dampened in some places by reductions in leakage into streams, whereas other areas show water level declines of tens of meters caused by the increased pumpage required to offset reduced surface water deliveries for irrigation (Figures 4c and 6a). Similar declines are present in wells screened below the Corcoran Clay (well 13_25144 and 14_28350) but some of the wells screened in the shallower aquifers (well 10_25517) only start to show declines at the end of the sustained drought at the end of the 21st century (Figure 6b). These complex relations can only be discerned from our supply and demand modeling framework.

[42] In highly developed hydrologic systems, secondary effects such as land subsidence can become a limiting factor to sustained conjunctive use. While subsidence is relatively less in some of the original historical subsidence



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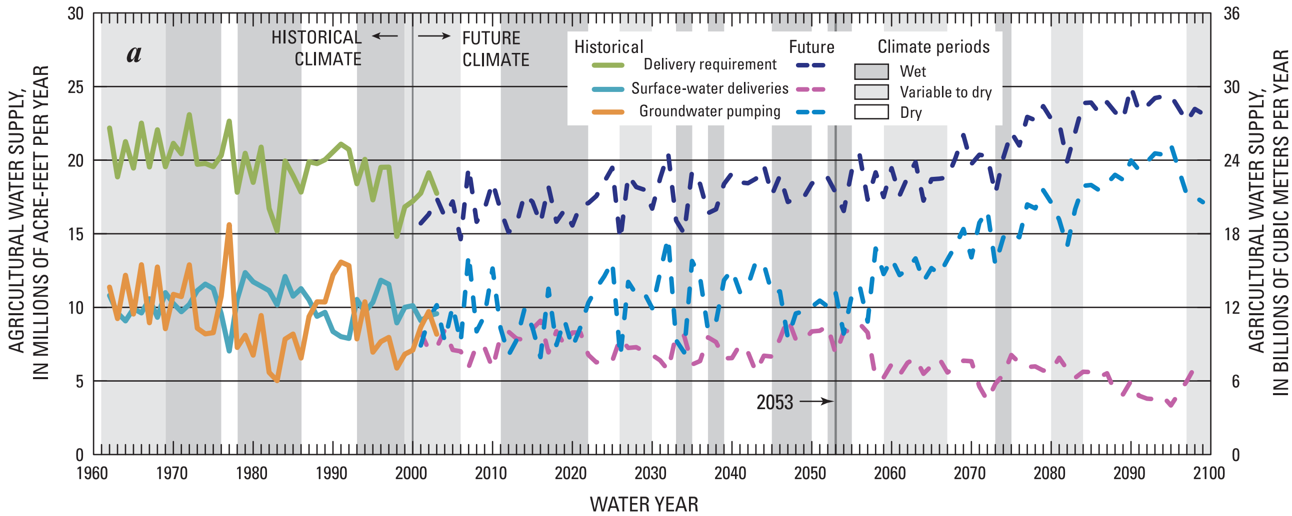

Figure 5. Graphs showing the hydrologic budgets with the GFDL-A2 scenario from CVHM for annual changes in (a) historical and future agricultural water supply and demand, (b) future changes in net streamflow infiltration, (c) future changes in groundwater storage, and (d) future changes in interbed storage, Central Valley, California.

regions on the western side of the San Joaquin Valley, some of the wells begin to approach the previous historical water level declines (well 14_28350) that would reinitiate additional land subsidence (Figure 6b). To the south in the Tulare basin where historical declines were greatest, the GFDL-A2 projection indicates the continuation of sustained water level declines of tens of meters (Figure 6c).

[43] Prior to the construction of the major canal delivery systems in the 1960s, storage depletion was a significant source of groundwater extractions, with about a third of the water supplied from fine-grained beds [*Ireland et al.*, 1984]. This storage depletion of water that came from fine-grained interbeds resulted in as much as 8.5 m (28 feet) of land subsidence [*Poland et al.*, 1975; *Ireland et al.*, 1984]. The historical simulation indicated as much as 3 m of additional simulated land subsidence during the more recent historical 42 year period (1961–2003) [*Faunt et al.*, 2009a, 2009b, 2009c, 2009d; *Hanson et al.*, 2010a] (Figure 7). The GFDL-A2 scenario yields additional extractions of water from interbed storage driven largely by pumpage during the dry conditions of the second half of the 21st century (Figure 5d). This loss of storage occurs largely in the Tulare Basin but is also present in the San Joaquin Basin and the northern regions that include the delta, eastside streams, and the Sacramento Valley.

[44] This integrated modeling method facilitates the analysis of the transition of conjunctive use that could result in new problems in unexpected regions. For example, much of the subsidence in this projection occurs adjacent to the Sierra Nevada where the transition from surface water- to groundwater-dominated irrigation is most extreme [*Hanson et al.*, 2010a]. The simulated future storage depletions are accompanied by renewed land subsidence in parts of the Tulare Basin (Figure 7) where federal, state, and local surface water canals traverse many of the areas projected to experience additional subsidence in the Sacramento, Delta subregion, San Joaquin, and Tulare basins. The integrated results help to indicate potential regions of land subsidence and, especially, differential subsidence that can threaten the integrity of these conveyances (Figure 7). Agricultural drainage and flood hazard zones, as well as transportation and urban infrastructure, might also be adversely affected by the transition of water supply to groundwater. If urban water demand increases at the 1.2% per year assumed here, storage depletion and land subsidence may also extend into urban areas. Thus, agricultural and urban demand driven by climate change and urban growth may collectively contribute to this secondary effect of groundwater storage depletion and limiting secondary effects.

[45] The supply and demand framework allows synthesis and analysis of basin-scale hydrologic budgets that can help water managers summarize the inflows and outflows of water across the landscape (Figure 8a) and in the groundwater flow system (Figure 8b). The time series of simulated landscape water budgets indicates reductions in precipitation, actual ET from groundwater uptake, and surface water deliveries, and an increase in groundwater pumpage (Figure 8a). Recharge and actual ET from water applied for irrigation remain relatively constant, and are largely supported by inefficient irrigation (Figure 8a). The groundwater budget shows the transition from recharge by deep percolation of precipitation to recharge from irrigation and from storage depletion that is caused by increased pumpage (Figure 8b). The projected increase in pumpage and resulting storage depletions, interbed storage losses, and increased leakage from streambeds during the sustained dry period of the late 21st century is driven by combinations of "business as usual" irrigation demands adjusting to the GFDL-A2 climate and increased water supply demands from urban growth (Figure 8b).

[46] The effects of climate change can also be assessed for specific subregions such as the delta. The analysis of increased urban growth combined with the small increase in sea level indicates that streamflow infiltration increases and groundwater outflow from the delta decreases under

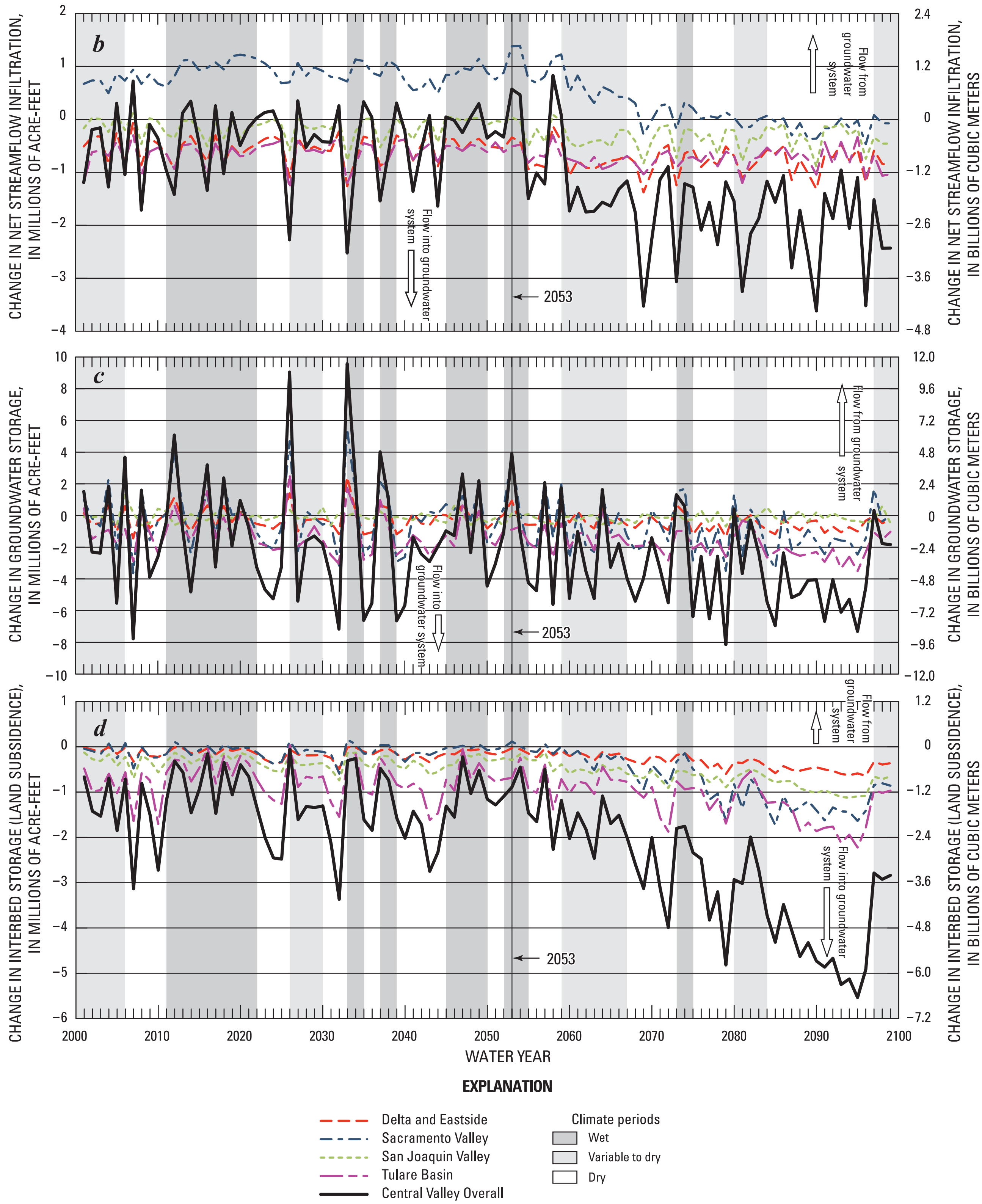

Figure 5. (continued)

the GFDL-A2 scenario. The increase in streamflow infiltration and storage depletion throughout the delta, and increased groundwater inflow at the delta's boundary over the century, underscore the potential effects of climate change from the GFDL-A2 scenario and urbanization on the hydrologic dynamics of the delta. These affects become greater with larger assumed percentages in growth of urban water demand, which underscores the potential combined effects of climate change on supply and demand as well as increased demand from additional urbanization.

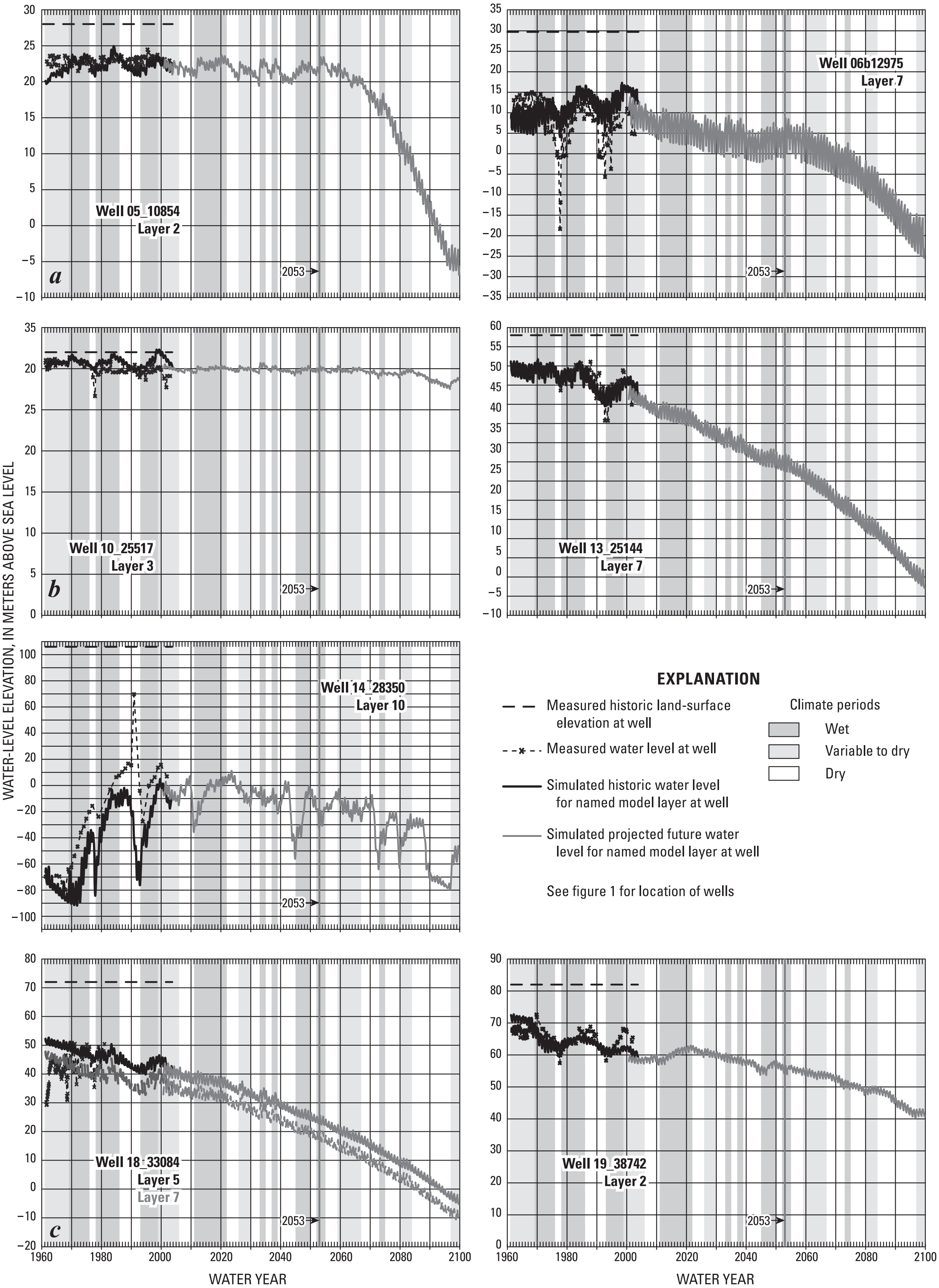

Figure 6. Graphs showing changes in groundwater levels for historical and future conditions with the GFDL-A2 scenario from CVHM for selected wells in (a) Sacramento Valley, (b) San Joaquin Valley, and (c) Tulare Basin, Central Valley, California.

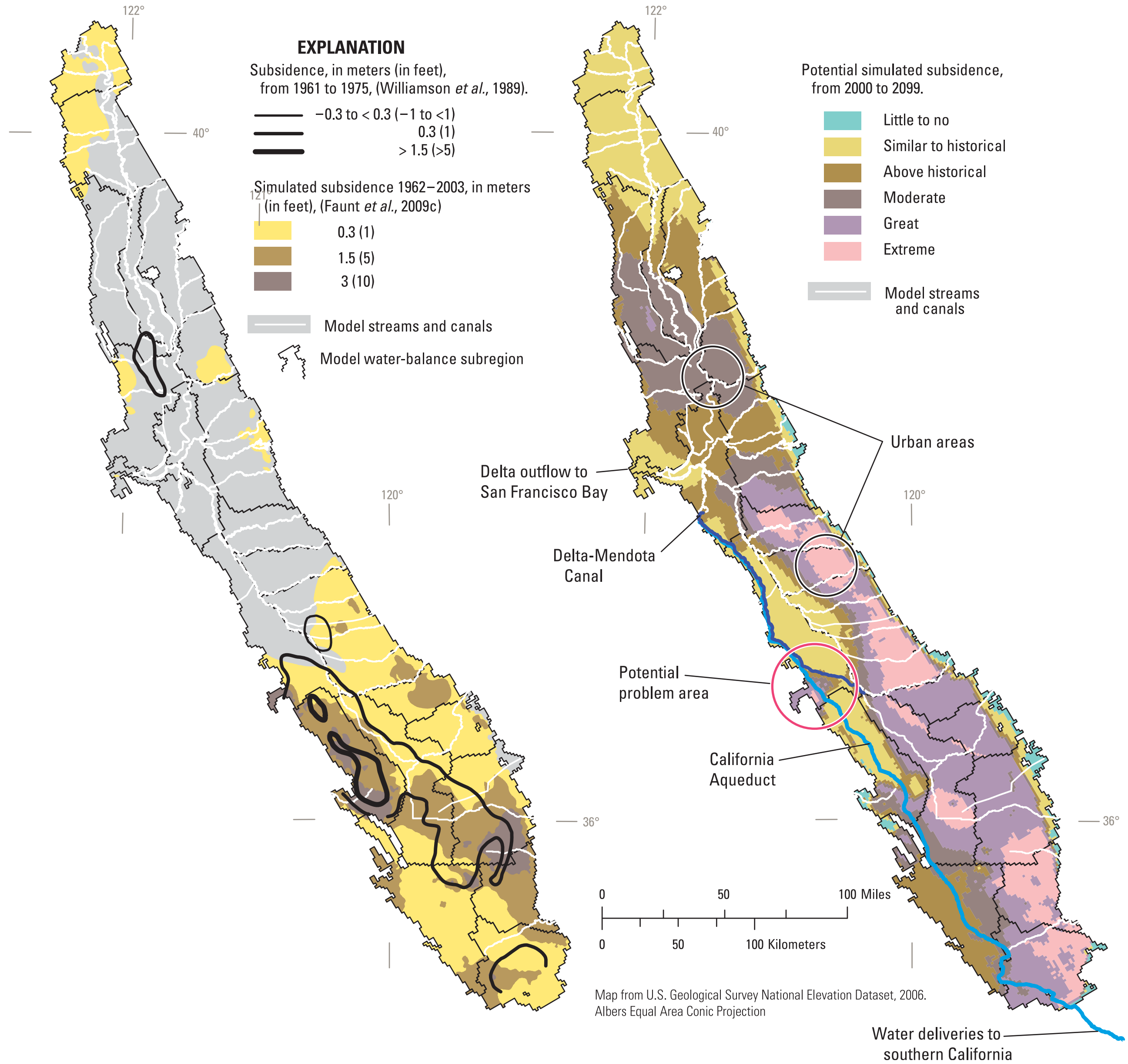

Figure 7. Map showing the historical land subsidence (1961–1975) and future land subsidence with the GFDL-A2 scenario and 1.2% urban growth from CVHM for the period 2000–2099, Central Valley, California. Modified from *Hanson et al.* [2010a].

4. Conclusions

[47] A method of linked physically based hydrologic models is demonstrated to provide a systematic analysis of direct and indirect effects of climate change on regional hydrologic systems. The feasibility of this supply and demand modeling framework method was illustrated here in the case of the California Central Valley and the adjacent Coast Ranges and Sierra Nevada where both climate change and climate variability affect conjunctive use and movements of water.

[48] While past extreme climate variability, such as pluvial periods and mega droughts, has affected the distribution of water in California, climate change due to greenhouse gas emissions will probably result in substantial temperature rises and could produce decreased precipitation, more sustained drought, and possibly an increased number of extreme events in the 21st century. Precipitation is the source of recharge and streamflow but in the Central Valley ET_p is greater than precipitation. In the application of the GFDL-A2 scenario, climate change results in diminished precipitation, decreased runoff from the surrounding mountains, warming-induced increases in ET_p, and consequently, increased pumpage and land subsidence in the Central Valley.

[49] This method simulates the transition from a predominantly surface water supply to groundwater supply because the models were designed to satisfy the need to incorporate the use and movement of water from the landscape, surface water and groundwater. In this scenario, the intermittent droughts in the first half of the 21st century are followed by severe persistent droughts in the second half of the 21st

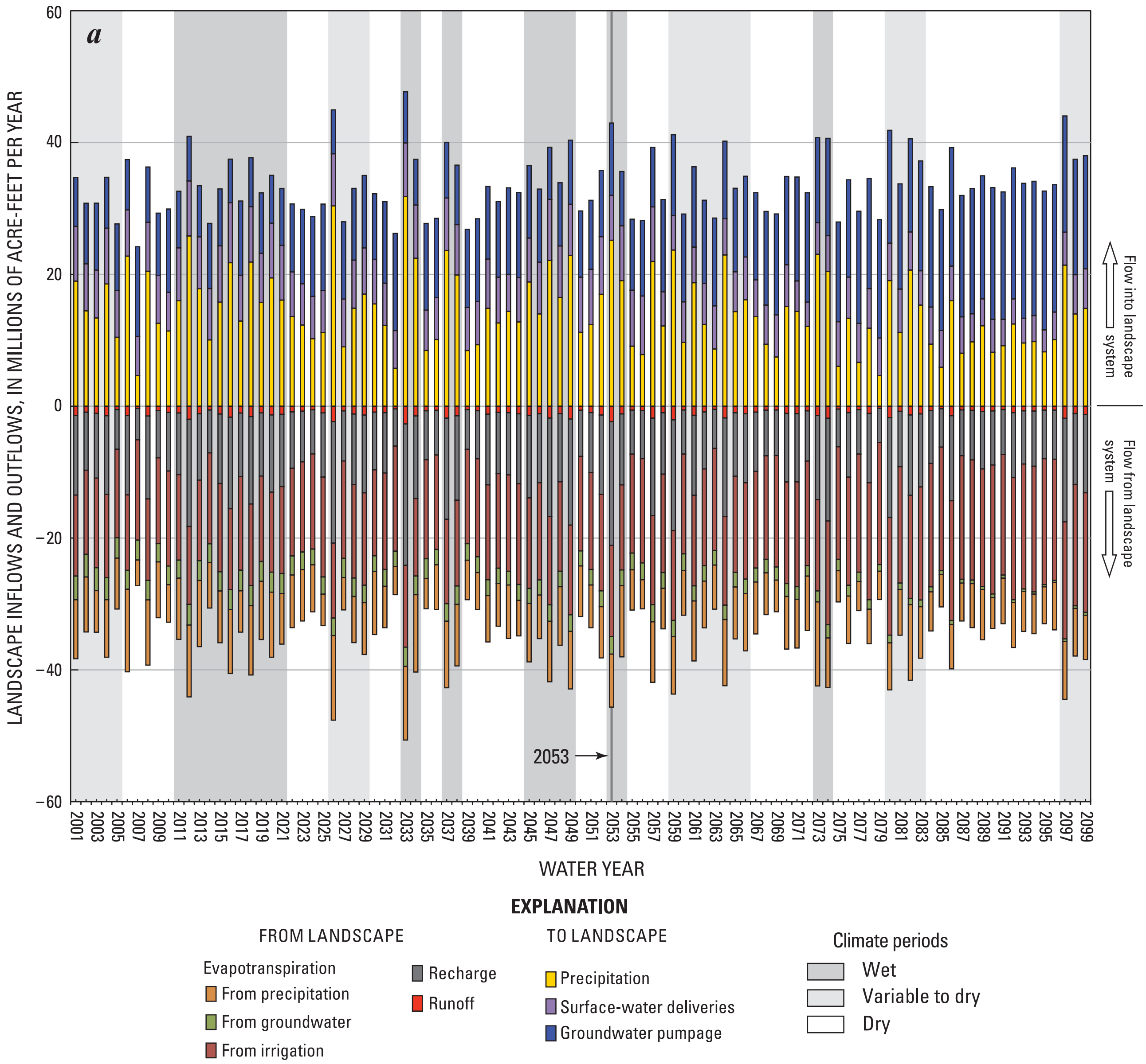

Figure 8. Graphs showing the future hydrologic budgets resulting from the use of the GFDL-A2 scenario in the CVHM of (a) the landscape and (b) the groundwater flow system, Central Valley, California.

century. However, because of the groundwater supply, these do not trigger a valley-wide operational drought (defined here as an interval when demand exceeds the engineered supplementary supplies so that the demands cannot be met by any available option). This analysis did not include adaptation by the agricultural sector, but even with this constraint, the existing engineered water supply and delivery systems may still be able to accommodate the projected changes. This ability to accommodate the projected changes is due, in large part, to the large number of wells that exist in the valley. Nonetheless the climatic droughts cause substantial effects on surface water and groundwater deliveries, and might trigger secondary effects such as increased land subsidence and differential land subsidence, reduced surface water deliveries and water for riparian habitat, and reductions in flows at the delta.

[50] The application of this modeling framework results in an example where these indirect effects of climate change and urban growth could become limiting factors for sustainability of the conjunctive use in the Central Valley. The combined future effects of climate change and urban growth have been assessed globally, and indicate an increased stress on water resources in California and other important watersheds elsewhere in the world [*Vorosmarty et al.*, 2010].

[51] In fact, the simulated reductions in outflow from the Sierra Nevada obtained from the GFDL-A2 scenario are accentuated farther downstream, where reduced flows from the delta reflect these reductions plus sustained irrigation demands and assumed, modest urban growth. Reductions in outflows from the mountains were greatest in the north and central parts of the Sierra Nevada and during the sustained droughts of the second half of the 21st century. The

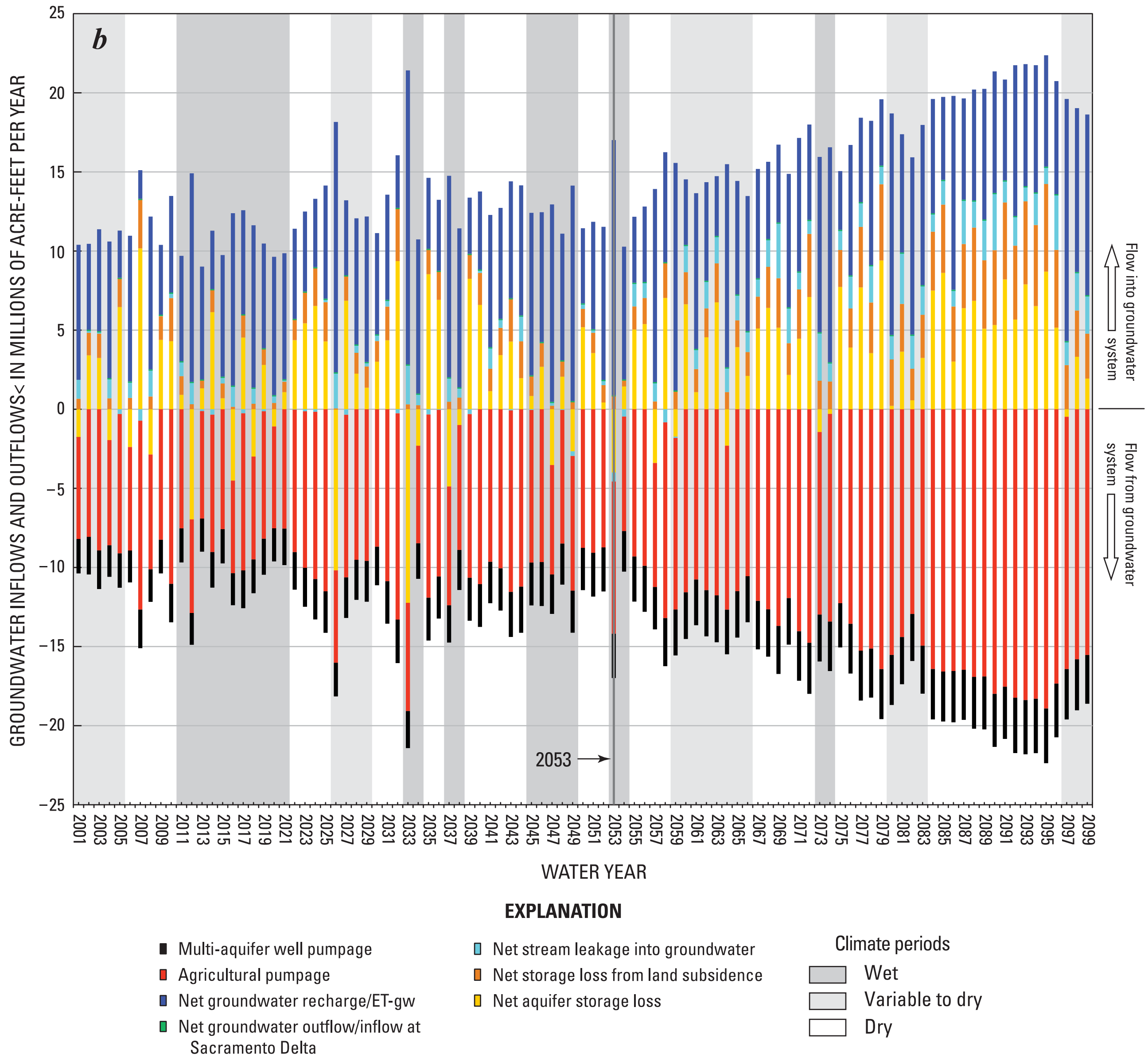

Figure 8. (continued)

reduced streamflows result in less surface water available for irrigation, urban water supply, and environmental uses. The changes in recharge, discharge, and groundwater storage in principal aquifers such as those of the Central Valley respond to climate change and the embedded climate variability that are greatest on the interdecadal scale. The effects from climate change are exacerbated by the modest urban growth imposed here, in agreement with *Vörösmarty et al.* [2000]. With land use held constant, the effects of the sustained droughts in the second half of 21st century are inseparable from the increasing natural and anthropogenic demands for water. Many other areas in the world may also be confronted by these combined effects.

[52] Increased demands for irrigation water to replace reductions in valley floor precipitation and plant uptake from groundwater is met, in the simulations, by increased groundwater pumpage. In turn, increased pumpage contributes to increased streamflow infiltration, reduced base flow, reduced groundwater outflows to the delta, increased depths to groundwater, and land subsidence. Meeting these demands ultimately results in the transition of conjunctive use from a surface water to a groundwater dominated system. This transition may cause additional land subsidence that could be hazardous to agriculture, transportation and urban infrastructure, and environmental habitat. Increased land subsidence is projected to occur where reductions in surface water supplies and related Sierra Nevada runoff are largest: in the Tulare Basin and along the southeastern San Joaquin and Sacramento Valleys. A long time may be required to recover from sustained groundwater storage depletion and captured surface water discharge [*Alley*, 2006].

[53] The linked models demonstrated here provide a supply and demand framework for hydrologic analysis of

streamflow, groundwater flow, pumpage, and related effects under a combination of climate change and urban growth that can be applied to other regional hydrologic systems. The simulation of a supply-constrained and demand-driven setting provides the basis for the analysis of conjunctive use and movement of water for human and natural components in the hydrosphere. Potential changes in groundwater storage, streamflow gains and losses, land subsidence, and consumption of water are linked in the modeling system to potential climate changes. Projections of the actual future climatic and hydrologic conditions are inherently uncertain, so it is not possible to provide accurate predictions. However, the present analysis of the Central Valley demonstrates that this method of linked models can provide an evaluation of potential points of vulnerability in the system and potential trends. In principle, with similar simulations of more climate and growth scenarios, the model system can also be used as part of a supply-constrained and demand-driven decision support system for planning and testing of adaptation strategies for part or all of a regional flow system such as the Central Valley. Because hydrologic predictions of actual future conditions are inherently uncertain and even nonunique for this particular model, this analysis provides trends and relative proportions of change in the hydrologic components on interannual to interdecadal periods of time from a climate change scenario that is not a forecast. Thus, only potential trends and relative proportions of the hydrologic budget predicted by the models may be considered reliable relative to the temporal scope and assumptions made within these projections of conjunctive use. This method can be applied in a wide variety of hydrologic settings and scales throughout the world's regional flow systems.

[54] The demand for water resources by people and agriculture also compete with environmental needs such as maintaining minimum streamflows, preventing seawater intrusions into and around the delta, and preserving habitats for fish and birds. Sustainable development is likely to require an integrated water management approach, and integrated resource modeling of the sort demonstrated here. The modeling approach used here has the potential to explore the long-term sustainability of system operations and conjunctive use through physical adaptation of the supply and demand components that could test alternate sources, uses, or policies. This could include the analysis of implementation of aquifer-storage-and recovery operations, imposing groundwater allotments to limit overexploitation of groundwater in selected regions, or drought deficiency optimization such as acreage optimization or water stacking. This approach can also facilitate physically based and physically constrained economic, environmental, or policy adaptation through linkages to other types of models. A suite of linked physically based, supply and demand framework models as is demonstrated here is likely to become a necessary tool for developing elements of a decision support system for evaluating the sustainability of conjunctive use within regional hydrologic systems.

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151 Temperature and precipitation trends in California: Global warming and Pacific Ocean influences

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Introduction

Recently, in the last decade, extreme weather events in California and, in general, the western US have increased discussion of the role of global warming in influencing weather-related hazards such as floods, droughts, heat waves, snow melt and wildfires. In California establishing precipitation and temperatures trends is especially important for resource management, flood and drought predication, and for managing future energy demands. Consequently, establishing the impacts, if any, of global warming on changing temperature and precipitation patterns in California is important to forecasting trends in these weather variables.

California has some of the most diverse microclimates in North America. Its complex topography and large latitudinal extent lead to the whole spectrum of climates, tropical climates excepted. Generally though, as with most of North America, California, regardless of which microclimate is examined, has been warming over the last several decades. LaDochy et al. (2007a) showed that the state warmed by about 1.1^{o}C (2^o F) from 1950-2000, although regional differences occur. The fastest warming rates are in the southern regions of the state where fast growing cities contributed to the warming trend through landscape changes related mostly to urbanization. Temperatures rose the fastest in counties with the largest populations and rural counties showed the slowest increases (Christy and Goodridge 1995). In most regions minimum temperature rates exceeded maximum temperature rates, leading to a decreasing diurnal temperature range (DTR). In agricultural areas, irrigation added to the warming, which is especially reflected in minimum summer temperatures, as increased water vapor reduced long-wave radiation cooling at night (Christy and Norris 2004; Nemani et al. 2001). Furthermore, differential heating between inland valleys and coastal regions during summer and early fall may be intensifying the sea breeze and increasing marine influences on warming trends. These enhanced marine influences may have led to recent maximum temperature cooling along the immediate coast (Thomas et al. 2011).

As temperatures climb, heat waves have become more frequent. Peterson et al. (2008) found that both maximum and minimum temperatures, when averaged over North America, have increased with the largest increases occurring in the West. The authors also noted that since 1950 the number of heat spells also increased. In California, Tamrazian et al. (2008) showed an increased frequency and duration of heat spells over the last 100 years in metropolitan Los Angeles. Deadly heat waves such as those occurring over several regions of California in 2006 point to an increasing danger to the growing state population (Gershunov et al. 2009). The all-time temperature maximum of 45^{o}C (113 ^{o}F) for downtown Los Angeles was broken during the latest heat wave on September 27, 2010 (NWS 2010).

While increasing temperature trends in the state have been documented, identifying similar trends in precipitation is not as simple. Several studies have looked at recent trends in precipitation, both in the United States and in California. Karl and Knight (1998) found a 10% increase in annual precipitation in the United States between 1910 and 1996 with over half of this increase coming from the upper 10th percentile of daily precipitation. Higgins et al. (2007) also found that daily precipitation events increased over much of the western U.S. in the last 5 decade period. The increased daily precipitation events correspond to similar increases in total annual rainfall amounts. Higgins et al. (2007) noted that the total number of heavy precipitation days increased substantially over portions of the West during the same five decade period. The increased intensity of rainstorms is particularly apparent in the summer for the U.S. in general. However, in the West, the largest increases in the frequency of daily precipitation (>1 mm) and in heavy precipitation totals in recent decades occur in the January-February-March (JFM) season (Higgins et al 2007). This seasonality nearly corresponds to the December, January, and February peak of California's annual precipitation, which accounts for fifty percent of the state's total precipitation (Mitchell and Blier 1997). Killam et al. (2011) discussed precipitation trends in California and documented increased annual precipitation means, number of days of rain, and increased intensities for the state as a whole. The authors also found regional differences.

Natural variability in the Pacific Ocean also appears to influence California temperature and precipitation trends. The Pacific Decadal Oscillation (PDO), a commonly recognized term in the scientific literature, was described by Mantua et al. (1997) to denote shifts in North Pacific sea surface temperature associated with swings in climate commonly persisting for 20-30 years. In the cool or negative phase, east Pacific sea surface temperatures (SSTs) are below normal. For the positive or warm phase, east Pacific SSTs are above normal. According to Mantua, cool or negative PDO phases occurred from 1890-1924 and from 1947-1976. Warm or positive phases typified the periods from 1925-1946 and from 1977 through the mid-1990's. A shift to the cool phase started in 1998, but was interrupted by two short periods of positive values from 2003-2007 and again in 2009-early 2010. Alfaro et al. (2004) showed that spring PDO values correlated well with summer temperatures in coastal California. A warming trend occurring around the Lake Tahoe basin in the east-central part of California correlates well with the PDO and to a lesser extent with El Nino-Southern Oscillation (ENSO) when monthly and annual temperature data are examined (Coats 2010). For the 331 California stations used in their study, LaDochy et al. (2007b) found a positive correlation between annual temperatures and the PDO throughout the state.

Superimposed on the PDO cycles are smaller-scaled El Niño/La Niña events persisting for approximately a year.

These events are typically defined as significantly warmer or cooler than normal sea surface temperatures in the central and eastern equatorial Pacific (Null 2008). Oceanic changes producing El Niño/La Niña events are interrelated with Pacific atmospheric changes termed the Southern Oscillation (SO).The SO phenomenon originates when surface air pressure in the western and eastern tropical Pacific oscillates in opposite directions, i.e., as one increases the other decreases, and vice versa. When the difference between the pressure measured at Darwin (western Pacific) and at Tahiti (eastern Pacific) is calculated, an "index" number, the Southern Oscillation Index (SOI) is generated (Halpert and Ropelewski 1992). Strong negative SOIs are associated with El Niño events, while strong positive SOI values are tied to La Niña periods. The SOI is a useful indicator of California climate. The combined El Niño and Southern Oscillation events are termed ENSO events.

Several studies show that the Pacific, especially the tropical Pacific, influence precipitation patterns in the western U.S. Sheppard et al. (2002) showed that ENSO and PDO effects could amplify each other, resulting in increased annual variability in precipitation over the Southwest. Kenyon and Hegerl (2008) also show how ENSO and Pacific decadal variability, such as PDO, affect the mean North American climate and its extremes, especially when both are in phase. Goodrich (2007) reported that during neutral ENSO years more than 80% of western U.S. climate divisions were drier than normal during the cold phase of PDO years, while 82% of western divisions were wetter than normal during warm PDO years. The probability of experiencing an El Niño event during the positive PDO phase is 29% and only 13% during the negative PDO phase. During the positive PDO phase, California only has a 10% chance of experiencing a La Niña event, but those chances increase to 40% during the negative phase. During the negative PDO phase, droughts during La Niña events can be devastatingly frequent and intense (Goodrich 2007).

When comparing the 1948-1975 period to the later 1976-2004 years, Higgins et al (2007) showed that a large increase in total precipitation from the earlier to later period could be explained by the Pacific Decadal Oscillation (PDO). The PDO was especially useful for also explaining the increases in heaviest precipitation (>90%) during the later period.

El Niño events have also been linked to greater precipitation in California, with strong, Type 1 El Niños averaging between 113 and 174% of normal precipitation for the water year (July 1-June 30) by climatic divisions (Monteverdi and Null 1998). Precipitation during the Type 1 El Niño events also increases from north to south. For La Niña events, southern California is typically drier than normal, however, northern California, and the Pacific Northwest, show higher than normal amounts of precipitation (LaDochy et al. 1999). Focusing on floods, Andrews et al. (2004) showed that the ratio of El Niño to non-El Niño annual peak floods varied from more than 10 near 32^{o}N to less than 0.7 near 42^{o}N. The cross-over point, where the number of floods were the same whether El Niño or not, is near 39^{o}N. Higgins et al. (2007) found that in winter, southwestern California averages up to 15% more days with measureable (> 1 mm) precipitation during moderate/strong El Niño phases compared to moderate/strong (m/s) La Niñas. Northwest California averaged up to 15% fewer wet days in winter during (m/s) El Niño years compared to La Niña ones. This well-known dichotomy between the northern and southern part of the state in terms of precipitation variance is known as a dipole (Dettinger et al. 1998). However, the largest fraction of extreme precipitation events (above the 90^{th} percentile) for the west coast part of the state occurred during neutral winters, often just prior to El Niño periods (Higgins et al. 2007). On the other hand, Becker et al. (2009) found that precipitation intensity in southern California increased more than 60% between El Niño and La Niña phases.

Climatic impacts associated with cool PDO phases are similar to La Niña events and those associated with warm PDO phases parallel El Niño episodes. Decadal-scale oceanic fluctuations account for 20 to 45 per cent of annual precipitation variance in the West (Cayan et al. 1998). Southern California climate is significantly modified by these interannual and interdecadal climate shifts.

In this study, we look at temperature and precipitation trends in California and how well warming trends and Pacific Ocean variability explain the record over the last several decades.

Methods

To establish the relationship between Pacific oceanic and atmospheric annual and decadal variations and California temperatures and precipitation, data spanning a period from approximately 1900 to present were analyzed.

Temperature and precipitation monthly and annual data from 1895 to present were acquired for the eleven California climate divisions from the Western Regional Climate Center, Desert Research Institute, Reno, NV California Climate Tracker: (http://www.wrcc.dri.edu/monitor/cal-mon/frames_version.html). Precipitation values are based on water years, July 1-June 30, as the rainy season in California generally lasts from late fall through early spring. Temperature and precipitation anomalies were also calculated based on deviations from the long-term (1901-2009) average. Temperature records for 331 California cooperatives and first-order stations (Fig 1) showing long-term continuous data (since at least 1950) were also analyzed in a previous study (LaDochy et al. 2007).

Daily precipitation records for California stations from NOAA National Climate Data Center (NCDC) were also analyzed to select those with long, continuous datasets. Sixteen stations from various regions of the state met the criteria of having a continuous and long (since 1925) data record. Trends in annual and seasonal precipitation were calculated for these sites as well as trends in intensities and frequencies of precipitation events.

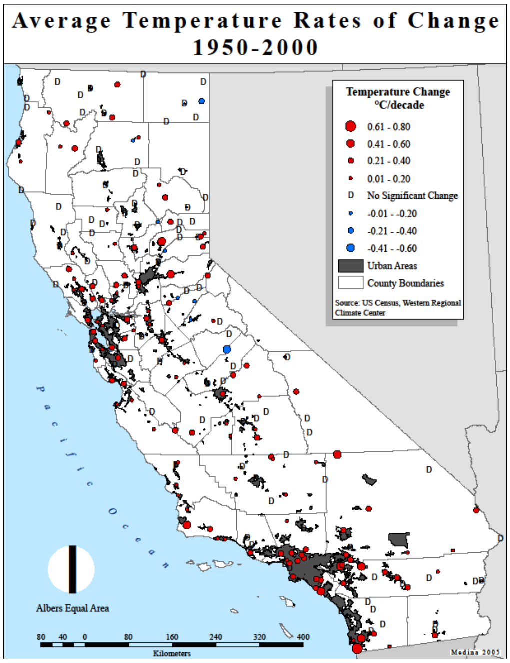

Fig. 1. Study area, California, showing mean annual temperature trends for 330 long-term stations.

Climatic indices included in the analyses are: PDO and SOI. Monthly and annual data, from 1900 to present, for these indices are from NOAA-CIRES CDC (http://www.cdc.noaa.gov/ClimateIndices/Analysis/). Other climatic indices were tested for their influence on southern California weather and climate, however the PDO and SOI were found to account for climate variations quite well.

Pearson correlations were calculated between monthly and annual temperatures and monthly and annual PDO values from 1900 to 2009. Seasonal values were also used to show the strength of relationships at different lag periods. Temperature values lagging PDO values from one to 12 months were also tested. Both SOI and PDO values (monthly, annually) were correlated with California precipitation for the period 1900-2009. As with temperature, different lag periods were also tested.

Using different lag periods between Pacific climatic indices and southern California temperatures and precipitation can show how useful these indices are for forecasting weather and climate in the region. Daily precipitation characteristics were also compared for the 16 long-term stations with PDO and SOI values to show general magnitudes of differences in precipitation totals for positive and negative indices. El Niño and La Niña years were chosen for comparisons of precipitation totals between the 16 climatic stations used in this study. Criteria for classifying El Niño and La Niña years included SOI, water year precipitation anomalies for the whole state, northern and southern California precipitation anomalies, and MSLs (mean sea level anomalies) and SSTs off Scripps Pier. The list of El Nino and La Nina years closely matched those of Florida State and Jan Null's Golden Gate Weather (http://ggweather.com/enso/years.htm).

Results

For the period 1895 to 2009 California annual temperatures show rates of increases per century of 0.87, 0.61 and 1.14°C (1.57, 1.10 and 2.05°F) for mean, maximum and minimum averages, respectively (see Fig 2a-c). However, these rates of warming actually increased more when using records from 1949 to present and 1975 to present. Overall state averages since 1975 increased more than twice the longest record (1895-2009) in all three temperature categories (see Table 1). Of the warmest 15 annual mean temperatures, 10 occurred since 1990, and 7 since 2000. Seasonal differences show that the largest warming trends occur in summer, Table 1, followed closely by spring. Fall and winter show the least warming. Minima rose faster than maxima overall, leading to a decreased diurnal temperature range, which has been reported in other U.S. regions (Gallo et al. 1999).

The California temperature record (Fig 3) shows large year to year variation, while the 5-year running mean highlights a systematic pattern of rising and falling temperatures, similar to the PDO signal. Removal of the warming trend in the temperature series results in the illumination of the decadal PDO pattern (Fig. 4). The detrended temperature records show a distinct switch from negative values below the trend (detrended values below zero) to positive values in the late 1970s, when an abrupt change in the PDO phase occurred. A partial explanation of the warming trend evident in the California temperature record is likely the warming tied to the current positive cycle of the PDO, which extends from 1977-97. LaDochy et al. (2004) found that the PDO is a good predictor of California temperatures and suggested that temperatures could be predicted by PDO values of up to two previous seasons.

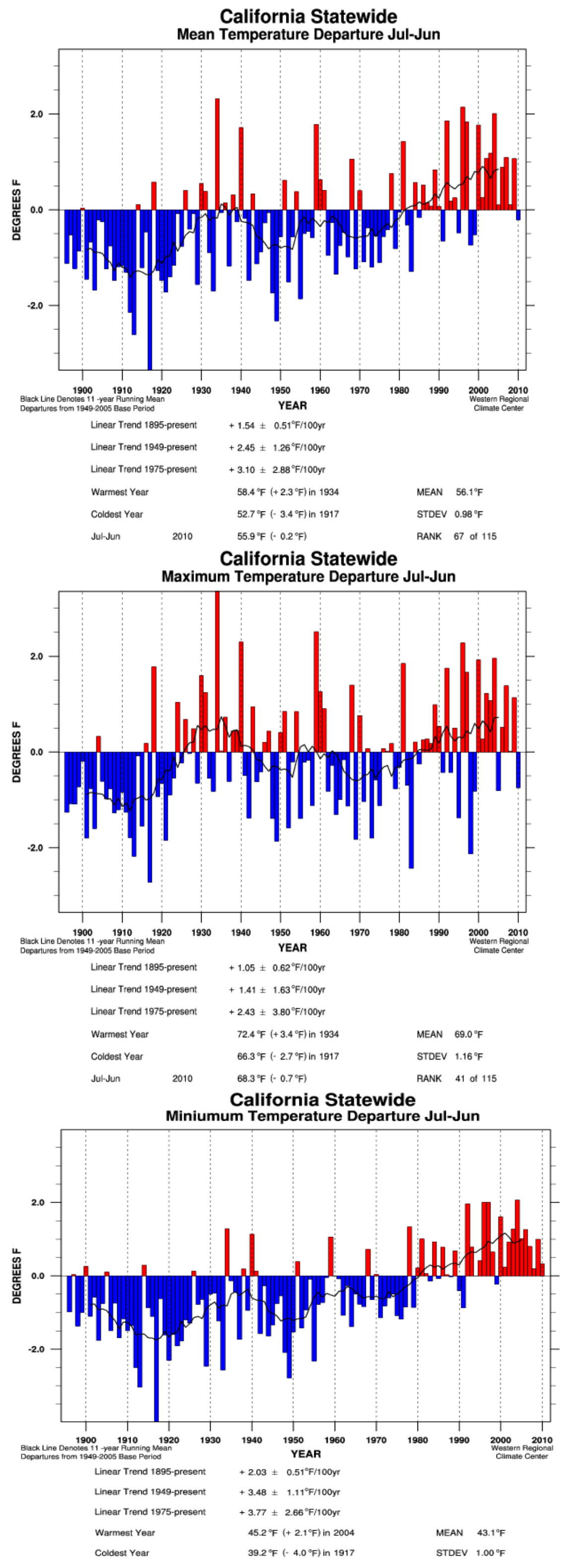

Fig. 2. California temperature trends for mean, max, min annual (water years) data, 1895-present.

A. Mean temperature Linear trends/ 100 yrs	Annual	Winter	Spring	Summer	Fall
1895-present	+0.87	+0.66	+0.95	+0.94	+0.85
1949-present	+1.45	+1.08	+1.98	+1.68	-0.56
1975-present	+2.06	-0.58	+2.86	+3.59	+1.97
B. Max temperatures 1895-present	+0.61	+-.51	+0.88	+0.42	+0.51
1949-present	+0.89	+0.43	+1.67	+1.04	-0.09
1975-present	+1.77	-2.17	+3.20	+3.31	+2.19
C. Min temperatures 1895-present	+1.14	+0.81	+1.01	+1.46	+1.19
1949-present	+2.01	+1.73	+2.31	+2.32	+1.22
1975-present	+2.34	+1.01	+2.51	+3.88	+1.71

Table 1. California annual (water year) temperatures, 1895-present, for mean, max and min linear trends in ^{o}C/100 years. Source: NOAA,WRCC.

Killam et al. (2011) indicated that the mean annual precipitation trend for the state shows a 14% increase for the long term record (since 1895), but a 17% decrease since 1975 (see Table 2A). Regionally, central and northern California show precipitation gains throughout the record, while southern California shows large decreases since the 1970s.

Interestingly, since about 1950, the northern regions record decreases in precipitation, while records of the southern regions show increases. Many climate studies use the more complete data record from the 1950-2000 period to document warming and increasing precipitation. This period marks a distinct shift in Pacific Ocean conditions from the cold phase to the warm phase of the PDO.

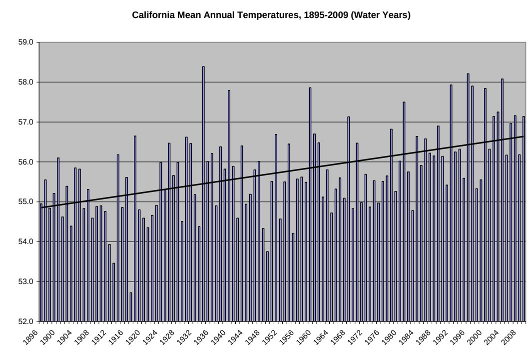

Fig. 3. California annual temperature trend, 1895-2009.

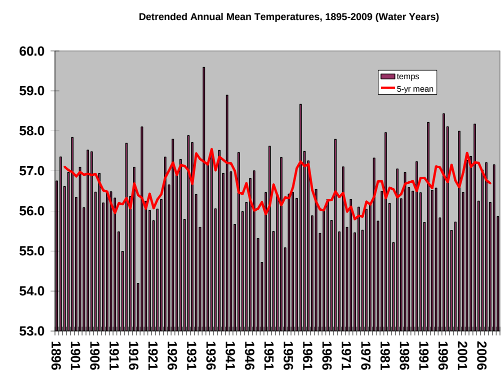

Fig. 4. California annual temperature detrended, 1895-2009.

Seasonally for the state, according to Killam et al. (2011), showed increases over the long term in winter precipitation from 1895-2009, particularly since the 1970s. During the same period, fall, spring and summer precipitations showed modest gains , but large decreases since the 1970s. Regionally, all regions showed winter increases for all time periods, but large decreases in spring, fall and summer since the 1970s (see Table 2B).

As discussed in the previous section, to evaluate precipitation characteristics more closely, daily precipitation data was collected for 16 met stations having

Mean precipitation Linear trends in inches/ 100 years	Annual	Winter	Spring	Summer	Fall
1895-present	+82.3	+49.0	+9.7	+5.6	+19.3
1949-present	+6.6	+42.7	+14.0	-4.8	-42.4
1975-present	-104.1	+194.1	-103.9	-29.2	-151.9

Mean precipitation Linear trends in inches/ 100 years	Annual	Winter	Spring	Summer	Fall
1895-present	+82.3	+49.0	+9.7	+5.6	+19.3
1949-present	+6.6	+42.7	+14.0	-4.8	-42.4
1975-present	-104.1	+194.1	-103.9	-29.2	-151.9

Mean precipitation Linear trends/ 100 yrs	N Central	N Coast	NE	Sierra	Sac Delta	Central Coast
1895-present	+247.9	-21.1	+52.1	+114.6	+128.8	+77.7
1949-present	-75.9	-219.7	-67.3	-8.1	+61.0	+82.3
1975-present	+98.8	+479.6	-31.5	-74.2	+26.9	+71.6
	San Joaquin	S. Coast	S. Interior	Mojave	Sonora	
1895-present	+36.6	+88.1	-10.2	+39.9	+24.1	
1949-present	+50.3	+75.7	+28.4	+57.9	+43.4	
1975-present	-135.4	-340.4	-642.4	-205.2	-245.1	

Table 2A. California annual (water trend in mm/ 100 years. B. Annual precipitation linear trend in mm/ 100 years. B. Annual precipitation linear trends by climatic regions

complete records from 1925 to present (Killam et al. 2011). These stations cover most of the climatic regions of the state. The trend in annual precipitation totals, when ordered by latitude, indicates an increase in the north and a slight decrease or no change in the south (Figure 5). The trend in the number of rainfall days closely followed annual totals (not shown). Seasonal trends follow closely those of the climatic regions, with largest increases in winter, followed by fall for most stations (Killam et al. 2011).

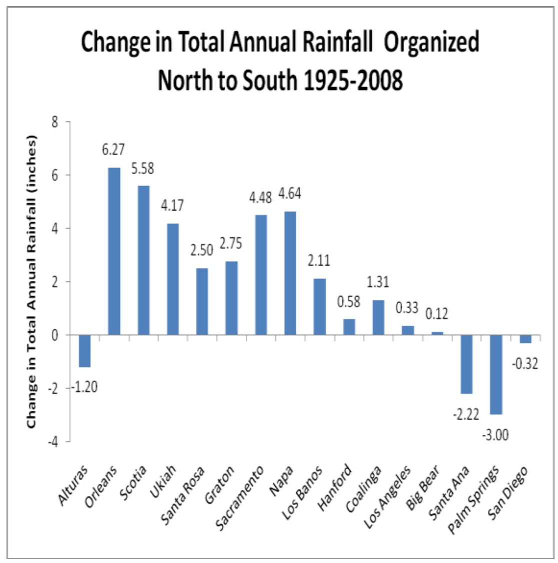

Fig. 5. Rainfall trends from north to south California, 1925-2009. Northern and central California wetter, southern California drier.

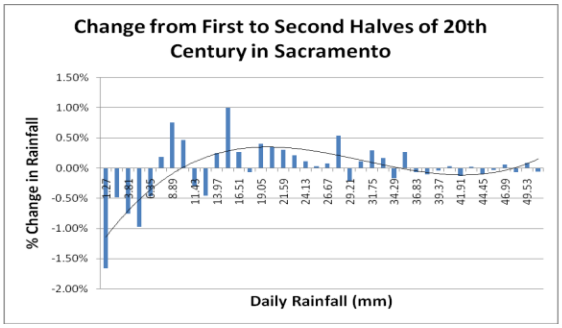

Fig. 6. Rainfall intensity shows increased moderate, heavy rains in Sacramento in second half of record.

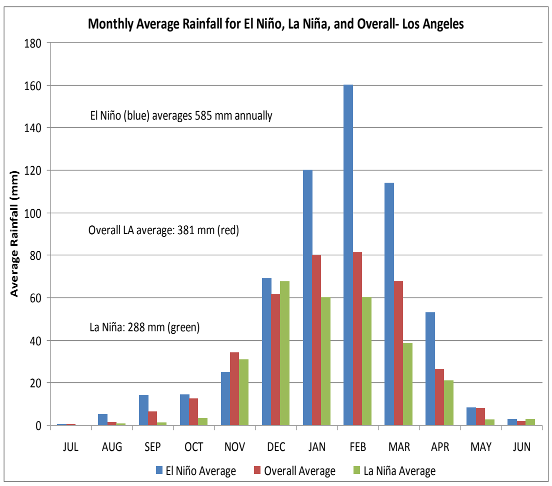

Fig. 7. Monthly average rainfall in Los Angeles by ENSO phases.

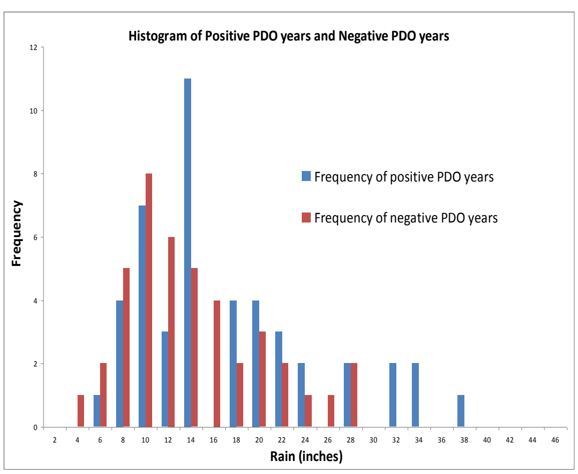

Fig. 8. Los Angeles rainfall vs. PDO phases.

Daily precipitation data was also analyzed by Killam et al. (2011) for trends in intensity, with histograms of varying precipitation amounts compared between the two halves of the century. The second half of the century at Sacramento displays less light rainfall and more moderate and heavy rainfall (Figure 6). The change in intensity is mostly focused in Northern California, though some Southern California stations such as Los Angeles show similar changes.

Annual precipitation totals were compared for positive and negative phases of ENSO and PDO. Although the variability is high, wetter years do occur during negative phases of SOI and positive phases of the PDO. For the 1925-2009 period, Los Angeles annual (water years) average precipitation was 605.79 mm (23.85”) during El Nino years, but only 263.65 mm (10.38”) for La Nina years (Figure 7). For positive phases of PDO, the Los Angeles average was 423.42 mm (16.67”), while only 335.53 mm (13.21”) for the negative phases (Killam et al. 2011). The SOI accounted for more of the precipitation variability for southern stations than for northern ones. For the 1946-2005 water years, SOI explained over 51% of the variability in the south coast climate division while only about 36% for the central coast and about 13% for the north coast. The relationships are stronger when SOI and PDO are in the same phase (negative SOI with positive PDO or positive SOI with negative PDO, see Figure 8). When analyzing just the heaviest rainfall events, a majority of them occurred in neutral ENSO years. While El Niño years generally have more days with precipitation and more intense rains than non-El Niño years, flooding associated with extreme precipitation events can also take place in La Niña or neutral ENSO years (Figure 9).

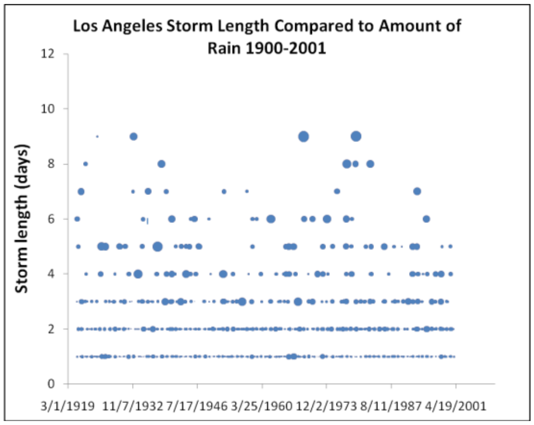

Fig. 9. Shows storm length, amounts for LA over study period. ENSO pattern is not apparent.

An analysis of global warming effects on precipitation appears to indicate an increase in both the intensity and amounts of precipitation for the central and northern portions of the state. However, this trend only explains less than 2% of the total variability in annual precipitation for the state. ENSO and PDO are much more useful in predicting precipitation in California. Minimizing the impacts of global warming on state precipitation trends would be short-sighted. Climate models and observational studies are showing that warming is leading to the emission of more water vapor into the atmosphere which subsequently leads to more and heavier rains in some regions, while others are becoming drier (IPCC 2009). This may be the case in California as well.

Discussion

In describing temperature and precipitation trends in California, regional differences must be accounted for. This is especially true for precipitation. Temperatures have increased throughout the state for the last century or more, with the warming rates increasing in the last few decades (Table 1). Minimum temperatures show greater warming than maximum temperatures, decreasing the diurnal temperature range. Seasonally, the state has warmed faster in spring and summer, particularly since the mid-1970s. Heat waves have also increased in the state, which does not bode well for health concerns. Regionally, the fastest temperature increases occur in the areas of greater urbanization, which are concentrated mostly in southern California, but more recently urbanization has also increased in the interior of the southeast region and the Central Valley. Since the 1970s, the fastest warming occurred in the interior regions, while the slowest occurred along the coast. This difference in warming between interior and coastal regions may reflect a marine influence as the California coastal waters have warmed slower than the state average, or only 1.3 ^{o}C for 1950-1999 (DiLorenzo et al. 2005). The coastal-interior heating differential also tends to enhance the marine influence as Tmax is reduced along the coast (Thomas et al. 2011). The Pacific also influences the temperature variability recorded by California stations. The PDO correlates well with annual average temperatures for all regions of the state (LaDochy et al. 2007). As PDO shifts from the warm phase to the cool phase, temperatures tend to decline. Since 1998, the PDO has been mostly negative, except for

2003-2007 and during the 2009-10 El Niño. The outlook based on a more negative phase of the PDO would be a decrease in state temperatures to below the trendline established and previously discussed.

temperatures. While the state as a whole has been getting wetter over the last last century, the northern regions have shown steady increases, while the southern regions show little increases and in some even decreases since the year) precipitation, 1895-2010, linear early 1900s. The southern regions especially show large decreases in precipitation since the mid-1970s (Table 2). Seasonally, all regions show increased winter precipitation throughout the 1895-present period, especially since the 1970s. In this last period, the northern regions experienced increased precipitation while precipitation decreased in southern regions. These regional differences in precipitation seem to be connected to the Pacific SSTs. El Niño events are associated with both greater precipitation amounts and days with measurable precipitation. La Niña events generally correspond with drier conditions. However the relationship of state precipitation and El Niño/La Niña events is stronger to the south than the north. The PDO either enhances or weakens these relationships depending on whether the El Niño/La Niña events are in phase with the PDO.. Recent rainfall patterns have shown decreased amounts statewide, especially in the southern regions. PDO values have been tending negative since 1998, although short positive years occur during 2002-2007 and 2009-early 2010. Interestingly, Los Angeles had a record rainfall year during the 2002-2007 period (Patzert et al. 2007) A moderate El Niño with wetter than normal rainfall occurred during the 2009-2010 period. Los Angeles had a record dry year at the end of the 2002-2007 period, when the PDO was switching back to a negative phase. Since then, the PDO and ENSO are in phase. Both are in cool phases. Unusually cool waters off the southern California coast in 2010 favor drier conditions.

The question of how much global warming effect California temperature and precipitation trends is difficult to answer. While non-urban stations have shown warming similar to global averages, land use changes have accelerated warming, especially in urban areas. Pacific SSTs also influence California temperatures, particularly the PDO, which accounts for the annual variability quite well. Warming may also be leading to rising precipitation trends, although more to the northern sections of the state than the south. A northward shift in storm track position has been detected in the West in the late winter and early spring (McAfee and Russell 2008). This may account for the wetter conditions to the north and the drying to the south of the state, as the subtropical anticyclone belt also may be shifting northward. In general, Pacific SSTs, especially ENSO and PDO, explain much of the annual variability in precipitation, although the relationships are stronger to the south.

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PRIMARY RESEARCH PAPER

Initial impacts of *Microcystis aeruginosa* blooms on the aquatic food web in the San Francisco Estuary

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Abstract The impact of the toxic cyanobacterium *Microcystis aeruginosa* on estuarine food web production in San Francisco Estuary is unknown. It is hypothesized that *Microcystis* contributed to a recent decline in pelagic organisms directly through its toxicity or indirectly through its impact on the food web after 1999. In order to evaluate this hypothesis, phytoplankton, cyanobacteria, zooplankton, and fish were collected biweekly at stations throughout the estuary in 2005. Concentrations of the tumor-promoting *Microcystis* toxin, microcystin, were measured in water, plankton, zooplankton, and fish by a protein phosphatase inhibition assay, and fish health was assessed by histopathology. *Microcystis* abundance was elevated in the surface layer of the western and central delta and reached a maximum of 32×10^9 cells l^{-1} at Old River in August. Its distribution across the estuary was correlated with a suite of phytoplankton and cyanobacteria species in the surface layer and 1 m depth including *Aphanizomenon* spp., *Aulacoseira granulata*, *Bacillaria paradoxa*, *Rhodomonas* spp., and *Cryptomonas* spp. Shifts in the phytoplankton community composition coincided with a decrease in the percentage of diatom and green algal carbon and increase in the percentage of cryptophyte carbon at 1 m depth. Maximum calanoid and cyclopoid copepod carbon coincided with elevated *Microcystis* abundance, but it was accompanied by a low cladocera to calanoid copepod ratio. Total microcystins were present at all levels of the food web and the greater total microcystins concentration in striped bass than their prey suggested toxins accumulated at higher trophic levels. Histopathology of fish liver tissue suggested the health of two common fish in the estuary, striped bass (*Morone saxatilis*), and Mississippi silversides (*Menidia audens*), was impacted by tumor-promoting substances, particularly at stations where total microcystins concentration was elevated. This study suggests that even at low abundance, *Microcystis* may impact estuarine fishery production through toxic and food web impacts at multiple trophic levels.

Keywords *Microcystis* · Phytoplankton species composition · Fish histopathology ·

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Food web · Microcystins · Cyanobacteria · Protein phosphate inhibition assay

Introduction

Microcystis aeruginosa (*Microcystis*) is a cyanobacterium species that can form harmful algal blooms (CHAB) in freshwater water bodies world wide (Chorus, 2005). Its distribution has spread into some estuaries including the Chesapeake Bay, the San Francisco Bay, and the Neuse River in the USA, the Swan River in Australia, and the Guadiana River in Spain and Portugal (Paerl, 1988; Sellner et al., 1988; Rocha et al., 2002; Robson & Hamilton, 2003, 2004; Lehman et al., 2005). *Microcystis* is considered a toxic CHAB because some species contain powerful hepatotoxins called microcystins that initiate cancer and promote tumor formation in the liver of humans and wildlife (Zegura et al., 2003; International Agency for Research on Cancer, 2006; Ibelings & Havens, 2008). It also produces a surface scum that impedes recreation, reduce aesthetics, lower dissolved oxygen concentration, and cause taste and odor problems in drinking water (Paerl et al., 2001). *Microcystis* and other freshwater cyanobacteria blooms are currently a worldwide concern because their frequency and distribution are increasing (Fristachi et al., 2008). Although the potential impact of *Microcystis* blooms on human health is known, its potential impact on the structure and function of aquatic food webs is poorly understood (Ibelings & Havens, 2008).

Microcystis can affect phytoplankton community composition through allelopathy (Legrand et al., 2003). Cyanobacteria produce a large array of metabolites including organic and amino acids, peptides, alkaloids, carbohydrates, and lipopolysaccharides that can affect higher trophic levels (Paerl et al., 2001; Smith et al., 2008). Differential response of phytoplankton and cyanobacteria (plankton) to these allelopathic substances affects plankton community composition and species diversity in laboratory cultures (Sedmak & Kosi, 1998; Suikkanen et al., 2005). In nature, the response of the plankton community is variable and probably depends on environmental conditions (Graneli et al., 2008), but the full impact of *Microcystis* on plankton communities in the field is poorly understood.

Many studies have demonstrated the effect of *Microcystis* or its toxins on zooplankton growth and survival. Microcystins either in zooplankton food or dissolved in the water column affect survival and growth rate of copepods, cladocera, and rotifers (Ghadouani et al., 2006; Federico et al., 2007). Secondary metabolites such as lipopolysaccharides in some non-toxic *Microcystis* strains can also inhibit zooplankton growth (Rohrlack et al., 2001, 2005). The greatest impact of *Microcystis* on natural zooplankton populations may be its poor food quality (Wilson et al., 2006). Low concentrations of polyunsaturated and saturated fatty acids compared with other plankton make *Microcystis* a nutritionally poor quality food (Müller-Navarra et al., 2000). The large diameter of the *Microcystis* colonies also makes them difficult to ingest, may physically clog feeding appendages and increase food rejection rate (Ghadouani et al., 2004). In addition, the presence of *Microcystis* in the water column and associated production of protease inhibitors may inhibit feeding in some zooplankton (Agrawai et al., 2001; Ferrão-Filho et al., 2002). Some or all of these factors may explain field and laboratory research which suggests *Microcystis* alters zooplankton community structure and total biomass by reducing the growth and survival of zooplankton, especially large (>1 mm) cladocerans like *Daphnia* (Ghadouani et al. 2006; Chen et al., 2007). The response of the zooplankton community to *Microcystis* is complex and depends on a variety of factors including season, length of exposure, and the *Microcystis* strain and how these interact with the fitness of each zooplankton species (Gustafsson & Hansson, 2004; Wilson & Hay, 2007).

At higher trophic levels, *Microcystis* blooms affect fish health through impacts on growth rate, histopathology, and behavior (Malbrouck & Kestemont, 2006). Microcystin enters the fish gut passively during swimming or actively through food intake, and accumulates in fish tissue (De Magalthães et al., 2001). Microcystin slows protein synthesis by inhibiting protein phosphatase 1 and 2A and promotes tumor formation and cancer in fish tissue (Fischer & Dietrich, 2000; van der Oost et al., 2003). Microcystin can increase heart rate and produce osmoregulatory imbalance by stimulating drinking in adults which makes fish more susceptible to toxins in the environment, including microcystin (Best et al., 2001, 2003). Recent research suggests microcystins also cause oxidative stress in fish by reducing the production of antioxidants and increasing lipid peroxidation in liver, kidney, and gill tissue (Bláha et al. 2004; Prieto et al., 2007). The lipopolysaccharides in *Microcystis* cells further decrease antioxidant formation in fish and may be more toxic than microcystin (Best et al., 2002). At a population level, *Microcystis* causes effects such as mortality and delayed hatching in fish embryos or may simply affect feeding rate (Malbrouck & Kestemont, 2006; Palíková et al., 2007).

Microcystis blooms are a fairly recent occurrence in San Francisco Estuary (SFE), and were first observed in the delta region in 1999 (Lehman et al., 2005). The population level during the summer bloom period is relatively low when compared with many *Microcystis* blooms worldwide which form a dense scum on the surface of the water column (Lehman et al., 2008). It is unknown, if this bloom is still in its initial stage of establishment, or has reached maximum abundance. Recent genetic studies indicate the *Microcystis* strain in SFE is genetically different from known strains (Moisander et al., 2009). However, the coincident appearance of *Microcystis* and a decline in a number of fish and zooplankton species of concern including delta smelt (*Hypomesus transpacificus*), striped bass (*Morone saxatilis*), and threadfin shad (*Dorosoma petenense*) and their calanoid copepod prey *Eurytemora affinis* and *Pseudodiaptomus forbesii* in the freshwater regions of the estuary suggest that there is a link between the fishery decline and the presence of *Microcystis* in the estuary since 2000 (Sommer et al., 2007). Research on *Microcystis* in 2003 and 2004 confirmed the presence of toxic microcystins in plankton and zooplankton in SFE (Lehman et al., 2005, 2008). We hypothesize that *Microcystis* directly or indirectly contributed to the decline in fish and zooplankton species of concern through toxicity or impacts on the food web.

The purpose of this study was to utilize a combination of plankton, zooplankton, and fish community composition, tissue microcystins concentration, and histopathology to determine if *Microcystis* may have influenced the production or health of organisms in the estuarine food web in 2005. Such information is invaluable for developing strategies to manage future estuarine food web resources impacted by this toxic cyanobacterium. It may also assist with developing a more comprehensive understanding of the factors that contributed to the decline in pelagic organisms and increase in *Microcystis* blooms in SFE since 2000 (Lehman et al., 2005; Sommer et al., 2007).

Materials and methods

Study area

San Francisco Estuary (SFE) consists of an inland delta that flows into a chain of downstream marine bays—Suisun, San Pablo, and San Francisco—and creates one of the largest estuaries on the west coast of North America (Fig. 1). The Sacramento River on the north and the San Joaquin River on the south converge just east of Suisun Bay to form a delta that contains 200 km^2 of waterways. The Sacramento River is the largest of the rivers that feed the delta, and has an average discharge of 498 ± 21 m^3 s^{-1} compared with 70 ± 7 m^3 s^{-1} for the San Joaquin River over the August and September period of this study. The delta has many kinds of habitats from shallow flooded islands that are 2 m deep to wide and deep river channels that are 13 m deep. Flow in the delta is influenced by tides that reach 2 m in depth, tidal velocities up to 30 cm s^{-1} and tidal excursions of up to 10 km. The delta is largely rural with a population of about 500,000 people within the cities of Sacramento, Stockton, and West Sacramento. Most of the 1,300 km of sloughs and 57 islands in the delta are used for agriculture and wildlife habitat.

Field sampling

Chlorophyll *a* and total microcystins concentration plus a suite of water quality conditions were sampled biweekly at each station between August 1 and September 30, 2005 at 10 stations throughout the freshwater to brackish water reaches of SFE (Fig. 1). Stations were selected that reflected different habitats within the delta including the brackish water habitat in Suisun Bay at Chipps Island (CI) and Middle Ground (SB), saltwater marsh habitat at Montezuma Slough (SM), freshwater habitat in the Sacramento River at Cache Slough (CS), the San Joaquin River at Turner Cut (SJ) and Old River near Ranch del Rio (OR), brackish water habitat in the Sacramento River at Collinsville (CV) and the San Joaquin River at

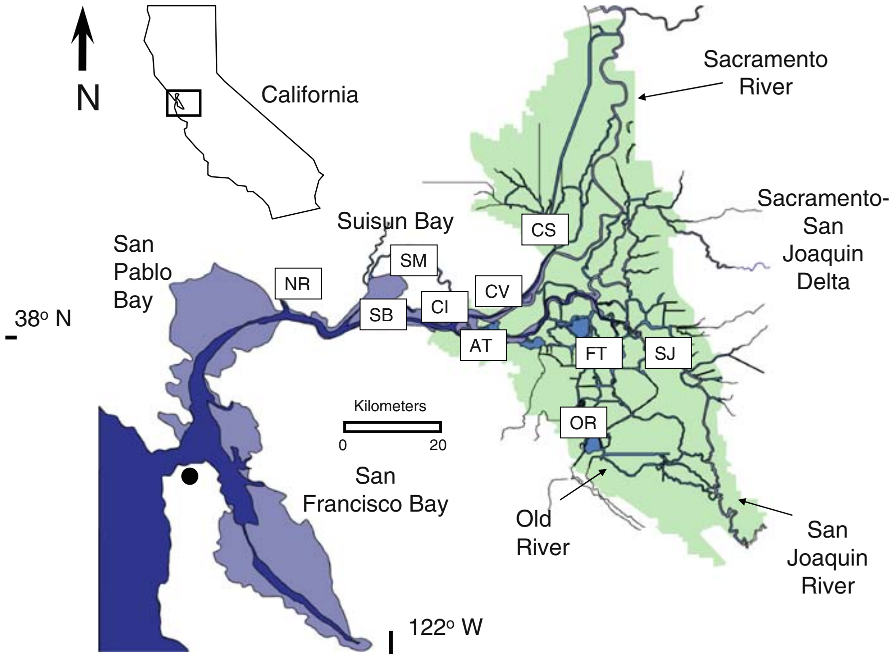


Fig. 1 Map of San Francisco estuary showing codes for sampling stations for Napa River (NR) at the City of Napa, Suisun Bay at Middle Ground (SB), Suisun Marsh at Montezuma Slough (SM), Chipps Island (CI), Sacramento River at Collinsville (CV) and Cache Slough (CV), Old River at Franks Tract (FT) and Ranch del Rio (OR), and San Joaquin River at Turner Cut (SJ) and Antioch (AT)

Antioch (AT), and flooded island habitat in Old River at Franks Tract (FT). A station was added in the Napa River (NR) outside of the delta which did not have a *Microcystis* bloom for perspective.

Microcystis colonies in the surface layer were sampled by horizontal surface tows of a 0.5 m diameter plankton net with 75 μm mesh netting as described in Lehman et al. (2005). Water samples containing plankton biomass were stored at 4°C and filtered within 2 h onto Millipore APFF glass fiber filters. Filters for microcystins analysis were folded, wrapped in aluminum foil, frozen, and stored at −80°C until laboratory analysis for toxin content. Filters for chlorophyll *a* analysis were preserved with 1 ml of saturated magnesium carbonate solution, immediately frozen and stored at −14°C until analysis for pigment content.

Pigments were extracted from glass fiber filters in 90% acetone and analyzed for chlorophyll *a* (corrected for phaeophytin) and phaeophytin using spectrophotometry (American Public Health Association et al., 1998). Water samples for identification and enumeration of plankton were preserved and stained with Lugol's iodine solution, and phytoplankton were counted at ×700 using an inverted microscope technique (Utermöhl, 1958). This magnification allowed clear identification of plankton cells >6 μm in diameter. Phytoplankton species were identified by taxonomic descriptions in Freshwater Algae of North America, Ecology, and Classification (Wehr & Sheath, 2003) and Cyanoprokaryota 1, Teil: Chroococcales (Komárek & Anagnostidis, 2001). *Microcystis aeruginosa* was identified as the only *Microcystis* species in each sample. Plankton cell carbon was calculated from cell volume computed from cell dimensions applied to simple geometrical shapes with correction for the small plasma volume in diatom cells (Menden-Deuer & Lessard, 2000).

Water quality conditions were determined from laboratory analysis of water collected near the surface using a van Dorn bottle sampler. Water samples for chloride, alkalinity, ammonium-N, nitrate-N plus nitrite-N, soluble reactive phosphorus, and silicate concentration were filtered through 0.45 μm pore size Millipore HATF04700 nucleopore filters. Water samples for dissolved organic carbon were filtered through Millipore APFF glass fiber filters. Filtered and raw water samples were either stored at 4°C or −14°C until analysis for nutrients (United States Environmental Protection Agency, 1983; United States Geological Survey, 1985) or dissolved microcystins analysis. Total suspended solids, total and dissolved organic carbon concentration, and alkalinity were determined by standard methods (American Public Health Association et al., 1998). Water temperature, pH, specific conductance, and dissolved oxygen were measured near the surface using a Yellow Springs Instrument (YSI) 6600 water quality sonde.

Zooplankton were collected at each station by a 3 min diagonal tow of a 0.5 m diameter plankton net fitted with a 150 μm mesh netting. Zooplankton were kept at 4°C and separated by pipette from *Microcystis* in the water sample using a dissecting microscope within 48 h of sampling. Zooplankton tissue was rinsed in distilled water and frozen at −80°C until toxin analysis. Zooplankton for identification and enumeration were dyed and preserved in 10% buffered formalin with rose bengal dye. Species identification and enumeration were conducted using a dissecting scope.

Juvenile striped bass (*Morone saxatilis*) and Mississippi silversides (*Menidia audens*) were collected at beaches near the edge of channels adjacent to the open water sampling station. Juvenile striped bass and Mississippi silversides were selected for this study because they occur throughout the estuary and prey on mesozooplankton and amphipods that may use *Microcystis* as a food source. Fish were sampled using a 30 × 1.8 m, 3.2 mm mesh beach seine. Sampling consisted of 2–8 hauls per station during flood tide when beaches were covered in water. Fish 30–300 mm were most vulnerable to this beach seine sampling technique (Nobriga et al., 2005). Live striped bass and Mississippi silversides were immediately placed in a cooler with river water, aerated with a stone aerator, and transported to a nearby laboratory boat for dissection. Only live fish were dissected for tissue analysis. Juvenile striped bass were not collected in sufficient quantity for analysis at FT and OR.

Fish were decapitated, and liver and muscle were surgically removed from each fish in less than 1 h after collection. The liver tissue of each fish was partitioned into two samples: one for analysis of total microcystins content and one for histopathology. For total microcystins analysis, tissue was wrapped in aluminum foil, flash frozen with liquid nitrogen and kept frozen at −80°C until analysis. Tissue samples for histopathological analysis were stored at room temperature in 10% neutral buffered formalin. Because the fish were small (typically <100 mm long), liver and muscle tissues from multiple striped bass were combined to get sufficient tissue for microcystins analysis. Mississippi silversides were so small that liver and muscle tissue could not be separated.

Microcystins analysis

Filters with plankton tissue for total microcystins analysis were extracted by sonication with 10 ml of 50% methanol containing 1% acetic acid, clarified by centrifugation, and the extract used for toxic microcystins analysis using the protein phosphatase inhibition assay (PPIA) technique, while anatoxin-a in plankton samples was measured by HPLC as described in Lehman et al. (2005). Dissolved microcystin concentration was computed as the difference between whole water and plankton tissue concentrations.

The toxic microcystins concentration in fish tissue was determined from lyophilized tissue (0.1 g dw liver or 0.6 g dw muscle) that was extracted with 50% methanol (MeOH) containing 1% acetic acid (HOAc) at a ratio of 10 ml solvent: 1 g dw tissue. The tissue was homogenized using a Biospec tissue tearor at 5,000–10,000 rpm for 1 min and then centrifuged at 3,000 rpm for 10 min. The supernatant was transferred to a glass tube, and the particulate material was re-extracted with the same volume of solvent. The pooled supernatants were taken to dryness in vacuo and resuspended in 1 ml of acidified 50% MeOH. PPIA was used to determine the total concentration of free microcystins, expressed as microcystin-LR equivalents, in the fish tissue. The PPIA method used for fish tissue was the same as that used for plankton and zooplankton tissue described above. The recovery of free microcystins in fish tissue was determined using an internal standard, [S-propyl-cys^7] microcystin-LR, synthesized from microcystin-LR (Smith & Boyer, 2009).

Histopathology

Histopathological analysis was conducted on fish liver tissue following the methods of Teh et al. (2004). After 48 h in 10% neutral buffered formalin, tissues were dehydrated in a graded ethanol series and embedded in a paraffin block. For each tissue block, serial sections (4 μm thick) were cut and stained with hematoxylin and eosin. Tissue sections were examined under a BH-2 Olympus microscope for common and/or significant lesions.

Tissues were screened and scored on an ordinal ranking system for a variety of histopathological features and lesions (0 = none/minimal, 1 = mild, 2 = moderate, and 3 = severe; and 0 = not present or infrequently observed, 1 = mildly affected in <10% of the tissue, 2 = moderately affected in 10–50% of the tissue, and 3 = severely affected in greater than 50% of the tissue, respectively). Due to the importance of the number of preneoplastic foci and tumors in the progression of fish hepatocarcinogenesis, basophil preneoplastic focus and hepatocellular adenoma lesions were enumerated rather than scored by severity.

Seven characteristics of the liver lesions were scored to identify toxic exposure in fish: glycogen depletion, eosinophilic protein droplets, cytoplasmic inclusions, single cell necrosis, fatty vacuolation, or lipidosis, macrophage aggregates and focal/multifocal parenchymal leukocytes or lymphocytes. Glycogen depletion was characterized by decreased hepatocyte size, loss of the 'lacy', irregular, and poorly demarcated cytoplasmic vacuolation typical of glycogen, and increased cytoplasmic basophilia (i.e., blue coloration). Eosinophilic protein droplets were characterized by the presence of proteins which appeared as refractile, eosinophilic (pink coloration), round, and well-demarcated cytoplasmic vacuoles. Cytoplasmic inclusions were characterized by the accumulation of foreign materials within the cytoplasm of hepatocytes. Single cell necrosis was characterized by cells having eosinophilic cytoplasm with nuclear pyknosis and karyorrhexis. Fatty vacuolation or lipidosis was characterized by excess lipids which appeared as clear, round, and well-demarcated cytoplasmic vacuoles. Macrophage aggregation was characterized as a cluster of macrophages packed with coarsely granular yellow–brown pigment. Focal/multifocal parenchymal leukocytes or lymphocytes were characterized by focal to multifocal aggregates of lymphocytes, occasionally mixed with other inflammatory cells. Cumulative assessment was based on the sum of the mean of individual lesion scores where higher total mean score indicated poorer fish conditions.

Statistical analysis

Due to the lack of normality in the data sets, all statistical analyses were computed using non-parametric statistics. Comparisons of physical, chemical, and biological data were computed using non-parametric statistical techniques for single and multiple comparisons, Wilcoxon and Kruskal–Wallis comparison tests (SAS, 2004). Correlation coefficients were computed using the non-parametric Spearman rank correlation coefficient (r_s). Data were reported as the mean ± the standard deviation.

Similar patterns in plankton and zooplankton community composition or carbon and their correlation with environmental factors were evaluated with Primer-e version 6 software (Clarke, 1993; Clarke & Gorley, 2006) using a combination of multidimensional scaling (MDS), analysis of similarities among data (ANOSIM), identification of variables that best explain the data variance (BEST), and multivariate comparisons of data patterns (RELATE). These were applied to patterns in plankton species composition over space or time by visualizing the data patterns using an MDS of the Bray Curtis dissimilarity index computed from the square root of density or carbon data. Similar patterns in plankton or zooplankton community composition and carbon among stations were quantified with ANOSIM, while similarities between patterns in physical (normalized) and plankton and zooplankton community composition or carbon were quantified by Spearman rank correlation coefficients using RELATE. Species which accounted for most of the variation in the plankton, zooplankton, or environmental data were identified by Spearman rank correlation coefficients applied to groups of variables using BEST.

Results

Plankton

Microcystis abundance was greatest ($P < 0.01$, ANOSIM) in the western and central delta (stations CV, AT, FT, SJ, and OR). Average *Microcystis* abundance (9×10^6 cells l^{-1}) at these stations was nearly an order of magnitude greater than at Suisun Bay stations SB and CI (1.0×10^6 cells l^{-1}) or the outlying stations SM, CS, and NR where *Microcystis* did not occur (Fig. 2). In the western and central delta, *Microcystis* abundance was elevated at stations CV, AT, and OR and significantly greater at stations OR and AT ($P < 0.05$). Spatial variability characterized *Microcystis* in the western and central delta where abundance ranged by orders of magnitude from no cells l^{-1} at station CV in early August to 32×10^9 cells l^{-1} at station OR in mid-August.

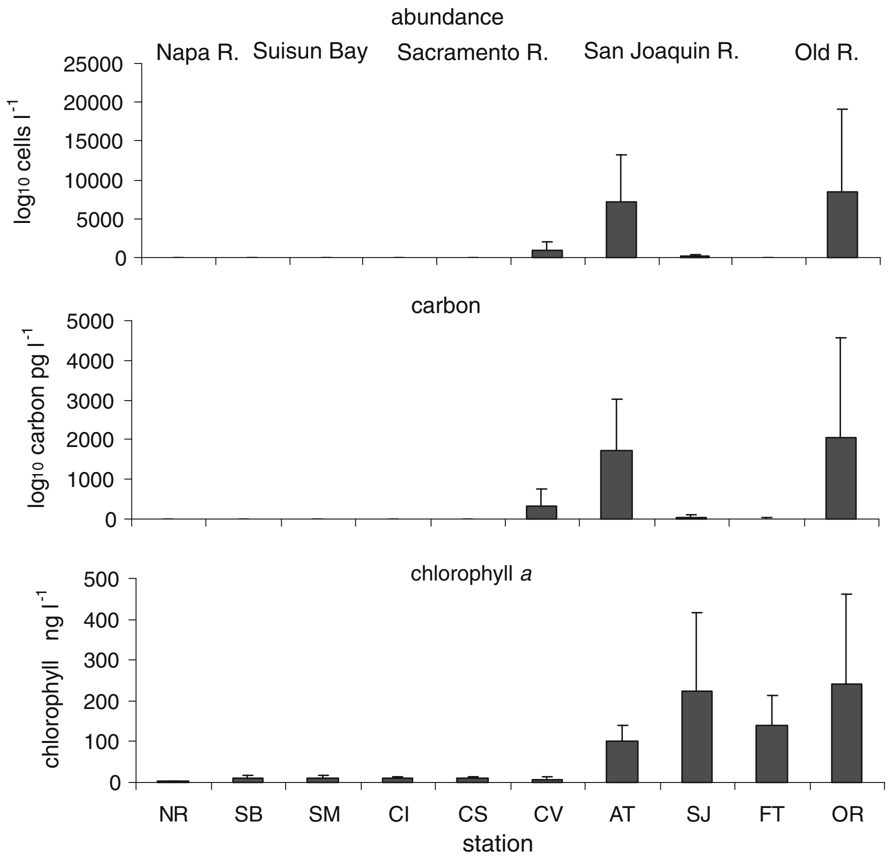


Fig. 2 *Microcystis* abundance, carbon, and chlorophyll *a* concentration at stations throughout the estuary

Chlorophyll *a* concentration increased with *Microcystis* carbon in the surface layer (Fig. 2). *Microcystis* carbon comprised about 90% of the plankton carbon, and was correlated with both total plankton carbon ($r_s = 0.83$; $P < 0.01$) and chlorophyll *a* concentration ($r = 0.76$, $P < 0.01$) for all stations combined. *Microcystis* carbon was also positively correlated with diatom, green algae, and miscellaneous flagellate carbon ($r_s = 0.43$, $P < 0.01$; $r_s = 0.74$, $P < 0.01$, and $r_s = 0.76$, $P < 0.01$, respectively). Chlorophyll *a* concentration and total plankton carbon were also correlated ($r_s = 0.82$; $P < 0.01$).

Plankton community composition varied with *Microcystis* abundance throughout the water column. In the surface layer, plankton community composition was correlated with *Microcystis* abundance for all stations combined ($P < 0.01$, RELATE). The variation in this plankton community was primarily due to the cyanobacterium *Aphanizomenon* spp., diatoms *Aulacoseira granualata* and *Bacillaria paradoxa*, green alga *Chlorella* sp., and miscellaneous flagellates ($r_s = 0.94$, BEST; Fig. 3). *Microcystis* comprised 5, 48, 100, 86, 100, and 95% of the total abundance at SB, CV, AT, SJ, FT, and OR, respectively, and less than 1% at the rest of the stations. *Microcystis* abundance was also significantly correlated ($P < 0.05$, RELATE) with the plankton community composition in the western and central delta where *Aphanizomenon* sp., *A. granulata* and *B.paradoxa* accounted for 92% ($r_s = 0.96$, BEST) of the variation. In addition, the abundance of cyanobacteria species including *Aphanizomenon* spp., *Planktolyngbya* spp., *Pseudodanabaena* spp., and *Merismopedia* spp. co-varied ($P < 0.01$, RELATE) with *Microcystis* abundance for all stations combined (Fig. 3). The plankton community at 1 m depth was also correlated with *Microcystis* abundance in the surface layer for all stations ($P < 0.05$, RELATE; Fig. 4). About 83% of the variation in the plankton community at 1 m was associated with the abundance of the cryptophytes *Rhodomonas* spp. and *Cryptomonas* spp., the green

Fig. 3 Average percent abundance of phytoplankton and cyanobacteria genera or species among stations. Only genera or species that comprised more than 1% of the abundance for any one station were included

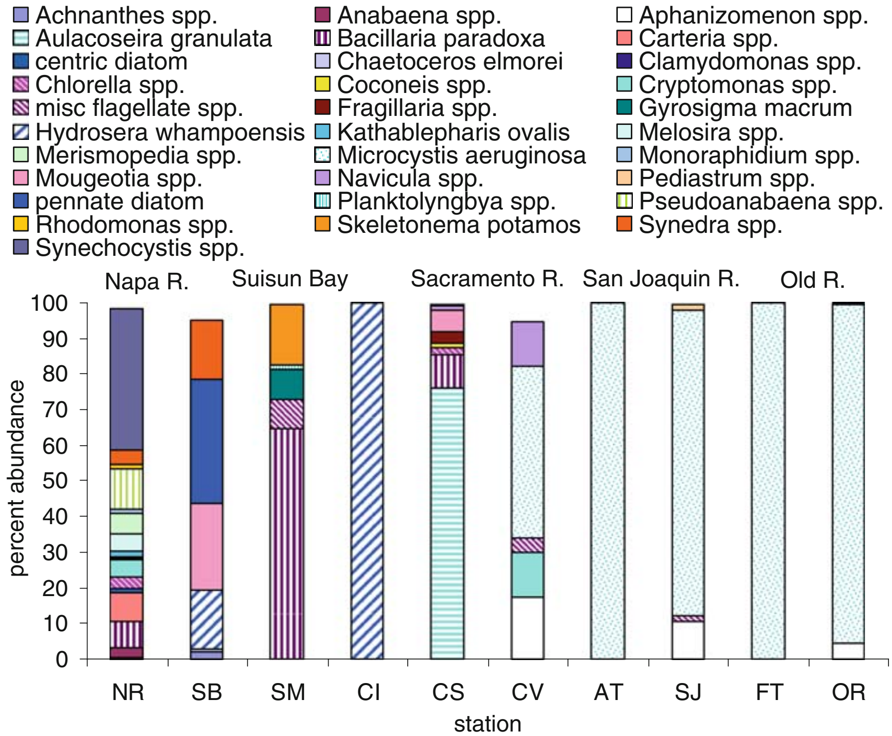
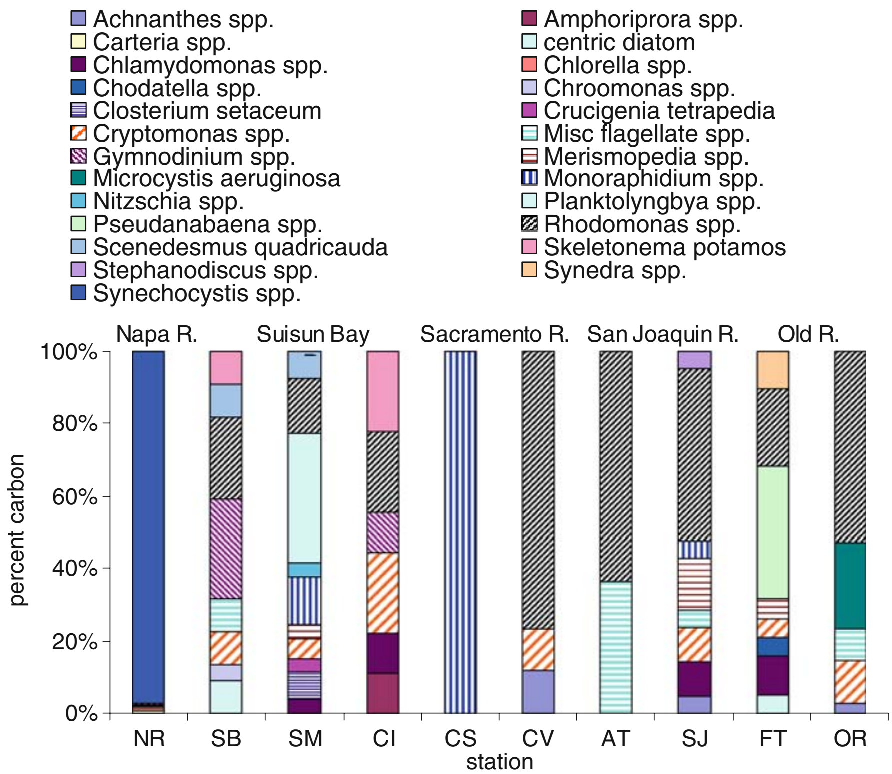


Fig. 4 Percent carbon of phytoplankton and cyanobacteria genera or species at 1 m depth. Only genera or species that composed more than 1% of the abundance for any one station were included



algae *Closterium setaceum* and *Monoraphidium* spp., and the dinoflagellate *Gymnodinium* spp. ($r_s = 0.91$, BEST) which were abundant in the western and central delta; 50% of this variation was due to *Rhodomonas* spp. alone ($r_s = 0.71$, BEST). Plankton community composition at 1 m depth was correlated with *Microcystis* abundance even on a small geographical scale. The cryptophytes *Rhodomonas* spp. and *Cryptomonas* spp., the cyanobacteria *Merismopedia* spp., and *Microcystis* and miscellaneous flagellates ($r_s = 0.86$, BEST) characterized differences in the plankton community at AT, OR, and CV compared with SJ and FT ($P < 0.05$, ANOSIM); most of this variation was due to *Rhodomonas* spp. ($r_s = 0.65$, BEST). *Microcystis* abundance was similarly greater at AT and OR compared with SJ and FT ($P < 0.05$, ANOSIM).

Differences in the plankton community composition affected the plankton carbon among groups. Plankton group carbon differed ($P < 0.05$, ANOSIM) between stations OR, CV, and AT and stations FT and SJ at 1 m (Fig. 5). Most of this difference was associated with diatom, green algae, and cryptophyte carbon ($r_s = 0.89$, BEST), and was characterized by a greater ($P < 0.05$) percentage of cryptophytes and a lower ($P < 0.05$) percentage of diatoms and green algae at stations OR, CV, and AT compared with stations SJ and FT. The difference was most striking for cryptophyte carbon which comprised 70–90% of the total carbon at OR, CV, and AT, but only 35–45% of the total carbon for nearby stations at SJ and FT. Most of the cryptophyte carbon was produced by *Rhodomonas* sp. and *Cryptomonas* sp.

Microcystis abundance was correlated with water quality conditions across regions ($P < 0.01$, RELATE). Water quality conditions differed ($P < 0.01$, ANOSIM) among the western and central delta (CV, AT, SJ, FT, and OR), Suisun Bay (SB, SM, and CI), CS and NR stations or station groups (Table 1). About 72% (BEST) of this variation was correlated with chloride, total organic carbon, and total suspended solids concentration which increased seaward. Among variables, *Microcystis* abundance was negatively correlated with chloride ($P < 0.01$, RELATE), total suspended solids ($P < 0.01$, RELATE), and total organic carbon ($P < 0.01$, RELATE), and positively correlated with nitrate-N ($P < 0.05$, RELATE), soluble phosphorus ($P < 0.05$, RELATE), and total nitrogen (nitrate-N plus ammonium-N; $P < 0.01$, RELATE) concentration.

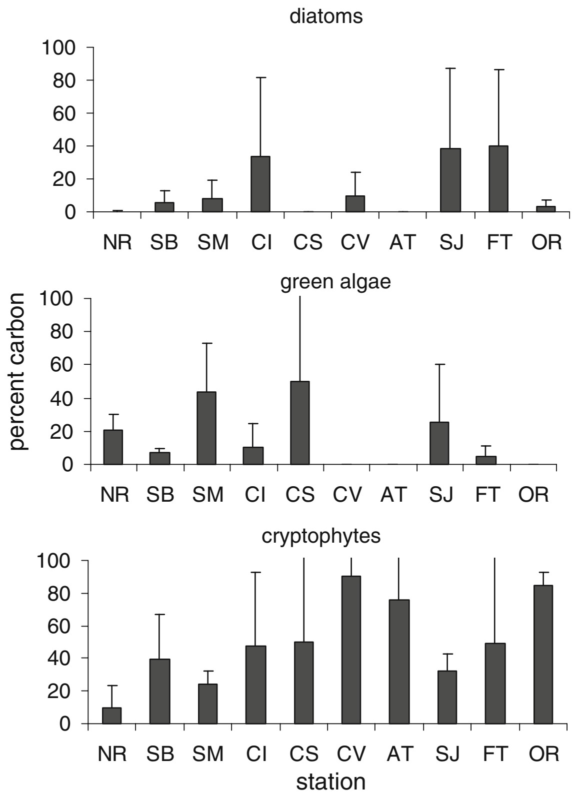


Fig. 5 Percent carbon for diatom, green algae, and cryptophyte carbon at 1 m depth

Although ammonium-N concentration was elevated at some stations in the western and central delta and the Sacramento River at stations at CS and CV, neither it nor the total nitrogen (nitrate-N and nitrite-N plus ammonium-N) to soluble phosphorus molar ratio (NP) was significantly correlated with *Microcystis* abundance across all regions or within the western and central delta separately. Plankton group carbon or plankton species abundance at 1 m was not significantly correlated with any of the water quality conditions measured, including the NP ratio.

Zooplankton

Zooplankton community composition differed ($P < 0.01$, ANOSIM) across the delta and was correlated with *Microcystis* abundance in the surface layer ($P < 0.01$, RELATE). Significant differences in the zooplankton community composition in the western and central delta and Suisun Bay ($P < 0.01$, ANOSIM)

Table 1 Average water quality conditions in the surface layer computed from biweekly data for stations sampled in the San Francisco Estuary between August and September 2005

Water quality variable	Stations									
	NR	SB	SM	CI	CS	CV	AT	SJ	FT	OR
Ammonium-N (mg l^{-1})	0.01	0.03	0.02	0.03	0.10	0.05	0.03	0.03	0.02	0.02
Chloride (mg l^{-1})	7,032.50	2,655.00	1,935.00	2,420.00	8.33	429.50	413.00	30.75	73.75	46.50
Nitrate-N (mg l^{-1})	0.01	0.31	0.22	0.32	0.20	0.28	0.24	0.22	0.11	0.17
Dissolved organic carbon (mg l^{-1})	2.93	1.65	4.30	1.71	1.90	1.72	1.82	2.09	2.00	1.89
Soluble reactive phosphorus (mg l^{-1})	0.03	0.07	0.06	0.07	0.05	0.06	0.06	0.04	0.05	0.05
Silica (mg l^{-1})	45.53	14.43	14.30	14.57	16.33	15.60	14.10	13.35	13.00	13.00
Alkalinity (mg l^{-1})	121.00	69.00	80.25	69.67	69.67	67.25	66.00	61.25	65.25	62.50
Total organic carbon (mg l^{-1})	3.20	1.71	4.65	1.99	1.85	1.90	1.86	2.05	1.85	2.13
Total phosphorus (mg l^{-1})	0.08	0.10	0.14	0.15	0.10	0.09	0.09	0.08	0.08	0.08
Total suspended solids (mg l^{-1})	10.38	23.75	41.25	61.00	20.33	34.25	9.75	3.75	2.50	2.75
Water temperature °C	21.19	20.98	21.51	19.34	21.18	20.73	20.78	23.37	22.44	23.03
Dissolved oxygen (mg l^{-1})	7.23	6.70	6.78	6.77	6.73	6.70	6.70	6.63	7.00	6.70
pH	7.69	8.09	8.04	8.16	7.89	7.97	8.34	7.83	8.60	8.08
Specific conductance µS cm^{-1}	18.80	7.69	5.73	7.22	0.16	1.38	1.73	0.23	0.36	0.21

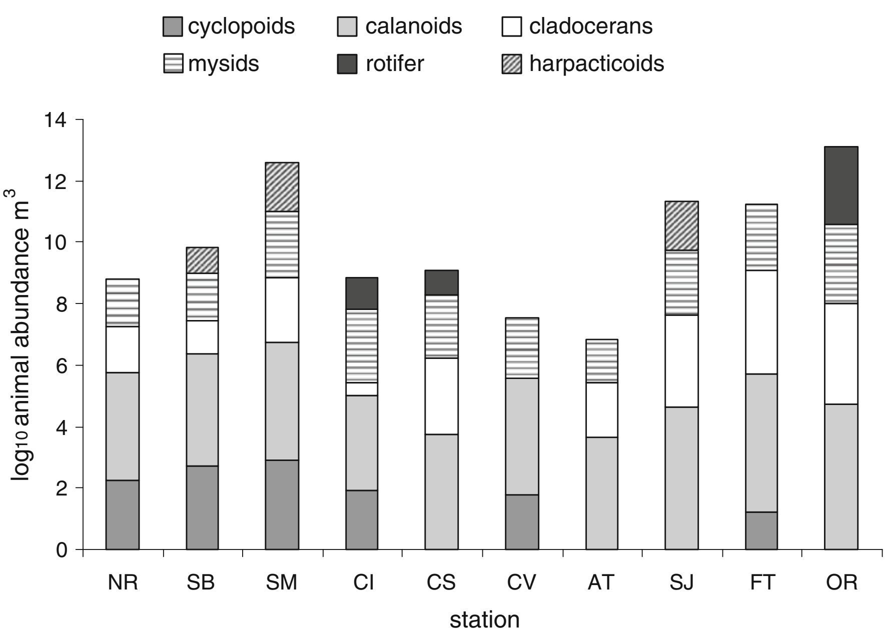


Fig. 6 Mesozooplankton abundance ($\log_{10}$ animals l^{-1}) by taxonomic group among stations determined from diagonal net tow samples

were also correlated with *Microcystis* abundance ($P < 0.01$, RELATE). Most of the variation in the zooplankton community in the western and central delta and Suisun Bay was due to calanoid and cyclopoid copepods and cladocera ($r_s = 0.80$, BEST; Fig. 6). Calanoid copepods in the western and central delta were characterized by nauplii and the freshwater copepod *Pseudodiaptomus* spp., and were significantly different ($P < 0.05$, ANOSIM) from Suisun Bay, where the brackish water calanoid copepod *Acartiella* spp. was abundant. Both *Pseudodiaptomus* spp. and *Acartiella* spp. accounted for 88% of the variation in the zooplankton community between the western and central delta and Suisun Bay ($r_s = 0.94$, BEST).

Microcystis carbon in the surface layer was significantly correlated with both total zooplankton carbon

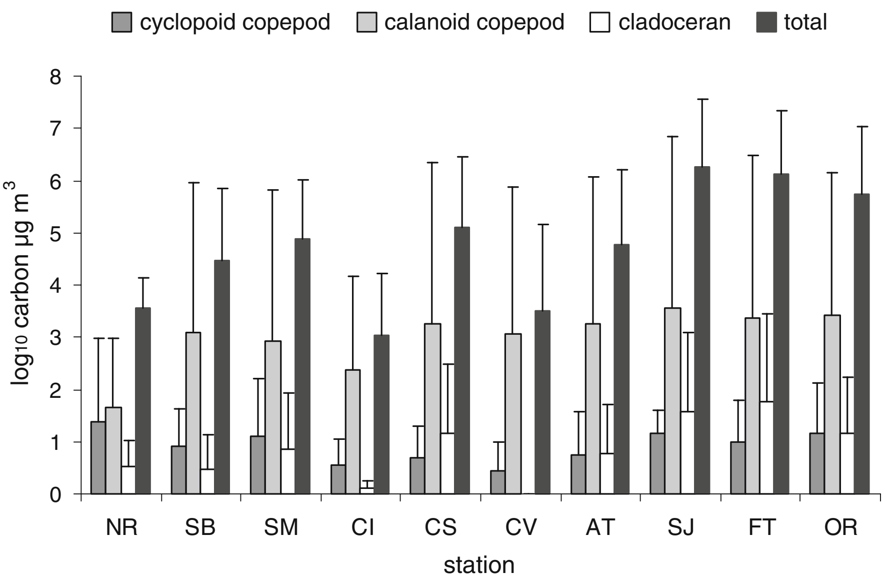


Fig. 7 Log_{10} average total and mesozooplankton group carbon (µg m^{-3}) and their standard deviation (*line*) among stations determined from diagonal net tow samples

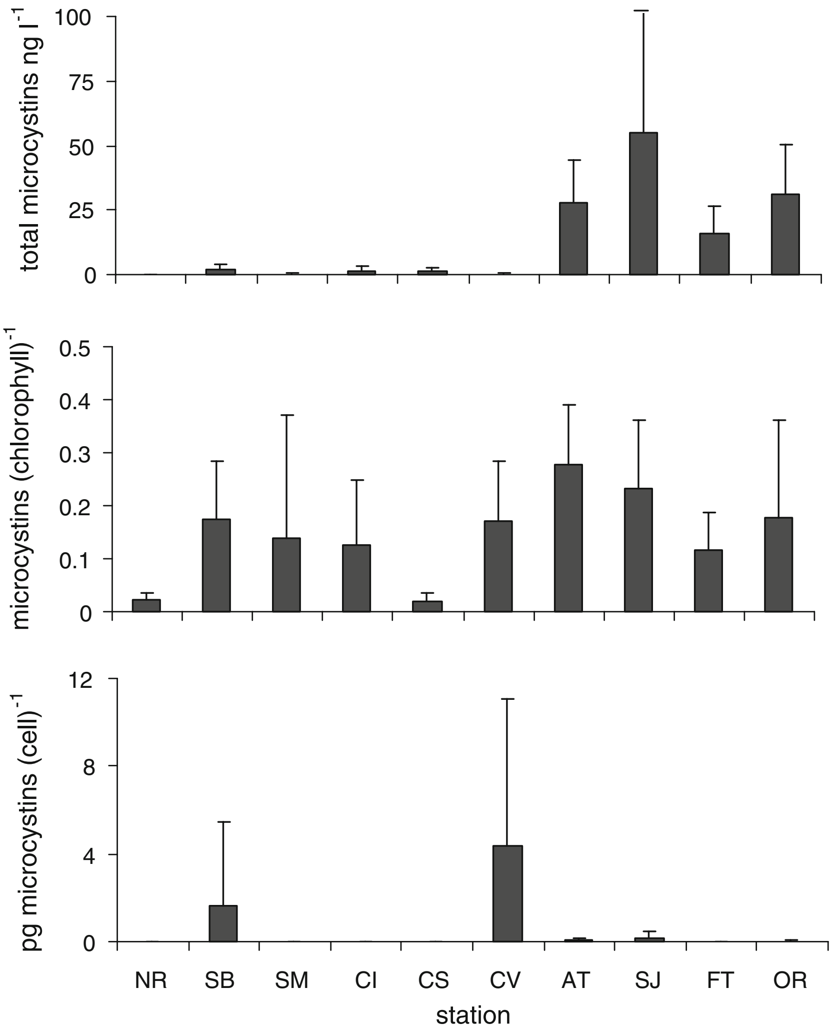
and zooplankton group carbon for all stations ($P <$ 0.01, RELATE) and for Suisun Bay and the western and central delta, separately ($P < 0.01$, RELATE). Calanoid copepod, cyclopoid copepod, rotifer, and cladocera carbon differed ($P < 0.01$, ANOSIM) between Suisun Bay, the western and central delta and the outlying stations NR and CS (Fig. 7). Nearly all of this difference in carbon among stations was due to the high biomass of the calanoid copepod *Pseudodiaptomus* sp. in the central delta ($r_s = 0.99$, BEST). Although the zooplankton group carbon differed between stations CV, SJ, and OR in the western and central delta, it was not associated with *Microcystis* abundance (Fig. 7). In contrast, *Microcystis* carbon was associated with differences in the cladocera to calanoid copepod carbon ratio among stations in the western and central delta ($P < 0.01$, RELATE). The cladocera to calanoid copepod carbon ratio was lower ($P < 0.01$) at stations OR, AT, and CV than FT and SJ (0.003 ± 0.003 and 0.02 ± 0.02, respectively).

Toxins in plankton and animal tissue

Microcystins were present in the surface plankton samples throughout the estuary where *Microcystis* occurred (Fig. 8). The highest total microcystins concentration in *Microcystis* tissue ($P < 0.05$, ANOSIM) occurred in the San Joaquin and Old rivers at stations AT, SJ, FT, and OR where it reached an average of 60 ng l^{-1}. Total microcystins concentration was correlated with both chlorophyll *a* concentration and *Microcystis* abundance for all stations ($r_s = 0.89$, $P < 0.01$; $r_s = 0.74$, $P < 0.01$), the Suisun Bay and western and central delta ($r_s = 0.87$, $P < 0.01$; $r_s = 0.68$, $P < 0.01$), and the western and central delta ($r_s = 0.79$, $P < 0.05$; $r_s = 0.45$, $P < 0.05$). The relative toxicity of *Microcystis* appeared to be uniform throughout the estuary because both total microcystins per unit chlorophyll *a* concentration and total microcystins per *Microcystis* cell were not statistically different among stations, despite large differences in average values (Fig. 8). Dissolved total microcystins concentration was above detection limits nine times during the sampling season, three times in August at CI, CS, and OR (0.05–3.1 ng l^{-1}), and six times in September at SB, CV, AT, FT, and OR (0.4–10.88 ng l^{-1}). Anatoxin-a concentration was low and below detection limits in plankton samples 17 times during the summer; range 2.4–143 pg l^{-1}.

Total microcystins were present in zooplankton and amphipod tissue throughout the estuary. Total microcystins in zooplankton and amphipod tissue ranged from 0.40 to 1.43 µg (g dry wt)$^{-1}$, and was greatest at SJ by a factor of 2 (Table 2). Low biomass precluded absolute measurements of total microcystins in most zooplankton and amphipod tissue samples. However, detection limits suggested average total microcystins concentration in animal tissue was low, and could only have reached as high as 3.99 µg (g dry wt)$^{-1}$ in zooplankton and 0.99 µg

Fig. 8 Average (*bar*) and standard deviation (*line*) of total microcystins concentration (μg l^{-1}), total microcystins per unit chlorophyll *a* and total microcystins per *Microcystis* cell (within the >75 μm size fraction collected in surface net tows). Total microcystins were measured by protein phosphatase inhibition assay



(g dry wt)$^{-1}$ in amphipod tissue in the central and western delta. A more thorough statistical evaluation of these trends was limited by the small sample size and qualitative nature of some of the data.

Total microcystins were present in the liver, muscle, and whole body tissues of juvenile striped bass and Mississippi silversides at all stations where fish occurred (Table 2). Total microcystins concentration in individual striped bass muscle tissue ranged by a factor of 3 from 1.03 to 3.42 μg (g dry wt)$^{-1}$, but averages among stations were similar (Table 2). Total microcystins concentration in striped bass liver tissue was slightly less than in muscle tissue and varied by a factor of 5 among samples (range 0.34–1.89 μg (g dry wt)$^{-1}$). Tissue concentrations were not statistically different among stations, but were elevated in individual samples at AT in the San Joaquin River and SM in Suisun Bay. Mississippi silversides contained similar amounts of total microcystins in liver and muscle tissue as striped bass (Table 2). As might be expected, total microcystins concentration in the whole body tissue of Mississippi silversides was more than an order of magnitude lower than for liver and muscle tissue alone. Absolute total microcystins concentrations and differences in concentration among samples were probably lower than the actual values due to the need to composite from 2 to 10 fish tissue samples for toxin analysis from these very small fish; this was particularly true for liver samples.

Histopathology

Histopathological analysis revealed that Mississippi silversides and juvenile striped bass were likely

Table 2 Average absolute and relative total microcystins concentration (μg (g dry weight)$^{-1}$) in mesozooplankton and fish tissue measured between August and September 2005 at stations throughout the estuary

Tissue type	Stations									
	NR	SB	SM	CI	CS	CV	AT	SJ	FT	OR
Zooplankton										
Mesozooplankton	<2.91	0.40; <0.35	0.66; <1.60	<3.99	1.05; <0.43	<0.22	<1.05	1.43 ± 0.62	<3.37	<3.14
Amphipod	<27.27	<0.99	<0.40	<0.64	<1.54	<0.24	<0.17	0.77; < 0.48	<0.5	<0.42
Striped Bass										
Muscle	2.92 ± 0.03	2.22 ± 0.09	2.30 ± 0.77	1.66 ± 0.93	2.14 ± 0.79	2.47 ± 0.74	1.61 ± 0.93	2.51 ± 0.41	2.98 ± 0.62	
Liver	1.20 ± 0.44	1.25 ± 0.30	1.41 ± 0.28	1.14 ± 0.56	0.94 ± 0.40	1.18 ± 0.15	1.48 ± 0.08	1.08 ± 0.13	1.04 ± 0.30	
Mississippi silversides										
Muscle			1.95 ± 0.16				1.98 ± 0.78			
Whole body	0.38 ± 0.06	0.37 ± 0.04	0.47 ± 0.16	0.39 ± 0.07	0.30 ± 0.05	0.40 ± 0.06	0.37 ± 0.13	0.46 ± 0.29	0.34 ± 0.04	0.34 ± 0.02
Liver			0.80				2.00 ± 0.39			

Toxic microcystins were measured by protein phosphatase inhibition assay

exposed to toxic substances including cancer causing substances throughout the estuary. Several types of histological changes were observed in juvenile striped bass liver tissue. Mild to moderate glycogen depletion occurred in liver tissue for all stations (Fig. 9). Mild, but elevated lesion scores for cytoplasmic inclusion, single cell necrosis and lipidosis also suggested the striped bass in the Sacramento River and San Joaquin Rivers were exposed to toxic contaminants and cancer causing substances. Hepatic preneoplastic foci and the presence of tumors in liver tissue further supported the exposure of striped bass at station AT to cancer causing substances in the San Joaquin River. Importantly, elevated lesion scores for cancer causing substances and the presence of tumors in striped bass liver coincided with elevated concentrations of total microcystins at AT. Liver lesion scores for the San Joaquin River differed from those in Suisun Bay where the maximum lesion scores resulted from a different suite of biomarkers, such as eosinophilic protein droplets, macrophage aggregates, and focal parenchymal leukocytes.

The liver tissue of Mississippi silversides also demonstrated histological changes characteristic of exposure to toxic substances throughout the estuary. Like striped bass, glycogen depletion was mild to moderate at most stations (Fig. 10). Liver lesion scores characteristic of exposure to toxic substances, single cell necrosis, and cytoplasmic inclusions, occurred in liver tissue for fish in San Joaquin River and Suisun Bay, while those for hepatic lipidosis were moderately elevated in liver tissue for Suisun Bay and Old River. Maximum lesion scores in liver tissue for glycogen depletion, eosinophilic protein droplets, and cytoplasmic inclusions occurred in Suisun Bay and San Joaquin River, Sacramento River, and the San Joaquin River, respectively. All of the remaining lesion scores were highest for Mississippi silversides in Suisun Bay at station CI.

Discussion

Phytoplankton

Microcystis forms dense surface blooms that may exert a pronounced effect on the surrounding plankton through its effect on the quantity and quality of the light field in the water column in the presence of

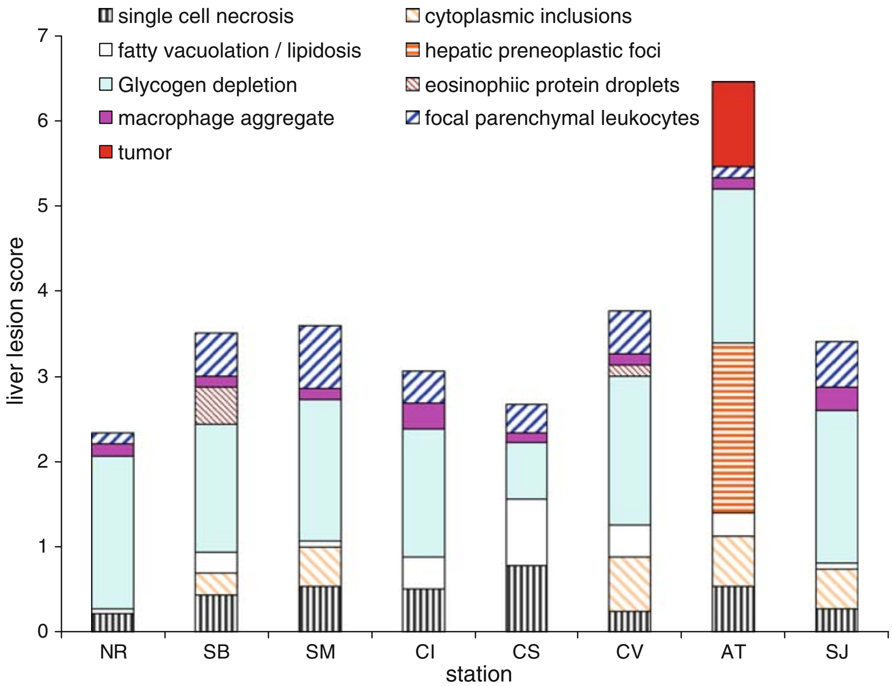


Fig. 9 Average liver lesion scores for each biomarker quantified in juvenile striped bass collected at stations throughout the estuary. No fish were present at stations FT and OR

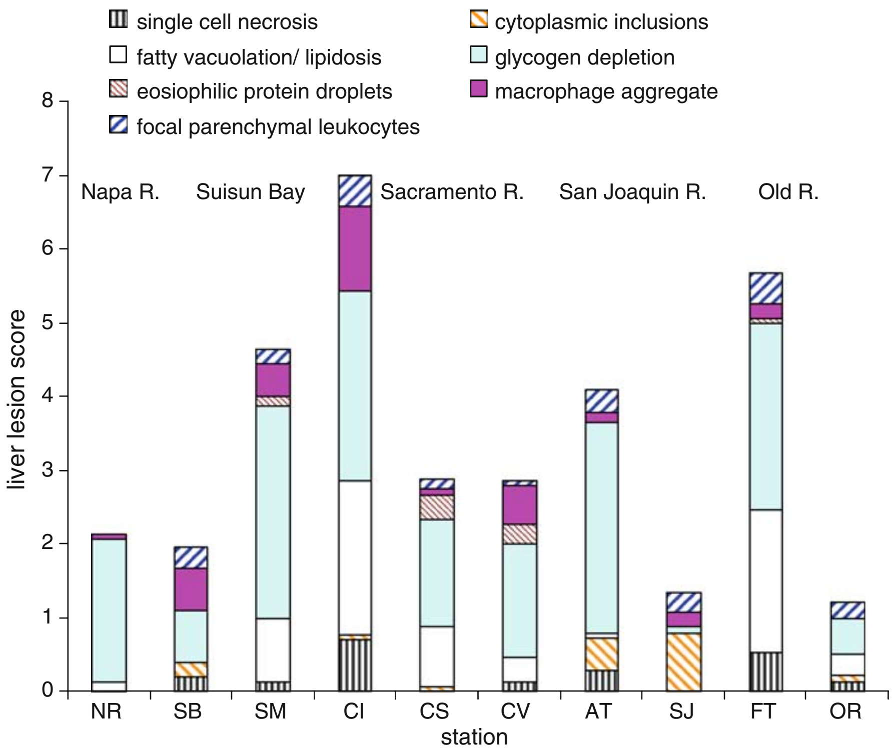


Fig. 10 Average liver lesion scores for each biomarker quantified in Mississippi silversides collected at stations throughout the estuary

carbonate concentrating mechanisms (Giordano et al., 2005) and nutrient uptake (Marinho & Azevedo, 2007). *Microcystis* contain gas vesicles that allow them to float on the surface of the water column where they can decrease light availability and primary productivity for plankton below the surface.

This may partly explain the decreased density of diatom, green algae, and other cyanobacteria at 1 m depth compared with cryptophytes with flagella that enable them to adjust their light position in the water column. *Microcystis* can alter the pH, and hence inhibit CO_2 uptake, giving preference to cyanobacteria with their enhanced carbonate concentrating capabilities (Giordano et al., 2005). However, the pH among the stations did not differ, suggesting that differences in carbonate concentrating mechanisms were not important in SFE. *Microcystis* co-occured with *Aphanizomenon* spp. This filamentous cyanobacterium has similar enhanced carbonate and light capturing capabilities through carboxysome and phycobilisomes as *Microcystis*, but because it has heterocysts that produce nitrogen needed for growth, it does not compete with *Microcystis* for nitrogen (Paerl et al., 2001). *Microcystis* is extremely flexible in its ability to use organic nitrogen and phosphorus and alternative forms of nutrients may provide a selective advantage for this species even though nutrients are rarely limiting in SFE (Jassby, 2005). Recent increases in ammonium concentration in the western delta may give a competitive advantage to *Microcystis* which rapidly assimilates ammonium over nitrate (Blomqvist et al., 1994; Jassby, 2005). However, recent reductions in river flow may have had a greater influence on abundance (Kuwata & Miyazaki, 2000; Lehman et al., 2008).

Microcystis may have affected plankton community composition through allelopathy by the production of microcystins or other bioactive peptides. Microcystins were associated with a decrease in diatom density and increase in the growth rate and number of cyanobacteria species in laboratory cultures (Sedmak & Kosi, 1998; Suikkanen et al., 2005). Microcystins may not have affected some phytoplankton, such as the chain diatom *Aulacoseira granulata* or the green alga *Monoraphidinium contortum* in SFE, which were common in the surface layer. Laboratory studies suggest these species grow well in the presence of *Microcystis* (Sedmak & Kosi, 1998; Jia et al., 2008). *Microcystis* can inhibit photosynthesis and the growth rate of the cyanobacteria *Nostoc* spp., *Anabaena* spp., and *Synechocystis* spp. (Vassilakaki & Pflugmacher, 2008; Singh et al., 2001) and may contribute to their absence or low density in SFE. The impact of *Microcystis* on algal growth is often species specific. *Microcystis* inhibited chlorophyll *a* synthesis in *Scenedesmus obliquus*, but increased the growth of *Scenedesmus quadricauda* in laboratory cultures (Sedmak & Kosi, 1998; Jia et al., 2008). Dissolved microcystins can also affect cell aggregation, increase cell volume, and production of photosynthetic pigments in *Scenedesmus quadricauda* (Sedmak & Eleršek, 2006). *Scenedesmus* spp. was not found in the surface or 1 m samples where *Microcystis* was abundant for this study, but has been a common species in the delta over time (www.iep.water.ca.gov). The increased abundance of the cryptophytes *Rhodomonas* spp. and *Crytomonas* spp. in SFE may also be due to species specific responses to *Microcystis*. Although elevated *Microcystis* abundance was associated with decreased abundance of the cryptophyte *Cryptomonas arosa* (Sedmak & Kosi, 1998), cryptophyte growth varied among species when exposed to filtrates from freshwater and brackish water cyanobacteria including *Nodularia*, *Aphanizomenon*, and *Anabaena* (Suikkanen et al., 2005). The mechanisms associated with the allelopathy of *Microcystis* are poorly understood, but the growth and photosynthesis of *Peridinium gatunense* were decreased by inhibition of carbonic anhydrase activity (Sukenik et al., 2002).

The loss of diatom and green algal carbon and increase in cryptophyte carbon associated with elevated *Microcystis* abundance was sufficient to affect the quantity and quality of the phytoplankton carbon available to the food web in SFE. Diatom and green algae have some of the largest cells by volume in the phytoplankton community within SFE, therefore their loss can remove a large portion of the total carbon available to the food web (Lehman, 1996). Because cryptophytes have a relatively low average biovolume, the increase in their carbon was insufficient to compensate for the loss of diatom and green algal carbon. This was true even though most of the cryptophyte carbon was composed of two relatively large volume species, *Rhodomonas* spp. and *Cryptomonas* spp. A decrease in the diatom and green algal biovolume was also associated with an increase in cyanobacteria and cryptophyte biovolume between 1975 and 1993 in SFE, but it was attributed to long term changes in environmental conditions, particularly flow (Lehman, 2000a). Nutrient concentrations are often thought to be the primary driver of plankton blooms, particularly cyanobacteria blooms (Paerl et al., 2001). Recent research suggested haptophytes, chlorophytes, and dinoflagellates increase with ammonium-N concentration in the Neuse River estuary (Rothenberger et al., 2009). However, nutrient concentration, including ammonium-N concentration and the NP molar ratio, did not account for the majority of the variation in *Microcystis* abundance in the surface layer or the distribution phytoplankton carbon among classes at 1 m depth for this study.

Zooplankton

Zooplankton carbon was positively correlated with *Microcystis* abundance. Most of the zooplankton carbon occurred in the western and central delta, and was composed of calanoid copepods. Copepods can actively reject toxic strains of *Microcystis*, and, therefore, are less likely to be affected by toxic blooms at low to moderate levels (DeMott & Moxter, 1991). In addition, some zooplankton can effectively use decomposed Microcystis as a food source (Hanazato & Yasuno, 1987). Copepod biomass was also not affected by *Microcystis* biomass in Steele Lake, Canada (Ghadouani et al., 2003). It is likely that the gradual seaward decrease in copepod carbon, dominated by the freshwater copepod *P. forbesii*, was due to other factors such as salinity or clam grazing in SFE (Kimmerer, 2004).

However, it is also possible that the presence of *Microcystis* and its toxins in the western and central delta affected the ability of calanoid copepods to reach maximum population levels. *P. forbesii* decreased in the western and central delta after 1999 and coincided with the appearance of *Microcystis* blooms (Lehman et al., 2005; Sommer et al., 2007). Although initial laboratory feeding studies indicated one of the common copepods in SFE, *Eurytemora affinis*, did not consume *Microcystis*, zooplankton tissue in SFE contained microcystins (Lehman et al., 2005, 2008). In Chesapeake Bay, zooplankton can consume some *Microcystis* even though they do not actively feed on this cyanobacterium (Sellner et al., 1993). Recent laboratory feeding studies confirmed that the survival of both *P. forbesii* and *E. affinis* was reduced when *Microcystis* exceeded 10% of the diet, and that *P. forbesii* was three times more sensitive than *E. affinis* (Ger et al., 2009). Dissolved microcystins also affect zooplankton growth and survival and can increase in the presence of zooplankton (Jang et al., 2003). Dissolved microcystins occurred occasionally and may have contributed to the variability in zooplankton composition and biomass.

Elevated *Microcystis* biomass was associated with a low cladocera to calanoid copepod ratio. *Microcystis* blooms are often associated with low cladocera biomass because large cladocera like *Daphnia* sp. are more sensitive to *Microcystis* than small cladocera (Chen et al., 2007). *Microcystis* is a poor quality food and both toxic and non-toxic *Microcystis* adversely affect cladocera survival, growth rate, reproduction rate, clutch size, feeding rate, and nutrition (Reinikainen et al., 1999; Rohrlack et al., 2001, 2005; Wilson et al., 2006; Abrantes et al., 2006; Federico et al., 2007). *Microcystis* blooms can also affect the growth rate of cladocera by physically inhibiting feeding (Lurling, 2003). The *Microcystis* strain may also be important in SFE where DNA analysis suggested the western delta had different and more toxic *Microcystis* strains than the central delta (Moisander et al., 2009; D. Baxa, personal communication).

Fish

Toxic *Microcystis* may adversely affect fish health in the estuary when hepatotoxic microcystins cause liver damage and tumors (Malbrouck & Kestemont, 2006; Ibelings & Havens, 2008). Five of the lesion types evaluated in this study, single cell necrosis, cytoplasmic inclusions, hepatic lipidosis, hepatic preneoplastic foci, and hepatocellular adenoma (tumor) are likely pathologic responses to toxic exposure in fish (Teh et al., 1997; Malbrouck & Kestemont, 2006). The combined presence of these lesions in juvenile striped bass liver tissue suggests fish in the Sacramento and San Joaquin River were recently exposed to toxins. Low concentrations in fish tissue may indicate the rapid depuration of microcystins or toxin dilution through the food web (Ibelings & Havens, 2008). The presence of hepatic preneoplastic foci and hepatocellular adenoma in these young fish suggests the toxin was carcinogenic and affecting the fish at a very early life stage, which is atypical. We hypothesize that microcystins within the *Microcystis* colonies either contributed to or were the cause of these histopathological changes in striped bass liver tissue in the San Joaquin River, especially at station AT where the combined presence of the five lesion types coincided with high total microcystins concentration. Ongoing research suggests *Microcystis* populations can be more toxic at AT than other stations in the estuary (D. Baxa, personal communication). Single cell necrosis and cytoplasmic inclusions in the liver tissue of Mississippi silversides further supported the contaminant exposure of fish in the lower San Joaquin River to *Microcystis* toxins. Dissolved microcystins may have contributed to the observed lesion scores, but anatoxin-a concentrations were probably too low.

Food web

Through its impact on multiple trophic levels, *Microcystis* may influence fishery production including the decline in pelagic organisms measured since 2000 in SFE (Sommer et al., 2007). The effects of *Microcystis* on food web organisms suggested by this study include direct impacts through nutrients, light, allelopathy, or toxicity on the growth and survival of phytoplankton, zooplankton, and fish or indirect impacts through the food web. The potential impact of *Microcystis* on phytoplankton group carbon maybe important for fishery production in SFE where the health and survival of key zooplankton food species like *P. forbesii* rely on the abundance of wide diameter diatom and green algae cells that provide good quality food in the optimum size range for filtering feeding (Müller-Navarra et al., 2000; Lehman, 2000b). This was supported by the strong positive correlation between total zooplankton and *Neomysis* shrimp carbon with diatom carbon between 1975 and 1993 in the estuary (Lehman, 2004), particularly after the depletion of diatoms following the invasion of the overbite clam in 1987 (Kimmerer, 2004). Although cladocera carbon was only a small percentage of the total zooplankton carbon compared with copepods, the decrease in the cladocera to calanoid copepod ratio may directly affect food availability for threadfin shad (T. Sommer, personal communication), an important forage species for picivores in SFE (Nobriga & Feyrer, 2007). Importantly, the impact of *Microcystis* on the aquatic community may be greater than suggested by impacts on copepods and cladocera. Microcystins are commonly present throughout the food web, and in SFE were measured in clams, worms, and jellyfish that also serve as food resources for fish (Ibelings & Havens, 2008; Lehman et al., 2005, 2008). Identifying the full impact of *Microcystis* on the SFE food web requires further information on high frequency spatial and temporal variability of the aquatic food web and body burdens across a larger suite of species and trophic levels.

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Sea Grant California

What controls harmful algal blooms and toxicity in the Sacramento-San Joaquin Delta?

Cécile Mioni, Delta Science Fellow from 2008-2011, UC Santa Cruz

SUMMARY

This project shows that harmful algae like it hot. All things being equal, surface water temperature is the best predictor of whether a harmful algal bloom will form in the Sacramento-San Joaquin Delta, though flow dynamics, nutrient pollution and microbial associations also may play a role.

RELEVANCE

Harmful blooms of cynobacterial algae are becoming more common and more intense all over the world, including the San Francisco Estuary, to the extent that cyanobacterial poisoning has been implicated in human and animal illness and death in 36 states in the U.S., including California.

In the San Francisco Estuary, the dominant bloom-forming algae since 1999 has been a group of cyanobacteria known as Microcystis, which produce microcystins.

Microcystins are nasty compounds. At acute doses, they can cause liver failure and death. At chronic low doses below the World Health Organization's 1 microgram per liter (mg/L) threshold for drinking water, they may promote liver cancer, and possibly colon cancer.

While water treatment facilities may remove cyanobacterial toxins, crops may be irrigated with untreated water. There is a documented case of a beet field in Oregon dying after being sprayed with contaminated water. It is also known that microcystin is very stable (resisting both freezing and boiling) and can persist on produce for several weeks.

Surveys of drinking water reservoirs in California show that cyanobacterial toxins are diluted to non-detectible levels; however, continued human-induced stress on the delta, combined with warming and other impacts from climate change, could result in yet more frequent and more toxic blooms. This will likely have consequences for people and ecosystems.

In 2011, a new kind of bloom was detected in the Delta – the filamentous cyanobacteria Aphanizomenon. The round cells in the net are Microcystis. Credit: Cécile Mioni

Former Delta Science Fellow Cécile Mioni collects samples of a massive algal bloom in 2009 in the Sacramento-San Joaquin Delta. Credit: April Hennessy

PROJECT

The major goals of this project were to identify what seeds, triggers and fuels harmful cyanobacterial blooms in the eastern San Francisco Estuary, where the Sacramento and San Joaquin rivers join and freshwater is diverted for drinking water and irrigation.

Ultimately, scientists hope to be able to predict toxic blooms, including the species of algae that will dominate, based on environmental parameters already monitored in the delta. Predictive models would improve managers' ability to respond to and mitigate blooms, and reduce their particular threats to public health, water quality and wildlife.

METHOD

Water samples were collected monthly from September 2008 to December 2009 at 21 stations in the delta that are part of existing monitoring programs. Eight stations were monitored in the summer of 2010 and 2011, with additional support from the Delta Science Program and the State Water Resources Control Board's Surface Water Ambient Monitoring Program (SWAMP).

Samples were tested for algae cell abundances and toxin concentrations. Nutrient levels, salinity, water clarity, irradiance, water temperature, and water residence time (flow) were also measured, as all may contribute to bloom formation.

RESULTS

A bloom of *Microcystis aeruginosa* was observed in 2009 but not the following summer, making 2010 the first "no bloom" year in the delta since the toxigenic algae were first detected in 1999.

Although there are no formal regulations in the U.S. for safe microcystin toxin levels in drinking water, the WHO's 1-mg/L advisory limit was exceeded in water samples collected from six stations during the 2009 bloom.

Levels of the liver-damaging toxin exceeded 5 mg/L at Antioch Bridge and Rancho del Rio at the bloom's peak in August. Notably, these elevated levels remained below the EPA's recreational water-contact exposure limit of 8 mg/L.

Analyses suggest temperature was the main "driver" of the bloom, as 2009 was a moderately strong El Niño year, and water temperatures were warmer than usual in the delta. Water temperatures dropped the following summer as the El Niño was replaced by the first strong La Niña episode since 1999. The theory is that the cold event suppressed algal growth.

Modeling suggests that a temperature threshold of 20ºC exists for the delta, above which blooms suddenly become more likely and intense. According to results from this project, the likelihood of a bloom increases from 10% to 50% when ambient surface water temperatures climb from 20ºC to 25ºC.

In the summer of 2011, another harmful algal bloom formed, as weakened La Niña conditions persisted. Much to the surprise of the scientists, a new kind of blue-green algae flourished, the saxotoxin-producing filamentous *Aphanizomenon flos-aquae*. (Saxotoxins are sodium-channel-blocking neurotoxins that accumulate in fish and shellfish, causing "paralytic shellfish poisoning.") Microcystis was detected at low levels only.

Since temperature alone cannot explain the species shift, the scientists involved in this project are exploring other explanations. One is based on the observation that concentrations of ammonia (a source of nitrogen) were lower than usual in 2011. Since Aphanizomenon is able to "fix" nitrogen from the atmosphere, while Microcystis cannot, Aphanizomenon may have outcompeted it under the relatively nutrient-poor conditions.

Ammonia levels overall – it should be noted – have more than doubled in some parts of the delta in the last two decades and may be connected to changes in the delta's food-web dynamics.

NEXT STEPS

The former Delta Science Fellow, Cécile Mioni, now a researcher at UC Santa Cruz, is currently working with Alex Parker, a marine microbial biogeochemist at the Romberg Tiburon Center, to explore why Aphanizomenon dominated in 2011. Were nutrient-poor conditions to blame? Or, was it because of the flip-flop in ocean conditions associated with El Niño and La Niña? Has there been some other shift in the delta? The first six months of 2012 have been warmer than normal, and if the warming continues into the summer and fall, it will allow them to further test and refine the hypothesis that temperature controls Microcystis blooms.

Mioni is also collaborating with UC Santa Cruz phytoplankton biologist Raphael Kudela to study the spatial and temporal (time) variability of toxin concentrations. Researchers have theorized that there are "seeding" grounds in the delta, where blooms form and are dispersed. Though this idea was not directly investigated during the Delta Science project, toxins level were observed to more than double, at a single site, over periods as short as a few hours. Algae cell counts could not explain the change. The scientists will be deploying an "artificial mussel" technology, known as SPATT (Solid Phase Adsorption Toxin Tracking), to record cumulative toxin exposure at a location.

With USC microbial chemist Sergio Sanudo-Wilhelmy, Mioni is also investigating the role of microbial symbiosis in regulating toxin production and algal cell growth in Clear Lake, Calif., the state's largest freshwater body. Microcystin contains a methane group, obtained from the amino acid methionine. Methionine contains cobalt and B12, which is produced only by bacteria. The scientists speculate that methionine and cobalt may be limiting compounds for microcystin synthesis and that microbial symbionts may help algae obtain the compounds they

RESEARCH MENTOR

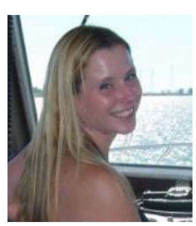
Adina Paytan, UC Santa Cruz

COMMUNITY MENTOR

Anke Mueller-Solger, Interagency Ecological Program

REPORT

Mioni, C.E., Kudela, R.M., Baxa, D. (2012) Harmful cyanobacteria blooms and their toxins in Clear Lake and the Sacramento-San Joaquin Delta (California). Surface Water Ambient Monitoring Program (10-058-150). Final Report, March 31, 2012.



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Phone: 858-534-4440; Email: casgcomms@ucsd.edu June 2012

ENGINEER'S REPORT AND REPORT OF THE

ASSESSMENT COMMISSIONERS

FOR THE

NORTH DELTA WATER AGENCY

ASSESSMENT ADJUSTMENT

Pursuant to Article XIII D of the California Constitution

MBK ENGINEERS
Water Resources • Flood Control • Water Rights

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November 3, 2010

Board of Directors
North Delta Water Agency
910 K St., Ste. 310
Sacramento, CA

Gentlemen:

In accordance with your request, enclosed are six copies of the final Engineer's Report and Report of the Assessment Commissioners for the North Delta Water Agency Assessment Adjustment. We have prepared this report pursuant to the requirements of Article XIIID of the California Constitution, and to support North Delta Water Agency's (Agency's) need to propose an increase in assessments.

We appreciate the opportunity to assist the Agency and hope it is successful in its effort to provide continued service to the landowners within the Agency.

Please call if you have any questions.

Sincerely,

George Basye, Commissioner

Mike Hardesty, Commissioner

Gary R. Kienlen, P.E., Comissioner

cc: Melinda Terry
Kevin O'Brien

CERTIFICATION

I, Gary R. Kienlen, 1771 Tribute Road, Suite A, Sacramento, California, hereby certify that this Engineer's Report and Report of the Assessment Commissioners, which includes the assessments and charges identified herein, was prepared, pursuant to the direction of the North Delta Water Agency Board of Directors, to the best of my knowledge of the available data and project development, and in accordance with Article XIII D of the California Constitution

REGISTERED PROFESSIONAL ENGINEER
Gary R. Kienlen
No. C 059041
Exp. 6/30/11
Civil
STATE OF CALIFORNIA

ENGINEER'S REPORT AND REPORT OF THE

ASSESSMENT COMMISSIONERS

FOR THE

NORTH DELTA WATER AGENCY

ASSESSMENT ADJUSTMENT

Pursuant to Article XIII D of the California Constitution

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GLOSSARY OF TERMS

Appropriative Water Right – A water right obtained by use or diversion of water for reasonable and beneficial purposes

Agency – North Delta Water Agency

CVP – Central Valley Project

C-2BR – Study of water use and water rights along the Sacramento River and in the Sacramento – San Joaquin River Delta conducted subsequent to the 1956 Cooperative Studies by the U.S. Bureau of Reclamation

C-650-B – Study of water use and water rights along the Sacramento River and in the Sacramento – San Joaquin Delta conducted subsequent to the 1956 Cooperative Studies by the California Department of Water on behalf of the Sacramento River and Delta Water Association

Deficiency –As used in this report deficiency is the water supply which, under pre-Project conditions, is not available to meet water requirements or water rights within the Agency.

Delta – Sacramento San Joaquin Delta as defined in Water Code § 12220 situated within Sacramento, San Joaquin, Solano and Yolo Counties

Delta Lowlands – Lands within the legal Delta that lie at an elevation of five feet or less above mean sea level

Delta Uplands – Lands within the periphery of the legal Delta that are higher than an elevation of five feet above mean sea level

Delta Water Agency – Created by the Delta Water Agency Act – Cal Statutes 1968 Chapter 419 – officially organized January 23, 1069. Dissolved on December 31, 1973 in accordance with Article 8 of the Delta Water Agency Act

DWR – Department of Water Resources

Four Basin Index – Sum of the projected unimpaired inflow to the Sacramento, Feather, Yuba, and American River Basins

Modified Natural Flow – As used in various studies referenced in this Engineers Report, modified natural flows comprise flows that would have existed without diversions from the Sacramento River but with the historical impairment of diversions on tributaries to either the Sacramento River or the channels of the Delta

MOU – Memorandum of Understanding dated May 26, 1998 between the Agency and DWR

Pre-Project Conditions – The baseline prior to Delta exports and the construction and operations of the CVP and SWP storage facilities

Pre-1914 Water Right – An appropriative water right initiated prior to the Water Commission Act of December 14, 1914

Post-1914 Water Right – An appropriate water right initiated in accordance with the Water Commission Act of December 19, 1914

Riparian Water Right – A water right that exists by reason of ownership of land abutting upon a stream or body of water. Riparian rights apply only to lands within the watershed of the stream or body of water; and with certain exceptions only to the smallest parcel abutting the water body

SRDWA – Sacramento River and Delta Water Users Association (active dates 1954-1970)

SWP – State Water Project.

SWRCB – State Water Resources Control Board

Unimpaired Flow –The natural flow of a river basin or watershed unaltered by upstream diversions, storage, or by export or import of water to or from other watersheds

USBR – United States Bureau of Reclamation

1956 Cooperative Study Program – Study of water use and water rights along the Sacramento River and in the Sacramento-San Joaquin Delta by the U.S. Bureau of Reclamation, the California Department of Water Resources, and the Sacramento River and Delta Water Association

Section 1 – Introduction

The North Delta Water Agency (Agency) Board of Directors is considering whether to increase the Agency's annual assessment (2011 Assessment Adjustment), which is levied upon lands receiving special benefits from the 1981 Contract Between State of California Department of Water Resources and North Delta Water Agency for the Assurance of a Dependable Water Supply of Suitable Quality (1981 Contract or Contract) (Exhibit I). To prepare the 2011 Assessment Adjustment, three assessment valuation commissioners (Commissioners) were appointed[1] to view and fix upon the lands of the Agency an assessment valuation per acre for each parcel which is in proportion to the benefits to be derived from the Agency's administration of the Contract and to prepare an assessment roll based upon that valuation. (North Delta Water Agency Act Section 5.20 (Stats. 1973, c. 283, as amended (Agency Act)) § 5.20; Water Code §§ 51322, 51323, 51346.) Proposition 218 imposes additional procedures, including the requirement that all assessment increases be supported by a detailed engineer's report. This Engineer's Report and Report of the North Delta Water Agency Assessment Valuation Commissioners (Engineer's Report) has been prepared to support any Assessment Adjustment to be adopted by the Agency's Board of Directors pursuant to the requirements of Article XIII D § 4(a) & 4(b) of the California Constitution; Government Code § 53750-53754; Agency Act § 5.20; and Water Code § 51200–51409.

North Delta Water Agency

The North Delta Water Agency was formed by the Agency Act, a special act of the legislature adopted in 1973. The Agency's boundaries encompass approximately 302,000 acres which includes portions of the Sacramento – San Joaquin Delta, as defined in Water Code § 12220 situated within Sacramento, Yolo and Solano Counties. The Agency also includes a small portion of the northeastern part of San Joaquin County comprising New Hope Tract, Canal

[1] The commissioners were appointed by the Sacramento County Board of Supervisors on March 24, 2009. In 2009, the Agency Act was amended to give the North Delta Water Agency Board of Directors the role and responsibilities otherwise granted to the Board of Supervisors under Water Code Section 51200 et seq. Agency Act § 5.20(a).

Ranch and Staten Island. (Agency Act § 9.1) A map showing the boundaries of the Agency along with the county boundaries is attached to this Engineer's Report (see Map 1). The purpose of the Agency is to take all reasonable and lawful actions, including to negotiate, enter into, administer, and enforce an agreement or agreements with the United States and the State of California, or either of them, to (1) protect the water supply of the lands within the Agency against intrusion of ocean salinity and (2) assure the lands within the Agency of a dependable supply of water of suitable quality sufficient to meet present and future needs for reasonable beneficial uses.

1981 Contract

Upon its formation, the Agency entered into negotiations with the State of California and the United States for contracts to assure adequate water quality and quantity for the water users within the Agency. In the process of those negotiations, the U.S. Bureau of Reclamation (USBR), on behalf of the United States, withdrew from the negotiations, which were then pursued solely with the State of California. These negotiations resulted in the 1981 Contract, executed on January 28, 1981, which provides for the assurances as to quality and quantity required by the Agency Act (See Exhibit I). To meet these assurances, the 1981 Contract requires the Department of Water Resources (DWR) to operate the State Water Project (SWP) to meet fixed water quality criteria at seven locations within the Agency. These criteria are in effect throughout the year, and must be met except under defined drought emergency conditions (which have not occurred since execution of the 1981 Contract). The Contract also states that DWR shall not through the conveyance of SWP water cause changes in the natural flow, flow direction, or water surface elevations to the detriment of the water users within the Agency. Further, DWR is required to repair or alleviate seepage or erosion damages resulting from the conveyance of SWP water to lands outside Agency and is responsible for modifications to diversion facilities should they be required as a result of the conveyance of SWP water (Contract § 6). Through the Contract DWR acknowledges the right of landowners within the Agency to divert water and agreed to furnish such water as may be required for reasonable and beneficial uses to the extent not authorized under water users' water rights.

In exchange, the 1981 Contract requires an annual payment to DWR, in two installments, to compensate for the reimbursable benefits provided to water users within the Agency. The reimbursable benefits are the enhanced water quality and quantity that result from SWP storage releases in excess of the natural flows available for diversion pursuant to Agency water users' water rights.

The Agency's Board of Directors has successfully administered and enforced the Contract since its execution in 1981 to assure that the required quality of water is maintained, and to assure the rights of water users within the Agency to utilize that water for agricultural, municipal and industrial purposes on lands within the Agency are acknowledged.

Compliance with the California Constitution

Proposition 218 requires any agency that proposes to levy a special assessment to identify all parcels that receive a special benefit from the property-related service being funded. For each identified parcel, the proportionate special benefit must be determined in relationship to the entire cost of the service. The agency must also separate the general benefits from the special benefits conferred on a parcel. Parcels owned or used by a governmental entity must be assessed unless they can be shown, by clear and convincing evidence, to receive no special benefit. (Cal. Const. Art. XIII D, § 4, subd. (a).).

This Engineer's Report describes the lands that receive special benefits from the 1981 Contract, and defines and explains the special benefits these lands receive from continued operation and maintenance of the 1981 Contract, and from the Agency's activities to enforce, administer, and otherwise ensure the benefits of the 1981 Contract. The amount of the assessment is proportional to the special benefits conferred and is distributed based on the acreage of land that receives the 1981 Contract's water quality and water supply benefits. This Engineer's Report also analyzes the nature of the benefits derived from the 1981 Contract, and concludes that the 1981 Contract does not provide any general benefits. Prior to the levy of an assessment, Article XIII D also requires the assessing agency to conduct an assessment ballot proceeding, and the assessment cannot be approved without approval by a majority of votes cast. This Engineer's Report is intended to provide the voters with factual information to assist in deciding whether or not to approve an increased assessment.

Section 2 – Background

Impact of the Federal and State Water Projects on Historical Water Rights within the Delta

The Agency is an outgrowth of the Delta Water Agency which, in turn, is an outgrowth of the negotiations and settlement between the Sacramento River Settlement Contractors and the USBR during the 1950s and 1960s. Completion of the Shasta Dam on the Sacramento River raised questions regarding the respective rights of water users and the USBR, as project operator, to water flowing down the river and into the Delta. Water users along the Sacramento River and within the Delta asserted their prior rights, which essentially had allowed development of most of the valley and of the entire Delta for agriculture before the Federal Central Valley Project (CVP) with its dam at Shasta was commenced. Negotiations extended over a period from the late-1940s to the mid-1960s in an attempt to resolve the nature of the water rights of the CVP and the rights of the prior or potential diverters of water from the Sacramento River and Delta.

These negotiations led to the development of the 1956 Cooperative Study Program. This program collected and analyzed extensive information and data concerning the hydrology, diversions, and water rights for the Sacramento River, and was conducted jointly by agreement among DWR, the USBR and the Sacramento River and Delta Water Association (SRDWA). SRDWA included most of the major water users on the Sacramento River, including those in the northerly portion of the Delta. Data on stream flow, diversions, and return flows available from the U.S. Geological Survey and DWR were collected. Calculations were made of modified natural flows.[2] USBR had previously made detailed studies of which lands next to the Sacramento River upstream of the City of Sacramento had appurtenant riparian water rights (generally the senior-most water rights in the State); these earlier determinations by the parties to the 1956 Cooperative Study Program were reviewed to

[2] Modified natural flows, as used in the various studies, comprise flows that would have existed without diversions from the main stem of the Sacramento River but with historical impairment of diversions from tributaries to the Sacramento River and from the channels of the Delta.

verify that the methods used were reasonable and accurate. Lands downstream of the City of Sacramento were not included in these detailed studies; however, the parties determined it was reasonable, for the purposes of the studies, to assume that all lands within the area described as the Delta Lowlands were riparian to the channels of the Delta, the Sacramento River, and other tributaries to the Delta. Information concerning appropriative water rights initiated under the common law[3] prior to 1914 (which are also very senior rights) was obtained, tabulated, and reviewed. Information on Post-1914 appropriative water rights was tabulated from the files of the State Water Rights Board, predecessor to the State Water Resources Control Board (SWRCB). Determinations of the extent of overlap between lands covered by various water rights, both appropriative and riparian, were reviewed and verified. Using this information and more, numerous studies were conducted to determine the scope of all known and assumed water rights on the Sacramento River system. Deficiencies in the available water supply necessary to satisfy those rights together with supplemental water requirements of diverters along the Sacramento River and the Delta in the absence of the operation of the CVP were also determined. Other information, such as water supply remaining at various points along the Sacramento River and in the Delta after satisfaction of water rights of various priorities was also computed.

In the early 1960s the USBR, acting at the direction of the U.S. Department of the Interior, concluded that it would be difficult to resolve the issues of the respective water rights on the Sacramento River and those within the Delta in the same negotiation. This was because the Delta involved water supply as well as a complex question of water quality. Accordingly, the USBR proceeded with negotiations leading to settlement contracts with the Sacramento River diverters above Sacramento and set aside the negotiations with the Delta water users for later consideration.

[3] The California Legislature adopted the common law of England as the rule of decision for legal cases in the State. The common law is a system of legal rules that judges made in deciding upon cases, rather than by statute or regulation.

Formation of North Delta Water Agency

In order to move forward with a possible settlement of the Delta water quality and quantity issues, the California Legislature formed a Delta Water Agency comprising the entire Delta as defined in Water Code Section 12220. The Delta Water Agency was formed in 1968 with the purpose of attempting to obtain a contract with the USBR as well as DWR, since the SWP had begun operation from its reservoir at Oroville on the Feather River.

Due to a difference in objectives and strategy among its various geographical sections, the Delta Water Agency failed to negotiate a contract and dissolved pursuant to a five-year "sunset clause." Before it expired, the representatives in the northern part of the Delta expressed the desire to form a separate agency. The North Delta Water Agency was formed by an act of the California Legislature on January 1, 1974. Following that lead, the Central Delta Water Agency and South Delta Water Agencies were subsequently formed by the California Legislature.

History of North Delta Water Agency Contract Negotiations

Although many Agency landowners hold significant riparian and appropriative rights, in some years the natural flow of the tributaries to the Delta (without being supplemented by upstream storage releases) is not adequate to supply the volume to sustain the necessary water quality for uses within the entire North Delta area for the entire year. In some years, insufficient inflow could potentially also lead to legal restrictions on diversions by even the senior-most water right holders within the Agency. Following its creation and organization, the Agency entered into negotiations with the USBR and DWR to develop a three-party agreement regarding water rights and water quality. These negotiations continued for five years (1974 through 1978). In March 1979, the Agency was informed that the U.S. Secretary of the Interior had decided to work directly with the State of California to resolve Delta water quality issues. As a result of the Secretary's decision, the Agency was advised by USBR representatives that it would be inappropriate to contract with individual Delta agencies to assure that the CVP would meet any particular water quality standards, including those set forth in SWRCB Decision 1485 (D-1485).

Following the withdrawal of the USBR from the negotiations, discussions were initiated for an agreement between DWR and the Agency. Agreement on a proposed contract was reached on January 17, 1980. The Contract was overwhelmingly approved by a vote of the landowners within the Agency; 154,723 votes were cast in favor of executing the Contract, and 20,296 votes were cast against. The 1981 Contract was executed on January 28, 1981. On May 14, 1981, the Sacramento County Superior Court issued a judgment determining that the 1981 Contract is valid in all respects, binding on the Agency and DWR, and in the best interests of landowners within the boundaries of the Agency.

Water Rights Background

Between 1974 and 1979 various analyses were conducted by DWR and the Agency to better understand the water rights within the Agency, the outflow required to meet Delta agricultural water quality standards, allocation of water right deficiencies, and the Delta Storage concept, which is explained below.

A longstanding and fundamental basis for classifying water rights in the northern Delta is the distinction between the Delta Lowlands and the Delta Uplands. The Delta Lowlands lie at elevations of five feet or less above mean sea level and are largely irrigated by gravity through siphons. The Delta Uplands are peripheral lands higher than five feet above mean sea level and are irrigated by pumping from the channels and sloughs. County Assessors' records obtained from Sacramento, San Joaquin, Solano, and Yolo Counties identify assessed parcels consisting of approximately 194,000 acres of the Agency lying within the Delta Lowlands and approximately 94,000 acres within the Delta Uplands. The County Assessors' acreages do not include areas such as the Sacramento River, the Deep Water Ship channel, and other waterways within the Agency's boundaries. A map of the Delta Upland and Delta Lowland areas within the Agency is attached (Map 2).

In January 1963 the USBR published a series of reports titled "Delta Uplands Service Area Investigations" (Delta Uplands Investigations). For the purposes of the reports, the USBR divided the Delta Uplands into thirteen areas. A separate report summarizing factual data on historic water use, land ownership, water rights, and irrigation and drainage facilities was prepared for each of the Delta Upland areas. In addition, detailed land ownership data was collected in order to identify which areas in the Delta Uplands could be credited with assumed riparian status. Although no legal determination was made, based on the USBR's review, the Delta Uplands Investigations identify approximately 12,000 acres of Delta Uplands within the Agency that were assumed to have riparian status. As explained in more detail later in this report, according to the files of the SWRCB approximately 39,000 additional acres within the Delta Uplands hold appropriative water rights.

As previously discussed, the 1956 Cooperative Study Program, for the purposes of the various studies, classified all lands within the Delta Lowlands as riparian. These lands were originally identified as "swamp and overflowed" lands by the California State Surveyor through his surveys which were approved by the U.S. Secretary of the Interior in the 1850s and 1860s. California acquired title to these lands pursuant to the "Arkansas Act" adopted by the U.S. Congress in 1850. That act allowed the states to receive title to all lands deemed "swamp and overflowed," provided the buyer of such lands would "reclaim" these lands to make them productive. At the time levees were constructed by reclamation districts in the late 19th Century to reclaim and protect these lands for agriculture, facilities and infrastructure were also constructed to convey water throughout the islands, clearly demonstrating an intent to maintain the riparian status of these lands.

In January 1964 the USBR published a series of reports titled Delta Lowland Service Area Investigations (Delta Lowlands Investigations). For the purposes of these reports the Delta Lowlands were divided into ten areas. The Delta Lowlands Investigations conclude that portions of the Delta Lowlands are also covered by appropriative water rights.

Water Quality Standards

The water quality standards that controlled the operation of the CVP and SWP (Projects) during this period (1974 to 1979) were the agricultural standards set forth in SWRCB Decision 1379 (D-1379). These standards, together with the estimated outflows required to meet these standards, were based on pre-Project conditions (i.e., with no exports from the Delta and no storage in the CVP and SWP reservoirs) and are as follows:

Table 1: D-1379 Agricultural Water Quality Standards

		Period	
Station	**Type of Year**	**April thru July**	**August thru December**
Blind Point	Non-Critical	350 ppm. Cl.	1,000 ppm. Cl
		2,800 cfs.	1,600 cfs.
	Critical	1,000 ppm. Cl.	1,000 ppm. Cl.
		1,600 cfs.	1,600 cfs.
Jersey Island & Emmaton	Normal and Below Normal	10 consecutive days between April 1 and May 31, 200 ppm. Cl. 3,100 cfs.	

Negotiations with DWR

By the time the USBR withdrew from the negotiations, most of the preliminary technical work to understand the Projects' impacts upon water users in the Delta had been completed. One significant change after the USBR's withdrawal was the revised water quality requirements as a result of D-1485, which was issued in August 1978. D-1485 did not change the basic agricultural water quality requirements in D-1379 but utilized different control points and limited the period of the requirements from April 1 to August 15 (formerly April 1 to December 31). To assure a water supply of suitable quality and quantity for all of the lands and users within the Agency, water quality criteria for the entire year were developed through discussions with DWR. As discussed in the 1979 memorandum by the Agency's engineer (Exhibit II) the criteria proposed by DWR were modified to allow for ramping of flows which provide for uniform transition between changes in criteria. These criteria, depicted graphically, formed Exhibit A of the 1981 Contract. The criteria are based on the Four-Basin Index which is the sum of the projected unimpaired inflow to the Sacramento, Feather, Yuba, and American River Basins, rather than year type, i.e. Critical, Dry, Normal, Wet, etc. This reflects the fact that the Delta receives flow from multiple watersheds; and therefore, the water supply is not easily classified by year type.

The 1956 Cooperative Study Program and subsequent studies determined the volume of water required to meet Delta water quality standards and satisfy riparian and appropriative water rights based on various assumptions. Pre-Project water supplies available to meet these requirements were also determined. This information was used by the Agency to determine the available water supply which existed in the Delta absent Project operations during the period 1924 through 1954. The analysis found that in some years the pre-Project water supply was insufficient to meet all of the demands, including riparian demands, within the Agency. It was further determined by the Agency that these "deficiencies" should be allocated to the water users. The analysis gave credit for water supplies available to Delta water users under the "Delta Storage" concept.

The Delta Storage concept recognizes that, under natural conditions (i.e., pre-Project operations), the Delta operated not as a flowing stream but as a storage reservoir which filled with fresh water during the high flows of winter and thereby sustained a usable level of quality for agriculture for a large part of the Delta until quite late in the season, often after the irrigation season had been completed. The Projects have changed the effect of the Delta storage by withholding, through storage upstream, much of the high winter flows that historically held out salt water from the San Francisco Bay and thus developed and maintained the high Delta water quality. This storage, combined with the effect of the pumping plants located at the southerly end of the Delta drawing water across the Delta channels, changed what had previously been storage of high winter flows of good quality water within the Delta into a condition more like a flowing stream. In short, much of the water released and exported by the Projects essentially replaces the naturally stored, usable water supply historically available to users within the Delta.

In negotiating with the Agency DWR did not evaluate the individual water rights of the water users within the Agency, but instead determined deficiencies in the ability of the pre-Project water supply to meet the quantity and quality demands within the Delta. This determination was based on studies it performed using water supply scenarios with and without the operation of the Projects. Based on its studies DWR proposed, and the Agency accepted, a deficiency figure for the purpose of developing the Contract payment for Project benefits. The original Contract payment was $170,000, and is subject to periodic escalation as set forth in the Contract. The 1981 Contract thus represents a Water Right Settlement Agreement between DWR and the Agency on behalf of its landowners recognizing the water rights of the lands within the North Delta area. Although the Projects' water rights are junior to almost all rights in the northern Delta, the Contract recognizes that these junior rights provide benefits to Delta water users by supplying flows which nature periodically fails to provide.

The Agency's Contract payment was based on the average annual deficiency in the water supply available to meet the water supply and water quality requirements of water rights of the lands within the Agency. The Contract payment represents the majority of the Agency's annual costs. The Agency is supported through annual assessments charged to the lands within its boundaries. Since the 1981 Contract was executed, however, considerable acreage within the Agency has been and is being acquired by State or Federal agencies. The Agency has received no contribution from many of these State and Federally owned lands for the benefits provided by the 1981 Contract. Proposition 218 requires all local agencies, including the Agency, to include State and Federal lands in an assessment to the extent they are benefited, and not to exempt them from payment unless clear and convincing evidence shows that they do not, in fact, benefit. (Cal. Const. Art. XIII D, § 4, subd. (a).). Because the Federal government's sovereign immunity exempts it from local assessments, however, the Agency will likely need to work with Federal agencies to make alternative payment arrangements in lieu of the assessment.

Section 3 – Existing Assessments

The Agency Act currently authorizes the Agency to assess a uniform charge per acre and a minimum charge of up to ten dollars ($10) per parcel. (Agency Act §§ 5.2, 5.3.) The current uniform charge per acre and the minimum charge per parcel were last increased by the Agency in 1997, and are as follows:

Uniform Charge per Acre = $1.80

Minimum Parcel Charge = $8.00

Section 4 – Description of Special Benefits

Special Benefits

Article 4, Sec. 4.1 of the North Delta Water Agency Act (Chapter 283 of the Statutes of 1973, amended by Chapter 332 of the Statutes of 2009) provides:

> *"The general purposes of the agency shall be to take all reasonable and lawful actions, including to negotiate, enter into, execute amend administer, perform and pursue legislative and legal actions to enforce one or more agreements with the United States, the State of California, or other entities that have for their general purposes either of the following:*
>
> *(a) To protect the water supply of the lands within the agency against intrusion of ocean salinity; and*
>
> *(b) To assure the lands within the agency a dependable supply of water of suitable quality sufficient to meet present and future needs."*

The special benefits conveyed to the lands within the Agency are derived directly from the 1981 Contract that the Agency negotiated pursuant to this authority, and are the assurance of a dependable water supply of suitable quality. Other than the 1981 Contract payment, all of the Agency's expenses and obligations are incurred in order to perform, enforce or otherwise ensure that Agency landowners receive the full benefits of the 1981 Contract.

Water Quality

The Agency ensures a suitable water quality for Agency landowners by enforcing the criteria set forth in Article 2 and Attachment A of the 1981 Contract. Article 2(a)(i) of the Contract states that *"[t]he State will operate the SWP to provide qualities at least equal to the better of: (1) the standards adopted by the SWRCB as they may be established from time to time; or (2) the criteria established in this contract…"*

A landowner's water rights do not entitle the diverter to the benefit of artificially enhanced levels of quality that would occur by the release of water from an upstream reservoir. (*Hudson v. West,* 47 Cal.2d 823, 842 (1957); *Pasadena v. Alhambra,* 33 Cal.2d 908, 947 (1949); State *Water Resources Control Bd. Cases*, 136 Cal.App.4th 674, 771 (2006) ("[a]s for the argument…that the Delta Protection Act gives Delta riparians and appropriators a right to water stored upstream by others, we disagree.").) Under natural (i.e., pre-Project) conditions, water quality in the Delta would vary seasonally, and in dry years could become unusable late in the season for beneficial purposes without diminishing crop yields, requiring expensive treatment, or causing other injuries and costs. The release of water by DWR to offset Project operations and meet the Contract criteria ensures a water quality that will be suitable for beneficial purposes regardless of the natural condition. The Contract criteria and the release of water by DWR pursuant to the Contract are not intended to provide a uniform water quality throughout the Agency, but to maintain a gradient or variation in water quality similar to that which occurs naturally. The Contract criteria were established to assure the DWR will maintain a dependable supply of water of adequate quality for agricultural, municipal, and industrial purposes within the Agency year round. As such, the Contract criteria are not limited to the major growing season of April 1 to August 15 as defined in D-1485 and other SWRCB decisions regarding water quality criteria for the Delta.

If DWR fails to meet the 1981 Contract criteria due to a defined drought emergency, it must compensate landowners for any crop losses or reduced yields that result. (Contract § 4(b)(iv).) Under this provision of the Contract, a special contract claims procedure is to be established by the State to expedite and facilitate the payment of compensation based on the reduced yield due to the drought emergency.

The SWRCB issued Revised Decision 1641 (D-1641) on March 15, 2000. This decision was part of the SWRCB's implementation of the 1995 Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary (1995 Plan) which in part set forth water quality objectives for various purposes within the Delta. The SWRCB conducted workshops in 2004 and 2005 to receive new information regarding water quality objectives contained in the 1995 Plan. In December 2006 the SWRCB adopted an amended Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary (2006 Plan) based on an evaluation of information received. Only minor changes were made to the 1995 Plan.[4] The water quality objectives contained in D-1641 and the 2006 Plan are identical to those identified in D-1485 for the uses identified in the 1981 Contract.

Water Supply

Article 8 (a) (ii) of the 1981 Contract provides that water users within the Agency may divert water for reasonable and beneficial uses for agricultural, municipal and industrial purposes. Article 8 (a) (ii) also provides that DWR shall furnish such water as may be required within the Agency to the extent not otherwise available under the water rights of water users.

These are significant benefits. Even the most senior water rights in the Delta (riparian and pre-1914) experience deficiencies during critical years when there would be insufficient water supplies for all users. The SWRCB has issued notices to all Delta diverters to cease diverting during such periods. For example, in the critical year of 1977, four years before the 1981 Contract was executed, in addition to appropriative water right holders the SWRCB sent notices to Delta riparian landowners stating that the natural flow of the Sacramento and San Joaquin River systems would be sufficient to supply only a fraction of Delta riparian water needs for the months of June, July and August. This was so even though fresh water was physically present in the channels due to operation of the Projects. Even riparians are not legally entitled to divert water attributable to Project storage releases. When there is insufficient water supply available for riparians, appropriators—even those with rights dating back prior to 1914—may not divert at all. More junior water right holders are also subject to periodic mandatory cutbacks in order to meet the salinity objectives of D-1641, which imposes fresh water outflow requirements within the Delta.

The 1981 Contract provides a supplemental water supply to offset the deficiencies of the water rights within the Agency. Therefore, since execution of the 1981 Contract, landowners within the Agency are no longer subject to these hydrological and regulatory deficiencies in supply. Water users within the Agency are able to continue to divert water for reasonable and beneficial

[4] Plan Amendment Report, Appendix 1 to the 2006 Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary December 13, 2006

use under the 1981 Contract when notices such as those sent in 1977 are sent to other Delta water users. Article 8 (a) (ii) provides for all diversions from the Delta channels for beneficial use on lands within the Agency's boundaries without restriction, with DWR furnishing the required water with releases from the SWP. The provisions of these articles are supported by a May 26, 1998 Memorandum of Understanding (MOU) between the Agency and DWR. The MOU states that it is the joint position of the Agency and DWR that any obligation imposed upon the use of water within the Agency to assist in achieving the objectives of the D-1641 is satisfied by the 1981 Contract. This is further supported by D-1641, which implements the water quality objectives for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary and assigns responsibility for any obligation within the Agency to DWR so long as the Contract and 1998 MOU remain in effect.

Benefited Lands

Proposition 218 requires the assessing agency to determine which lands receive special benefits from the services being funded by the assessment. The 1981 Contract—which is the source of the special benefits provided by the Agency—applies to all lands within the Agency exclusively. The benefited lands do not include the lands underlying the Delta channels or other permanent watercourses, since they are physically incapable of having water applied for beneficial purposes.

General Benefits

Proposition 218 requires any local agency proposing to increase or impose a special assessment to "separate the general benefits from the special benefits conferred on a parcel." (Cal. Const. art. XIIID § 4.) The rationale for separating special and general benefits is to ensure that property owners are not charged a special benefit assessment in order to pay for general benefits provided to the general public or to property outside the area being assessed. Thus, a local agency carrying out a project that provides both special and general benefits may levy an assessment to pay for the special benefits, but must acquire separate funding to pay for the general benefits. (*Silicon Valley Taxpayers' Assn., Inc. v. Santa Clara County Open Space Authority,* 44 Cal. 4th 431, 450 (2008).)

But the 1981 Contract provides only special benefits. Special benefits are benefits "particular and distinct over and above general benefits conferred on real property located in the district or to the public at large." (Cal. Const. art. XIIID § 2(i).) Because the Contract ensures a supply of water of suitable quality for the benefit of parcels of land within the Agency, the benefits by their nature do not accrue directly to the general public. This conclusion is supported by the fact that the 1981 Contract functions as a settlement agreement between the benefited landowners and DWR. The Contract established a means by which the DWR can operate the SWP while ensuring a water supply to those whose property may otherwise by deprived of a suitable water supply during the entire year. By contrast, general benefits provided to the public at large are discussed in terms of general enhanced property values, provision of general public services such as police and fire protection, and recreational opportunities that are available to people regardless of the location of their property. (*See, e.g.*, Cal. Const. art. XIIID §§ 2(i), 6(2)(b)(5); *Silicon Valley Taxpayers,* 44 Cal. 4th 431. 450–56.)

Section 5 – Analysis of Special Benefits

Overview and Summary of Allocation

The Agency does not directly deliver water, operate or maintain water storage or conveyance facilities, or own water rights. Rather, the property-related services provided by the Agency are to administer, enforce, and otherwise ensure the receipt of benefits provided by the 1981 Contract, which assures a dependable water supply of suitable quality for lands within the Agency. Most such lands had appurtenant water rights before the execution of the Contract (and lands that did not would presumably be entitled to acquire water rights senior to those of the Projects pursuant to Water Code §§ 11460-11465, 12200-12227). The special benefits derived from the Contract are provided by the release of sufficient water from the SWP to ensure a minimum quality of water in the northern Delta at all times and to furnish such water supplies as may be required within the Agency to the extent not otherwise available under water rights. In short, the Contract ensures the release of stored water to make up for the deficiency in natural flow needed to supply water of suitable quality to lands within the Agency regardless of hydrological shortages. The payment for the 1981 Contract is to compensate DWR to the extent of the average deficiencies which were estimated by the parties to the Contract to occur. Each parcel in the Agency therefore benefits to the extent that the Contract makes up for that parcel's portion of the deficiency.

Much technical work has been done by the USBR, DWR, and the water users to determine and classify the water right deficiencies within the Agency, beginning with the 1956 Cooperative Study Program. The 1956 Cooperative Study Program and subsequent related studies determined water right deficiencies based on priority groups. These determinations served as the basis for negotiation of the project water quantities contained in the settlement contracts between the USBR and water right holders along the Sacramento River. The priority groups used in the 1956 Cooperative Study Program for the purposes of analyzing the yields and deficiencies of water rights along the Sacramento River and the Delta are as follows:

- Riparian – All Lands within the Delta Lowlands,
- Pre-1927 – Appropriative and "other" rights with priorities on or before July 30, 1927,[5]
- 1927-1938 – Appropriative and "other" rights with priorities between July 30, 1927 and August 2, 1938[6],
- 1938-1954 – Appropriative and "other" rights with priorities between August 2, 1938 and December 31, 1954[7], and
- Post-1954 – Appropriative and "other" rights with priorities after December 31, 1954.

The 1981 Contract makes up for the entire deficiency in all surface water rights within the Agency, thereby ensuring the necessary quality for all uses throughout the year and providing a sufficient quantity to satisfy all reasonable and beneficial uses. The entire volume required to offset the deficiency is the collective measure of special benefit to all lands within the Agency. The proportional special benefit under the Contract to each parcel within the Agency is it's share of that deficiency. The 1956 Cooperative Study Program classified each priority group by its relative water right deficiencies; and therefore, is the foundation upon which to define the proportional special benefit that the Contract confers upon the individual parcels within the Agency.

Because the water quality benefits afforded by the Contract are dependent upon a sufficient supply of water to hold back the intrusion of salt water from the San Francisco Bay, these benefits are inseparable from the water supply benefits of the Contract. Therefore the special benefit is providing the volume of water that, absent the Contract, would not be available to meet either or both the water quality and quantity requirements of the lands within the Agency.

[5] Priority date of initial water rights filed for the CVP
[6] Priority date of supplemental water rights filed for the CVP
[7] End of period covered in the 1956 Cooperative Study Program and subsequent studies

Delta Uplands and Lowlands

The 1956 Cooperative Study Program was a landmark for defining the Delta. For the purposes of the studies, the 1956 Cooperative Study Program adopted a new definition of the Delta which was ultimately incorporated into Section 12220 of the Water Code in 1959. The Delta can be divided into the following area groupings:

Table 2: Delta Areas

Water Surfaces	51,000	acres
Upland land areas	266,000	acres
Lowland land areas	421,000	acres
Total Delta Area	738,000	acres

Riparian Water Rights

There is no California statute defining riparian rights; rather they are defined by the common law. Under that law, lands that bordered a natural watercourse at the time title was originally transferred from the Federal or State government acquired an appurtenant right enabling the owner to share in the reasonable and beneficial use of that watercourse's natural flow within the watershed.

Riparian Water Rights within NDWA

For the various studies conducted for the 1956 Cooperative Study Program all of the Delta Lowlands were classified as riparian to the channels of the Delta, with the correlative right to share the natural flow of the Sacramento River and other tributary streams of the Delta.[8] This classification is empirically reasonable. Due to the many sloughs and other watercourses in the Delta Lowlands, most if not all parcels were riparian at the time of Federal patenting. The ditch and distribution systems throughout the Delta Lowlands demonstrate landowners' general intention to preserve the riparian entitlement for all parcels that were ultimately separated from

[8] Department of Water Resources "Report on 1956 Cooperative Study program - Water Use and Water Rights Along Sacramento River and in Sacramento-San Joaquin Delta" Vol. 1, March 1957. (p. 21).

the watercourse. In connection with related study programs including the Delta Upland Investigations and to aid in future negotiations with individuals, the USBR also identified certain parcels in the Delta Uplands that could be credited with riparian status. This determination was made by identifying the smallest ownership parcels abutting the various unaltered natural water courses within the Delta Upland areas from a review of County Assessor's plats. The Delta Upland Investigations thus identified approximately 12,000 acres within the Agency which could be credited with riparian status.

Appropriative Water Rights

An appropriative right may be acquired for the irrigation of a particular tract of land, or for other beneficial purposes, by performing certain acts required by California law, including taking or diverting the water from a stream or other sources and using it on or in connection with the land. When a supply of water to which several appropriative rights have attached is not enough for all, the prior rights have preference over those rights initiated at a later date. Each water right is entitled to its full quantity of water before any water may be taken for rights that are later in time. This superiority over later rights is called the priority of an appropriative right. In California riparian rights since they have a priority dating to when the appurtenant land was first acquired from the government, are normally senior to appropriative rights.

Prior to 1872, appropriative water rights in California could be acquired by simply taking and beneficially using water. In 1872 the Civil Code established a permissive procedure for perfecting an appropriation of water. This procedure involved posting a notice and recording it with the County Recorder of the county within which the water was intended to be used, the date of priority being the date of posting. If the statutory procedure was followed, and appropriation of water was made with due diligence, the priority of the right relates back to the date of posting. Since 1914, appropriative rights have been acquired by filing an application with a designated State agency, currently the SWRCB, obtaining a permit and then putting the water to beneficial use. The State itself made filings for use in coordinated development of the water resources of the State, including filings on Sacramento, Feather and American River waters in 1927 and 1938. Some of these filings were ultimately assigned to the USBR.

Appropriative Water Rights within NDWA

Appropriative rights in the northern Delta include pre-1914 rights as well as rights authorized by SWRCB-issued permits and licenses. All permits and licenses are available for public review. Many pre-1914 right holders have filed Statements of Diversion and Use with the SWRCB.[9] For this Engineer's Report, a thorough search was made of the SWRCB files to document the appropriative rights held by landowners within the Agency.

This search found that the places of use of some of the appropriative rights overlap the places of use of other appropriative or riparian rights. When the place of use covered by appropriative water rights are reduced for overlap with other appropriative or riparian rights, lands within the Delta Uplands of the Agency with identifiable appropriative rights amount to approximately 39,128 acres. Approximately 43,000 acres within the Delta Upland areas of the Agency were found to have no identifiable water rights. Some of these lands may have unreported pre-1914 or other water rights, may be diverting pursuant to the entitlements of the 1981 Contract, may be utilizing groundwater, or may not have historically utilized water.

Evaluation of Water Requirements for Delta Water Users

To determine the benefits that the 1981 Contract provides to water users in the northern Delta, it is imperative to understand the availability of water to supply the various priority classes of Delta water right holders under natural conditions (prior to the operation of the Projects) and after development of the Projects (damming and regulation of the Delta tributaries). Water supplies available under natural conditions are considered to be part of the landowners' water rights. Additional supplies available (and corresponding needs met) as a result of the development of the Projects are considered to be the benefits of the 1981 Contract, per Contract Recital (a). The supplies are considered both in terms of water quantity and quality.

[9] With certain exceptions, beginning July 1, 2010, most surface water diversions will need to be reported to the SWRCB annually under threat of financial penalty. (Water Code § 5100 et seq.)

Delta Water Requirements

Because riparian rights are correlative among all riparians along a particular watercourse, the riparians in the Delta must share the available water not only with each other, but also with riparians along the Sacramento River and other tributary streams. The amount of water used[10] by riparians in the Delta and along the Sacramento River for the months of April through October were derived based on numerous historical studies (discussed further below) as follows:

Table 3: Riparian Water Demands

Riparian Area	Apr	May	June	July	Aug	Sep	Oct	Total
			*(In **1,000** acre-feet)*					
Delta Lowlands 421,000 ac	78	82	130	193	177	128	134	922
Delta Uplands 28,700 ac	3	8	10	12	12	8	1	54
Along Sacramento River 169,000 ac	19	60	75	82	75	45	14	370
Total	100	150	215	287	264	181	149	1,346

To calculate the water supply available to satisfy these riparian demands without the influence of the Projects, it was first necessary to estimate the historically available modified natural flows. These flows (which are reported in Table 306, Volume II**,** of the 1956 Cooperative Study Report) were calculated or taken from records for the period April through October of each year from 1924 through 1954.[11]

The USBR concluded from their studies that sufficient water was available to satisfy all riparian requirements in the Delta and along the Sacramento River except during July and August of critical years. This conclusion can be confirmed by reducing the monthly quantities of water

[10] The amount of water used in the Delta Lowlands is based on channel depletion. Channel depletion, or the total amount of water removed from the channels for beneficial use without being pumped back into the watercourse, is considered an accurate measure of water use in the Delta and has been relied on by DWR and the Agency for decades.

[11] The months of November through March were excluded from the study period because for all years, sufficient flows were found to exist during those months to satisfy all assumed local rights along the Sacramento River and in the Delta.

initially available in the Delta identified in the 1956 Cooperative Study Report, by the total riparian requirements along the Sacramento River and the Delta. The results of these computations are given in attached Table A which indicates water was available to satisfy the estimated riparian requirements in all months except for July and August of the critical years 1924, 1931 and 1934, and in August of 1939 as indicated by zero water remaining after satisfaction of riparian demands.

As part of the negotiations between the USBR and the SRDWUA several additional studies were conducted after the 1956 Cooperative Study Program. These additional studies relied on the same data and information developed for the 1956 Cooperative Study Program; however, different assumptions on water rights and irrigation demands were made. Two of these studies – C-2BR, conducted by the USBR, and C-650B, conducted by the DWR at the request of Sacramento River and Delta water users – became the basis for negotiations of the Sacramento River Settlement Contracts. In those negotiations the yields of the water rights determined by the two studies were averaged. Delta water users were involved in the discussions that led to the assumptions used in the Studies C-2BR and C-650B which included water use within the Delta as well as along the Sacramento River. Therefore, these two studies provide an appropriate basis for determining Project benefits of water users within the Agency.

The results of Studies C-2BR and C-650B are summarized in a series of tables which identify the water supply remaining at various locations along the Sacramento River for various water right priority groups. Both studies used the same numbering convention for the tables as was used in the 1956 Cooperative Study Program. Four of the tables from these two studies[12] summarize the water remaining in the Delta after the satisfaction of water rights of various priorities. Table B through Table E, attached; show the monthly quantity of water remaining in the Delta for various water right priority groups determined by averaging the available water determined in Studies C-2BR and C-650B. Months in which zero water remains in the Delta[13] indicates the studies found insufficient water supplies available to satisfy the assumed rights of the water users within a

[12] Tables 317, 326, 330, and 334 from Studies C-2BR and C-650B

[13] The studies did not literally find there would be no water in the Delta. The Delta can never be emptied because it is refilled both by fresh water from upstream sources and, when upstream flows diminish, from the inexhaustible San Francisco Bay. "Zero water" refers to how much usable water is left in the channels after all water users in a particular class have been satisfied.

particular water right priority group. In other words, zero water remaining indicates a deficiency in the supply available to meet the water rights of the priority group.

Outflow Required for Delta Agricultural Standards

Usable quality is an indispensable element of the water supply in the Delta. The Projects are significant undertakings designed to redistribute the principal water resources of California. To harness the Central Valley Basin waters and make them available where they would be of greatest benefit to water users outside the area where the water originates, the Projects modify the natural water distribution and are intended to regulate and control the flow of its rivers and streams, including the flows and hydraulics of the Delta channels. These massive changes in natural flow would inevitably alter the historical water quality in the Delta, and required the SWRCB to develop minimum salinity standards that would need to be maintained by the Projects as a condition of their operation so landowners could continue putting water to beneficial use in the Delta. To meet these criteria, the Projects would need to ensure a sufficient outflow of fresh water to hold out the saline waters of the San Francisco Bay.

The SWRCB proposed water quality standards for the protection of agricultural uses in the western Delta in D-1379. These criteria were:

> For non-critical years, at Blind Point on the San Joaquin River, April through July, 350 mg/l chloride content; August through March, 1,000 mg/l chloride content (based on a running average of mean daily readings for any 14 consecutive days).
>
> For critical years the April through July criteria may be relaxed to 1,000 mg/l chlorine content.
>
> For normal and below normal years at Jersey and Emmaton, an average of mean chloride content for at least 10 consecutive days between April 1 and May 31 maximum 200 mg/l.

SWRCB Criteria for the interior channels at Rio Vista, San Andreas Landing, Clifton Court Ferry and Terminous are:

Table 4: D-1379 Water Quality Criteria

Period	Type of Year	Jan thru Mar	Apr thru Jul	Aug thru Dec
		(EC maximum millimhos)		
Running average of mean daily for any consecutive 14 days	Normal or above	1.25	1.25	1.25
	Below normal	1.25	1.25	1.40
	Dry or critical	1.25	1.40*	1.40*
Average of mean daily for any calendar month	Normal or above	0.88	0.88	0.88
	Below normal	0.88	0.88	1.05*
	Dry or critical	0.88	1.05*	1.05*
Average of mean daily for any calendar year	Normal or above	0.80	0.80	0.80
	Below normal	0.80	0.80	0.88*
	Dry or critical	0.80	0.88*	0.88*

*The EC value at any of these 4 stations may reach, but not exceed the starred value shown, but the average of the EC value at the 4 stations shall not exceed the adjacent unstarred value.

The criteria allowed for certain adjustments for interior channels at Terminous, Rio Vista, San Andreas Landing and Clifton Court Ferry whenever the recorded EC in Sacramento River at Green's Landing exceeded a running average 14-day or a mean monthly value of 0.240 millimhos. These interior water quality criteria generally are considered to be met when the Blind Point criteria is maintained.

Prior to the operation of Shasta Dam the limit of maximum intrusion of salinity of 1,000 parts of chlorides per million parts of water remained just below Blind Point on the San Joaquin River and Toland Landing near Emmaton on the Sacramento River during 1923 and 1927, as shown on the map prepared by DWR entitled Historical Salinity Intrusion (Exhibit III). On the basis of this information and a chart prepared by Consulting Engineer Gerald H. Jones (Exhibit IV), showing outflows from Sacramento-San Joaquin Delta required for control of salinity within the Delta, the following estimate of outflow requirements for D-1379 agricultural standards was prepared:

Table 5: D-1379 Agricultural Water Quality Standards

Station	Type of Year	Period: April thru July	Aug. thru Dec.
Blind Point	Non-Critical	350 ppm Cl	1,000 ppm Cl
		2,800 cfs	1,600 cfs
	Critical	1,000 ppm Cl	1,000 ppm Cl
		1,600 cfs	1,600 cfs
Jersey Island Emmaton	Normal and Below Normal	10 consecutive days between Apr 1 and May 31, 200 ppm Cl 3,100 cfs	

Monthly outflow schedules for various types of years required to maintain the agricultural standards for the period April through October, assuming that the 200 ppm Cl for 10 days requirement would be delivered in April, are:

Table 6: Estimated Monthly Outflow to Meet D-1379 Standards

Year Type	Apr	May	June	July	Aug	Sept	Oct	Total
				*(In **thousands** of acre-feet)*				
Non-critical	174	173	168	173	99	96	99	982
Critical	126	99	96	99	99	96	99	714

The D-1379 water quality standards were intended to be maintained as first priority operating criteria for any and all projects or parts thereof that may be constructed and operated as part of the CVP and SWP facilities.[14] Under this restriction the Delta water quality standards must be maintained before any water is diverted for Project uses or to supplement the water rights of appropriators along the Sacramento and Feather Rivers and in the Delta. Therefore, these standards are assumed to be equivalent to riparian rights in priority.

Neither D-1485 nor D-1641 changed the basic agricultural water quality requirements contained in D-1379. However, these later decisions utilize different control points and limit the season to April 1 to August 15 and utilize flow criteria for fish and wildlife benefits for the period outside this season. The monthly outflows shown in Table 6 based on the D-1379 requirements provide

[14] California SWRCB, "Delta Water Rights Decision, Decision 1379" (July 1971) p. 50.

a reasonable estimate of the water quantity required for meeting Delta water quality requirements for agricultural, municipal and industrial uses.

Deficiencies in Water Rights

There are no specific outflows associated with the 1981 Contract criteria. However, the monthly outflow schedule developed for D-1379 provides a reasonable basis for allocating the special benefits of the Contract associated with maintaining water quality. Assuming a different outflow requirement changes the overall deficiencies of the various water right classifications, but does not significantly change the proportionality of those deficiencies among the various water right classifications.

To account for the water supply required to meet water quality requirements, the estimated monthly outflows identified in Table 6 were subtracted from the water supply remaining in the Delta identified in Table A through Table E. The results are shown in Table F through Table J. Months showing zero water remaining in the Delta indicate insufficient water supplies are available under pre-Project conditions to meet the water quality standards and the water supply requirements for that particular water right classification; in other words the water rights were "deficient". For example, attached Table F identifies the water available in the Delta after meeting the riparian and Delta outflow requirements identified in Table 6. Table F indicates that during the 31-year study period there were 41 months in which the water supply was insufficient to meet both the riparian and the Delta outflow requirements. During these months the supplemental water supply afforded by the 1981 Contract would allow the riparian water users within the Agency to continue to divert and to fully satisfy their water requirements. During the 31-year study period, deficiencies in flows required to maintain the agricultural standards occurred during some months for all water right classifications. The number of months in which deficiencies occurred for each water right classification, the months showing zero water available, were summarized and are shown in Table 7.

Table 7: Summary of Monthly Water Supply Deficiencies by Water Right Group
(Number of months in which deficiency occurs)

Priority Group	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
Riparian	0	0	3	14	19	5	0	41
Pre-1927	0	1	5	25	31	9	0	71
1927-1938	0	2	7	26	31	22	4	92
1938-1954	2	5	13	27	31	31	22	131
Post 1954	2	5	13	30	31	31	24	136

In part to account for area of origin considerations, the parties to the negotiations of the Sacramento River Settlement Contracts assumed that there were no deficiencies in riparian and appropriative water rights of the local users during the months of April, May, or October. They further agreed that the assumed deficiencies for June would be 50% of the calculated deficiency[15]. The 1981 Contract is similar to the Sacramento River Settlement Contracts in that it settled a dispute as to the respective water rights of the Projects and the local water users while also requiring a payment for the benefits provided by the Projects to the local users. Additionally, the Agency, like the Sacramento River Settlement Contractors, is within the area of origin of the Sacramento River and its tributaries. Therefore, it is reasonable, for the purposes of allocating the benefits of the 1981 Contract, to utilize similar assumptions regarding the average yields and deficiencies for the water rights within the Agency.

Table 8 shows the frequency of deficiency in the water supply available to the various water right priority groups identified above after adjusting for the assumptions used in the negotiations of the Sacramento River Settlement Contracts:

- No deficiencies in water rights within the Agency during the months of April, May and October; and,
- Deficiencies in the month of June are assumed to be 50% of the average deficiencies determined by Studies C-2BR and C-650B.

[15] It was recognized that sufficient water was generally available to meet the water rights of local users through mid-June. Therefore, the USBR and the Sacramento River Settlement Contractors agree to use 50% of the deficiencies determined by the C-2BR and C-650B studies during their negotiations.

Table 8: Adjusted Monthly Water Supply Deficiencies by Water Right Group
(Number of months in which deficiency occurs)

Priority Group	Apr	May	Jun	Jul	Aug	Sep	Oct	Total	Average Water Supply Deficiency %
Riparian	0	0	1.5	14	19	5	0	39.5	18.2□
Pre-1927	0	0	3	25	31	9	0	68	31.1□
1927-1938	0	0	4	26	31	22	0	83	38.0□
1939-1954	0	0	7	27	31	31	0	96	44.0□
Post-1954	0	0	7	30	31	31	0	99	45.4□

The water right priority groups were established as follows: (1) riparian, (2) pre-1927 appropriative, which are the appropriative rights senior to all water rights for the CVP; (3) 1927-1938 appropriative, which are the appropriative rights senior to a substantial portion of the water rights of the CVP; (4) 1939-1954 appropriative, which are the appropriative rights senior to the water rights of the CVP but junior to the water rights of the SWP; and (5) post-1954 appropriative, which are the appropriative rights junior to the CVP and the SWP. These are the classifications used as the basis for the Sacramento River Settlement Contracts.

Summary of Proportional Special Benefits

The special benefits afforded by the 1981 Contract are the ability to continue to divert water when water supplies absent the Contract would be insufficient to satisfy the rights of the water users within the Agency. The benefits of the Contract accrue in the order of the deficiency of the water right (i.e., the more senior water rights receive the least benefit and the more junior water rights receive the most. As described previously in this report, riparian rights have the lowest average annual deficiency; and therefore, parcels with riparian rights receive the least benefit under the Contract. Conversely, post-1954 water rights are deficient most often; and therefore, parcels with post-1954 water rights receive the greatest benefit.

Allocation of the special benefits afforded by the 1981 Contract are based on the average annual deficiency for each water right priority group as shown in Table 8. Table 9 identifies the proportional benefit attributable to the lands within each water right classification. The proportional benefit for each water right priority group is based on the percentage of time the water rights for a particular water right priority are determined to be deficient as shown in Table 8. The proportional benefit attributable to each acre within the water right priority group is determined by dividing the Average Annual Deficiency for a particular water right priority by the Average Annual Deficiency for Riparian Water Rights. For example, for Pre-1927 Appropriative water rights, the Average Annual Water Right Deficiency of 31.1% is divided by 18.2%, the deficiency for Riparian water rights, to arrive at the Proportional Special Benefit of 1.71.

Table 9: Proportional Special Benefits by Water Right Priority

Water Right Priority	Average Annual Water Right Deficiency [1]	Proportional Special Benefit [2]
<u>Delta Lowlands</u>		
Riparian	18.2□	1.00
<u>Delta Uplands</u>		
Riparian	18.2□	1.00
Pre-1927 Appropriative	31.1□	1.71
1927-1938 Appropriative	38.0□	2.09
1938-1954 Appropriative	44.0□	2.42
Post-1954 Appropriative	45.4□	2.49
No Identifiable Right	45.4□	2.49

[1] Average Annual Deficiencies are based on Study C-650-B conducted by DWR for SRDWA, and USBR Study C-2BR
[2] Special benefits are proportional to the deficiency, with a factor of 1.0 for riparian, and weighting factors in relation to 1.0 for the other priorities.

Landowners within the Agency with non-riparian lands that are not covered by an existing appropriative water right can divert water for beneficial uses pursuant to the 1981 Contract. Any water right application filed to cover these lands would have a priority as of the date the application is accepted by the SWRCB. Therefore, as indicated in Table 9, lands with no identifiable water rights have deficiencies equivalent to those of other post-1954 water rights.

Other Assessment Classifications

As shown in this report all lands within the Agency receive special benefits pursuant to the 1981 Contract. As described above the special benefits received are proportional to the relative deficiency of the water rights attributable to each parcel within the Agency. The Assessment Commissioners have determined the special benefits afforded to certain parcels may not accrue in direct accordance with the water right priorities described above. These exceptions include privately owned lands on Sherman Island and lands that do not abut or have physical access to surface water channels. The latter are referred to herein as Isolated Lands. The proportional special benefits attributable to the Sherman Island Private Lands and the Isolated Lands are described below.

Sherman Island Private Lands

Article 5 of the 1981 Contract specifically provides for the construction of facilities to serve water overland to Sherman Island. These facilities are described in the report entitled "Overland Agricultural Water Facilities Sherman Island," dated January 1980. The Contract states that when these facilities are in place, the water quality criteria for the Sacramento River at Emmaton shall apply at the overland facility's intended intake on Three Mile Slough. Water quality within the remainder of the Agency is protected by the standards at the upstream interior stations and the steep gradient resulting from these standards.

DWR never built the overland facility, however, and instead acquired the majority of the lands on Sherman Island through a land acquisition program. Water quality easements were obtained on certain other lands not acquired by DWR. These easements released DWR from meeting specific water quality requirements in the Delta Channels adjacent to the affected lands. On January 21, 1997, the Agency and DWR executed an amendment to the 1981 Contract allowing the Emmaton criteria to be moved upstream to the northwest end of Three-Mile Slough as provided in the 1981 Contract. On May 29, 1998, the Sacramento County Superior Court issued a judgment determining that all the provisions of the amendment are valid, binding on the Agency and DWR, and in the best interests of the Agency and landowners within the boundaries of the Agency.

Following the 1997 Contract Amendment, the Agency's payment to DWR was reduced to account for lands owned in fee by DWR including the lands purchased on Sherman Island. No corresponding reduction in the payment was made for the lands on which DWR acquired water quality easements. Lands on Sherman Island not purchased by DWR are still covered by the Contract and continue to receive the special benefits of the assurance of a dependable supply of suitable quality. DWR has recognized that lands on Sherman Island continued to receive benefits pursuant to the 1981 Contract.

Moving the water quality monitoring station to Three Mile Slough results in some reduction in the water quality that would otherwise accrue to lands on Sherman Island under the Contract had the overland facility been built. Agency records of water quality at Emmaton and Three Mile Slough do demonstrate that meeting the quality criteria at Three Mile Slough, despite the steep salinity gradient, assures a relatively high water quality at Emmaton as well at most times. But based on a review of the Agency's water quality monitoring data during critical years such as 1991, the Agency's engineering staff have concluded that, in the channels off Sherman Island, the water quality would be expected to drop below the criteria level during at least half of the months in which there is a pre-Project water supply deficiency for riparians.[16] Regardless of the exact water quality, the Contract nonetheless ensures Sherman Island landowners may legally divert as much water as is necessary for any reasonable and beneficial uses during all deficiency periods, and Sherman Island landowners have never, to the Agency's knowledge, stopped diverting water since execution of the Contract (as occurred periodically prior to construction of the Projects). To reflect the reduced water quality, the proportional special benefit for the privately owned lands on Sherman Island is adjusted to 50% of the special benefits allocated to Delta Lowland Riparian parcels.

Lands Not Utilizing Surface Water Supplies

As described previously in this report, lands utilizing surface water supplies that hold post-1954 or no underlying water rights receive the greatest proportional benefit under the 1981 Contract and therefore are assessed at the highest rate. The Commissioners' understand there are certain lands within the Agency that have no underlying water right and do not have physical access to Delta channels. For the purposes of this report these lands are referred to as Isolated Lands. There are two types or classifications of Isolated Lands within the Agency: lands with no physical access to Delta channels that are utilizing groundwater in lieu of surface water supplies

[16] Creating a model to determine the number of days in which the water quality has been reduced below the Contract criteria during riparian deficiency periods would be prohibitively expensive, and at any rate could not reflect landowners' decisions to use the water anyway when quality is only slightly below the criteria.

and lands with no physical access to Delta channels that have not been and are not being irrigated or otherwise using water.

Although these Isolated Lands may not currently be utilizing surface water supplies they do derive special benefits under the Agency's Contract. The proportional special benefits attributable to the Isolated Lands within the Agency are described below.

Isolated Groundwater Lands

Isolated Groundwater Lands are parcels that use water but which do not currently have physical access to surface water supplies; that is, there are no diversion or conveyance facilities connecting these parcels to the surface channels. These parcels have historically used groundwater to meet beneficial use requirements. The special benefits enjoyed by Isolated Groundwater Lands include:

a) The right and ability under the Contract to divert surface water for reasonable and beneficial use when and if access to a channel is acquired;

b) Maintenance of groundwater levels as a result of percolation from drainage or surface water irrigation on adjacent or nearby lands pursuant to the 1981 Contract; and

c) Reduced competition for groundwater supplies by those utilizing surface water pursuant to the 1981 Contract

The groundwater level and reduced competition benefits enjoyed by these lands are directly related to the diversion and use of water by neighboring lands afforded by the 1981 Contract. The proportional benefits to Isolated Groundwater Lands are determined to be forty percent (40%) of the special benefits allocated to post-1954 appropriative water rights, which is the priority classification applied to lands that do not already have surface water appropriative rights.

Isolated Non-Irrigated Lands

Isolated Non-Irrigated Lands are parcels that do not have physical access to surface water supplies; that is, there are no diversion or conveyance facilities connecting these parcels to the surface channels. These parcels have historically not used surface water or ground-water for irrigation or other beneficial uses. The special benefits enjoyed by Isolated Non-Irrigated Lands are the right and ability under the 1981 Contract to divert surface water for reasonable and beneficial use at any time in the future. The proportional benefits to Isolated Non-Irrigated Lands are determined to be twenty-five percent (25%) of the special benefits allocated to post-1954 appropriative water rights, which is the priority classification applied to lands that do not already have surface water appropriative rights.

Determination of Isolated Lands

The counties do not keep records of which parcels use groundwater or use no water. It is recommended that the Agency adopt a policy under which landowners may petition the Agency to be assessed as Isolated Lands until such time as surface water use may begin. Landowners with parcels to be considered for the Isolated Lands assessment should be required to submit appropriate evidence that the lands qualify under the policy. Such evidence may include but not be limited to the following:

a) History of aerial photography showing the land is undeveloped;

b) Soil reports demonstrating the land is non-irrigable; and

c) History of pump tests, power records, and other data to demonstrate only groundwater is used on the lands.

Section 6 – Allocation of Proportional Special Benefits

As previously identified in this Engineer's Report, the special benefits derived from the 1981 Contract are the assurance of a dependable water supply of suitable quality. Because the water quality benefits afforded by the Contract depend on a sufficient supply of water to repel intrusion of salt water from the San Francisco Bay, these benefits are inseparable from the water supply benefits of the Contract. The water supply required to meet certain water quality requirements is analyzed in Section 5 of this report and incorporated into the water supply benefits associated with the Contract. The Commissioners have determined it is appropriate to allocate the special benefits of the Contract on the basis of the deficiencies in the water rights appurtenant to the lands within the Agency as described in the Section 5 of this report. Table 10 summarizes the proportional special benefit to be allocated to each parcel within the Agency.

Table 10: Allocation of Proportional Special Benefits

Water Right Priority	Average Annual Water Right Deficiency [1]	Proportional Special Benefits [2]
Delta Lowlands		
Riparian	18.2□	1.00
Sherman Island Private Lands_[3]	-	0.50
Delta Uplands		
Riparian	18.2□	1.00
Pre-1927Appropriative	31.1□	1.71
1927-1938 Appropriative	38.0□	2.09
1938-1954 Appropriative	44.0□	2.42
Post-1954 Appropriative	45.4□	2.49
No Identifiable Water Rights	45.4□	2.49
Isolated Groundwater Lands [4]	-	1.00
Isolated Non-Irrigated lands [5]	-	0.62

[1] Average Annual Deficiencies are based on Study C-650-B conducted by DWR for SRDWA, and USBR Study C-2BR
[2] Special benefits are proportional to the Average Annual Water Right Deficiencies of the Riparian Water Right Priority Group
[3] Adjusted to 50□ of the proportional special benefit allocated to Delta Lowland Riparians.
[4] Determined as 40□ of the proportional special benefit allocated to lands with no identifiable water right.
[5] Determined as 25□ of the proportional special benefit allocated to lands with no identifiable water right.

In accordance with the 1997 Contract Amendment the Agency does not assess parcels owned by DWR. However, should ownership of these lands change; these parcels should be assessed based on the water right priority appurtenant to those lands.

Privately owned lands on Sherman Island continue to receive special benefits in water supply and certain water quality from the 1981 Contract. As identified in Section 5 of this report the Commissioners recognize the water quality benefits to these lands may have diminished as a result of moving the change in the water quality compliance location upstream from Emmaton to Three mile Slough. The water supply benefits, the ability to continue to divert water for reasonable beneficial uses during times of shortage, however, remain unchanged. Therefore, the privately owned lands should be assessed as described in Section 5 of this report.

The Commissioners recognize there are lands within the Delta Uplands for which no water rights have been identified. Absent the 1981 Contract appropriative water rights would need to be acquired before water could be delivered to them. These lands with no identifiable water rights generally receive the greatest benefit and therefore should be assessed at the highest level as identified in Table 10. The Commissioners recognize however, that some of these lands have no access to the surface water channels within the Agency, i.e., they are Isolated Lands. Assessments for Isolated Lands should be reduced if and when the owners of these lands provide adequate evidence to the Agency to support a reduced assessment as shown in Table 10.

Classification of Parcels within NDWA Based on Water Right

To prepare the Assessment Roll, the Commissioners classified each parcel within the NDWA based on its appurtenant water rights as explained in Section 5. Although these classifications are based on a detailed technical review of the best information available to the NDWA, the Commissioners recognize that some classifications could be appropriately modified based on further information submitted by the landowner. It is therefore recommended that the Agency, in approving this Assessment Adjustment, reserve to itself the right to modify a classification based upon evidence submitted by the landowner if (1) deemed by the Agency Board to be justified by the facts presented, and (2) the modification would be consistent with the determinations in this Engineer's Report.

Minimum Assessment

As allowed under the Agency Act and identified previously in this report, the Agency currently assesses a minimum charge for small parcels. It is assumed that the Agency will exercise its authority to levy a minimum assessment for small parcels to ensure that the landowners pay for their special benefit while also covering the Agency's cost in collecting a relatively small payment per parcel.

ATTACHED TABLES

LIST OF ATTACHED TABLES

Table A – Water Remaining in the Delta after Satisfaction of Riparian Demands

(Before water quality requirements are satisfied)[1]

*(In **thousands** of acre-feet)*

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
1924[2]	643	336	33	0	0	46	221	1,279
1925	4,079	3,163	1,260	291	68	144	361	9,366
1926	3,945	1,274	296	47	14	126	299	6,001
1927	5,328	3,305	2,118	473	171	199	407	12,001
1928	3,932	1,954	510	147	80	171	329	7,123
1929	1,205	1,170	529	58	17	134	271	3,384
1930	2,082	1,385	626	113	64	213	387	4,870
1931[2]	536	304	75	0	0	41	160	1,116
1932[2]	2,026	2,870	2,024	474	52	79	206	7,731
1933[2]	1,453	1,239	1,147	106	2	82	239	4,268
1934[2]	1,056	397	139	0	0	31	177	1,800
1935	6,758	4,009	2,150	309	84	160	396	13,866
1936	3,651	2,886	1,742	330	88	184	317	9,198
1937	4,119	3,720	1,849	319	60	129	432	10,628
1938	7,251	6,871	4,840	1,426	373	334	577	21,672
1939	1,261	539	147	3	0	127	281	2,358
1940	7,271	2,843	1,301	234	107	247	381	12,384
1941	6,608	4,955	2,813	993	290	238	446	16,343
1942	5,023	4,324	3,419	971	250	289	511	14,787
1943	4,360	2,869	1,681	378	200	215	476	10,179
1944	1,491	1,742	752	40	63	165	349	4,702
1945	2,541	2,791	1,596	324	140	210	523	8,125
1946	2,665	2,606	906	174	111	240	379	7,081
1947	1,706	604	469	26	32	169	510	3,516
1948	4,000	3,600	2,456	350	106	228	430	11,170
1949	2,509	1,831	496	18	37	147	215	5,253
1950	3,139	2,295	1,178	114	31	198	753	7,708
1951	2,044	2,324	614	55	82	271	493	5,883
1952	6,698	6,721	3,886	1,025	308	404	511	19,553
1953	2,369	2,774	2,289	550	189	393	526	9,090
1954	4,207	2,028	568	128	180	318	472	7,901
Total	**105,956**	**79,729**	**43,909**	**9,576**	**3,199**	**5,932**	**12,035**	**260,336**
Average	**3,418**	**2,572**	**1,416**	**309**	**103**	**191**	**388**	**8,398**
Number of Deficient Months	**0**	**0**	**0**	**3**	**4**	**0**	**0**	**7**

[1] Includes satisfaction of all riparian demands along the Sacramento River, the Delta Uplands and the Delta Lowlands before water quality requirements are met.

[2] Denotes Critical Year.

Table B – Water Remaining in the Delta after Satisfaction of all Pre-1927 Appropriative and Other Rights

(Before water quality requirements are satisfied)[1]

*(In **thousands** of acre-feet)*

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
1924[2]	511	103	0	0	0	0	215	829
1925	3,950	2,980	1,004	0	0	101	386	8,421
1926	3,816	1,091	46	0	0	62	310	5,325
1927	5,199	3,122	1,862	116	0	156	432	10,887
1928	4,024	1,771	254	0	0	128	354	6,531
1929	1,076	987	273	0	0	70	282	2,688
1930	1,953	1,202	370	0	0	170	412	4,107
1931[2]	410	76	0	0	0	0	154	640
1932[2]	1,897	2,687	1,768	206	0	36	231	6,825
1933[2]	1,324	1,056	891	0	0	18	250	3,539
1934[2]	927	214	0	0	0	0	188	1,329
1935	6,629	3,826	1,894	0	0	117	421	12,887
1936	3,522	2,703	1,486	25	0	141	342	8,219
1937	3,990	3,537	1,593	4	0	86	457	9,667
1938	7,122	6,688	4,584	1,069	30	291	602	20,386
1939	1,132	356	0	0	19	63	292	1,862
1940	7,142	2,660	1,045	0	0	204	406	11,457
1941	6,479	4,772	2,557	636	0	195	471	15,110
1942	4,894	4,141	3,163	614	0	246	536	13,594
1943	4,231	2,686	1,425	21	0	172	501	9,036
1944	1,362	1,559	496	0	0	122	374	3,913
1945	2,412	2,608	1,340	41	0	167	548	7,116
1946	2,536	2,423	650	0	0	197	404	6,210
1947	1,577	421	213	0	0	126	535	2,872
1948	3,871	3,417	2,200	0	0	185	455	10,128
1949	2,380	1,648	240	0	0	104	240	4,612
1950	3,010	2,112	922	0	0	155	778	6,977
1951	1,915	2,141	358	0	0	228	518	5,160
1952	6,569	6,538	3,630	668	0	361	536	18,302
1953	2,240	2,591	2,033	193	0	350	551	7,958
1954	4,078	1,845	312	0	0	275	497	7,007
Total	**102,178**	**73,961**	**36,609**	**3,593**	**49**	**4,526**	**12,678**	**233,594**
Average	**3,296**	**2,386**	**1,181**	**116**	**2**	**146**	**409**	**7,535**
Number of Deficient Months	**0**	**0**	**4**	**20**	**29**	**3**	**0**	**56**

[1] Includes satisfaction of all assumed Riparian and Pre-1927 Appropriative and Other Rights of local water users along the Sacramento River above Sacramento and in the Delta Uplands and Lowlands to the extent of the available supply and before water quality requirements are met.

[2] Denotes Critical Year.

Table C – Water Remaining in the Delta after Satisfaction of all Pre-1938 Appropriative and Other Rights

(Before water quality requirements are satisfied)[1]

*(In **thousands** of acre-feet)*

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
1924[2]	376	100	0	0	0	0	78	554
1925	3,167	2,612	806	0	0	29	220	6,834
1926	3,322	888	39	0	0	13	157	4,419
1927	4,196	2,718	1,642	98	0	63	268	8,985
1928	3,454	1,443	183	0	0	49	202	5,331
1929	704	763	232	0	0	43	152	1,894
1930	1,559	935	351	0	0	106	260	3,211
1931[2]	230	67	0	0	0	0	33	330
1932[2]	1,505	2,335	1,652	201	0	5	100	5,798
1933[2]	864	755	766	0	0	3	131	2,519
1934[2]	636	90	0	0	0	0	67	793
1935	5,446	3,328	1,774	0	0	56	270	10,874
1936	3,047	2,412	1,308	20	0	84	202	7,073
1937	3,136	3,173	1,383	0	0	44	304	8,040
1938	6,505	6,326	4,177	966	36	158	432	18,600
1939	832	262	0	0	0	22	152	1,268
1940	6,525	2,316	933	0	0	121	242	10,137
1941	5,360	4,410	2,169	523	0	87	302	12,851
1942	4,029	3,528	2,743	512	0	123	317	11,252
1943	3,518	2,280	1,169	0	0	66	298	7,331
1944	1,022	1,289	395	0	0	31	209	2,946
1945	1,970	2,234	1,151	36	0	104	377	5,872
1946	1,999	2,082	551	0	0	92	242	4,966
1947	1,160	350	26	0	0	30	364	1,930
1948	3,000	3,055	1,778	0	0	49	290	8,172
1949	1,796	1,317	204	0	0	21	99	3,437
1950	2,422	1,817	888	0	0	87	390	5,604
1951	1,440	1,723	295	0	0	121	348	3,927
1952	5,799	6,127	3,280	563	0	168	366	16,303
1953	1,639	2,010	1,594	111	0	167	380	5,901
1954	3,155	1,483	156	0	0	111	326	5,231
Total	**83,813**	**64,228**	**31,645**	**3,030**	**36**	**2,053**	**7,578**	**192,383**
Average	**2,704**	**2,072**	**1,021**	**98**	**1**	**66**	**244**	**6,206**
Number of Deficient Months	**0**	**0**	**4**	**22**	**30**	**3**	**0**	**59**

[1] Includes satisfaction of all assumed Riparian, Pre-1927, 1927-38 Appropriative and Other Rights of local water users along the Sacramento River above Sacramento and in the Delta Uplands and Lowlands, and the assumed 1927 Right of the United States at Shasta Dam to the extent of the available supply and before water quality requirements are met.

[2] Denotes Critical Year.

Table D – Water Remaining in the Delta after Satisfaction of all Pre-1954 Appropriative and Other Rights

(Before water quality requirements are satisfied)[1]

*(In **thousands** of acre-feet)*

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
1924[2]	87	0	0	0	0	0	0	87
1925	2,980	2,501	639	0	0	0	25	6,145
1926	3,135	708	0	0	0	0	0	3,843
1927	4,009	2,665	1,497	0	0	0	71	8,242
1928	3,274	1,344	0	0	0	0	0	4,618
1929	524	604	0	0	0	0	0	1,128
1930	1,372	817	5	0	0	0	51	2,245
1931[2]	0	0	0	0	0	0	0	0
1932[2]	1,330	2,241	1,403	0	0	0	0	4,974
1933[2]	677	651	526	0	0	0	0	1,854
1934[2]	463	0	0	0	0	0	0	463
1935	5,259	3,213	1,529	0	0	0	0	10,001
1936	2,860	2,306	1,121	0	0	0	60	6,347
1937	2,949	3,078	1,228	0	0	0	0	7,255
1938	6,325	6,231	4,112	0	0	0	96	16,764
1939	661	0	0	699	0	0	241	1,601
1940	6,345	2,213	680	0	0	0	45	9,283
1941	5,180	4,315	2,102	266	0	0	110	11,973
1942	3,842	3,413	2,666	244	0	0	88	10,253
1943	3,331	2,165	1,060	0	0	0	71	6,627
1944	867	1,173	131	0	0	0	13	2,184
1945	1,783	2,143	975	0	0	0	187	5,088
1946	1,819	1,986	285	0	0	0	43	4,133
1947	973	38	0	0	0	0	174	1,185
1948	2,820	2,960	1,728	0	0	0	94	7,602
1949	1,609	1,219	0	0	0	0	0	2,828
1950	2,235	1,712	557	0	0	0	200	4,704
1951	1,253	1,608	0	0	0	0	157	3,018
1952	5,619	6,032	3,209	298	0	2	175	15,335
1953	1,452	1,895	1,523	0	0	0	190	5,060
1954	2,975	1,388	0	0	0	0	136	4,499
Total	**78,008**	**60,619**	**26,976**	**1,507**	**0**	**2**	**2,227**	**169,339**
Average	**2,516**	**1,955**	**870**	**49**	**0**	**0**	**72**	**5,463**
Number of Deficient Months	**1**	**4**	**11**	**27**	**31**	**30**	**11**	**115**

[1] Includes satisfaction of all assumed Riparian and Appropriative and Other Rights water users along the Sacramento River above Sacramento and in the Delta Uplands and Lowlands with priorities prior to January 1, 1954, including the assumed 1927 and 1938 Rights of the United States at Shasta Dam and in the Delta, to the extent of the available supply before water quality requirements are met.

[2] Denotes Critical Year.

Table E – Water Remaining in the Delta after Satisfaction of all Pre-1955 Appropriative and Other Rights

(Before water quality requirements are satisfied)[1]

*(In **thousands** of acre-feet)*

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
1924[2]	114	0	0	0	0	0	0	114
1925	3,030	2,446	555	0	0	0	11	6,042
1926	3,185	651	0	0	0	0	0	3,836
1927	4,059	2,552	1,413	0	0	0	34	8,058
1928	3,316	1,288	0	0	0	0	0	4,604
1929	574	547	0	0	0	0	0	1,121
1930	1,422	761	0	0	0	0	24	2,207
1931[2]	30	0	0	0	0	0	0	30
1932[2]	1,375	2,181	1,319	0	0	0	0	4,875
1933[2]	727	601	442	0	0	0	0	1,770
1934[2]	505	0	0	0	0	0	0	505
1935	5,309	3,163	1,445	0	0	0	28	9,945
1936	2,910	2,256	1,037	0	0	0	0	6,203
1937	2,999	3,007	1,144	0	0	0	55	7,205
1938	6,367	6,160	4,036	590	0	0	193	17,346
1939	701	0	0	0	0	0	0	701
1940	6,387	2,158	596	0	0	0	21	9,162
1941	5,222	4,244	2,030	157	0	0	65	11,718
1942	3,892	3,363	2,589	135	0	0	79	10,058
1943	3,381	2,115	976	0	0	0	60	6,532
1944	891	1,118	53	0	0	0	5	2,067
1945	1,833	2,080	891	0	0	0	139	4,943
1946	1,861	1,928	201	0	0	0	20	4,010
1947	1,023	9	0	0	0	0	126	1,158
1948	2,862	2,889	1,619	0	0	0	51	7,421
1949	1,659	1,163	0	0	0	0	0	2,822
1950	2,285	1,663	473	0	0	0	152	4,573
1951	1,305	1,563	0	0	0	0	111	2,979
1952	5,661	5,961	3,140	56	0	0	127	14,945
1953	1,502	1,845	1,452	133	0	0	142	5,074
1954	3,017	1,317	0	0	0	0	88	4,422
Total	**79,404**	**59,029**	**25,411**	**1,071**	**0**	**0**	**1,531**	**166,446**
Average	**2,561**	**1,904**	**820**	**35**	**0**	**0**	**49**	**5,369**
Number of Deficient Months	**0**	**4**	**12**	**26**	**31**	**31**	**11**	**115**

[1] Includes satisfaction of all assumed water rights of local water users along the Sacramento River above Sacramento and in the Delta Uplands and Lowlands, and the United States at Shasta Dam and in the Delta with priorities prior to January 1, 1955 to the extent of the available supply before water quality requirements are met.

[2] Denotes Critical Year.

Table F – Water Remaining in the Delta after Satisfaction of all Riparian and Water Quality Requirements [1]

*(In **thousands** of acre-feet)*

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
1924[2]	517	237	0	0	0	0	122	876
1925	3,905	2,990	1,092	118	0	48	262	8,415
1926	3,771	1,101	128	0	0	30	200	5,230
1927	5,154	3,132	1,950	300	72	103	308	11,019
1928	3,758	1,781	342	0	0	75	230	6,186
1929	1,031	997	361	0	0	38	172	2,599
1930	1,908	1,212	458	0	0	117	288	3,983
1931[2]	410	205	0	0	0	0	61	676
1932[2]	1,900	2,771	1,928	375	0	0	107	7,081
1933[2]	1,327	1,140	1,051	7	0	0	140	3,665
1934[2]	930	298	43	0	0	0	78	1,349
1935	6,584	3,836	1,982	136	0	64	297	12,899
1936	3,477	2,713	1,574	157	0	88	218	8,227
1937	3,945	3,547	1,681	146	0	33	333	9,685
1938	7,077	6,698	4,672	1,253	274	238	478	20,690
1939	1,087	366	0	0	0	31	182	1,666
1940	7,097	2,670	1,133	61	8	151	282	11,402
1941	6,434	4,782	2,645	820	191	142	347	15,361
1942	4,849	4,151	3,251	798	151	193	412	13,805
1943	4,186	2,696	1,513	205	101	119	377	9,197
1944	1,317	1,569	584	0	0	69	250	3,789
1945	2,367	2,618	1,428	151	41	114	424	7,143
1946	2,491	2,433	738	1	12	144	280	6,099
1947	1,532	431	301	0	0	73	411	2,748
1948	3,826	3,427	2,288	177	7	132	331	10,188
1949	2,335	1,658	328	0	0	51	116	4,488
1950	2,965	2,122	1,010	0	0	102	654	6,853
1951	1,870	2,151	446	0	0	175	394	5,036
1952	6,524	6,548	3,718	852	209	308	412	18,571
1953	2,195	2,601	2,121	377	90	297	427	8,108
1954	4,033	1,855	400	0	81	222	373	6,964
Total	**100,802**	**74,736**	**39,166**	**5,934**	**1,237**	**3,157**	**8,966**	**233,998**
Average	**3,252**	**2,411**	**1,263**	**191**	**40**	**102**	**289**	**7,548**
Number of Deficient Months	**0**	**0**	**3**	**14**	**19**	**5**	**0**	**41**

[1] Includes satisfaction of all riparian demands along the Sacramento River, the Delta Uplands and the Delta Lowlands and water quality requirements to the extent of the available supply.

[2] Denotes Critical Year.

Table G – Water Remaining in the Delta after Satisfaction of all Pre-1927 Water Rights and Water Quality Requirements [1]

(In **thousands** of acre-feet)

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
1924[2]	385	4	0	0	0	0	116	505
1925	3,824	2,881	908	0	0	5	287	7,905
1926	3,690	992	0	0	0	0	211	4,893
1927	5,073	3,023	1,766	0	0	60	333	10,255
1928	3,898	1,672	158	0	0	32	255	6,015
1929	950	888	177	0	0	0	183	2,198
1930	1,827	1,103	274	0	0	74	313	3,591
1931[2]	284	0	0	0	0	0	55	339
1932[2]	1,771	2,588	1,672	107	0	0	132	6,270
1933[2]	1,198	957	795	0	0	0	151	3,101
1934[2]	801	115	0	0	0	0	89	1,005
1935	6,503	3,727	1,798	0	0	21	322	12,371
1936	3,396	2,604	1,390	0	0	45	243	7,678
1937	3,864	3,438	1,497	0	0	0	358	9,157
1938	6,996	6,589	4,488	970	0	195	503	19,741
1939	1,006	257	0	0	0	0	193	1,456
1940	7,016	2,561	949	0	0	108	307	10,941
1941	6,353	4,673	2,461	537	0	99	372	14,495
1942	4,768	4,042	3,067	515	0	150	437	12,979
1943	4,105	2,587	1,329	0	0	76	402	8,499
1944	1,236	1,460	400	0	0	26	275	3,397
1945	2,286	2,509	1,244	0	0	71	449	6,559
1946	2,410	2,324	554	0	0	101	305	5,694
1947	1,451	322	117	0	0	30	436	2,356
1948	3,745	3,318	2,104	0	0	89	356	9,612
1949	2,254	1,549	144	0	0	8	141	4,096
1950	2,884	2,013	826	0	0	59	679	6,461
1951	1,789	2,042	262	0	0	132	419	4,644
1952	6,443	6,439	3,534	569	0	265	437	17,687
1953	2,114	2,492	1,937	94	0	254	452	7,343
1954	3,952	1,746	216	0	0	179	398	6,491
Total		**70,915**	**34,067**	**2,792**	**0**	**2,079**	**9,609**	**217,734**
Average		**2,288**	**1,099**	**90**	**0**	**67**	**310**	**7,024**
Number of Deficient Months	**0**	**1**	**5**	**25**	**31**	**9**	**0**	**71**

[1] Includes satisfaction of all assumed Riparian and Pre-1927 Appropriative and Other Rights of local water users along the Sacramento River above Sacramento and in the Delta Uplands and Lowlands and water quality requirements to the extent of the available supply.

[2] Denotes Critical Year.

Table H – Water Remaining in the Delta after Satisfaction of all Pre-1938 Appropriative and Other Rights and Water Quality Requirements [1]

(In ***thousands*** *of acre-feet)*

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
1924[2]	250	1	0	0	0	0	0	251
1925	3,041	2,513	710	0	0	0	121	6,385
1926	3,196	789	0	0	0	0	58	4,043
1927	4,070	2,619	1,546	0	0	0	169	8,404
1928	3,328	1,344	87	0	0	0	103	4,862
1929	578	664	136	0	0	0	53	1,431
1930	1,433	836	255	0	0	10	161	2,695
1931[2]	104	0	0	0	0	0	0	104
1932[2]	1,379	2,236	1,556	102	0	0	1	5,274
1933[2]	738	656	670	0	0	0	32	2,096
1934[2]	510	0	0	0	0	0	0	510
1935	5,320	3,229	1,678	0	0	0	171	10,398
1936	2,921	2,313	1,212	0	0	0	103	6,549
1937	3,010	3,074	1,287	0	0	0	205	7,576
1938	6,379	6,227	4,081	867	0	62	333	17,949
1939	706	163	0	0	0	0	53	922
1940	6,399	2,217	837	0	0	25	143	9,621
1941	5,234	4,311	2,073	424	0	0	203	12,245
1942	3,903	3,429	2,647	413	0	27	218	10,637
1943	3,392	2,181	1,073	0	0	0	199	6,845
1944	896	1,190	299	0	0	0	110	2,495
1945	1,844	2,135	1,055	0	0	8	278	5,320
1946	1,873	1,983	455	0	0	0	143	4,454
1947	1,034	251	0	0	0	0	265	1,550
1948	2,874	2,956	1,682	0	0	0	191	7,703
1949	1,670	1,218	108	0	0	0	0	2,996
1950	2,296	1,718	792	0	0	0	291	5,097
1951	1,314	1,624	199	0	0	25	249	3,411
1952	5,673	6,028	3,184	464	0	72	267	15,688
1953	1,513	1,911	1,498	0	0	71	281	5,274
1954	3,029	1,384	0	0	0	15	227	4,655
Total		**61,200**	**29,120**	**2,270**	**0**	**315**	**4,628**	**177,440**
Average		**1,974**	**939**	**73**	**0**	**10**	**149**	**5,724**
Number of Deficient Months	**0**	**2**	**7**	**26**	**31**	**22**	**4**	**92**

[1] Includes satisfaction of all assumed all Riparian, Pre-1927, 1927-38 Appropriative and Other Rights of local water users along the Sacramento River above Sacramento and in the Delta Uplands and Lowlands, including the assumed 1927 Right of the United States at Shasta Dam and water quality requirements, to the extent of the available supply.

[2] Denotes Critical Year.

Table I – Water Remaining in the Delta after Satisfaction of all Pre-1954 Appropriative and Other Rights and Water Quality Requirements [1]

*(In **thousands** of acre-feet)*

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
1924[2]	0	0	0	0	0	0	0	0
1925	2,854	2,402	543	0	0	0	0	5,799
1926	3,009	609	0	0	0	0	0	3,618
1927	3,883	2,566	1,401	0	0	0	0	7,850
1928	3,148	1,245	0	0	0	0	0	4,393
1929	398	505	0	0	0	0	0	903
1930	1,246	718	0	0	0	0	0	1,964
1931[2]	0	0	0	0	0	0	0	0
1932[2]	1,204	2,142	1,307	0	0	0	0	4,653
1933[2]	551	552	430	0	0	0	0	1,533
1934[2]	337	0	0	0	0	0	0	337
1935	5,133	3,114	1,433	0	0	0	0	9,680
1936	2,734	2,207	1,025	0	0	0	0	5,966
1937	2,823	2,979	1,132	0	0	0	0	6,934
1938	6,199	6,132	4,016	0	0	0	0	16,347
1939	535	0	0	600	0	0	142	1,277
1940	6,219	2,114	584	0	0	0	0	8,917
1941	5,054	4,216	2,006	167	0	0	11	11,454
1942	3,716	3,314	2,570	145	0	0	0	9,745
1943	3,205	2,066	964	0	0	0	0	6,235
1944	741	1,074	0	0	0	0	0	1,815
1945	1,657	2,044	879	0	0	0	88	4,668
1946	1,693	1,887	189	0	0	0	0	3,769
1947	847	0	0	0	0	0	75	922
1948	2,694	2,861	1,632	0	0	0	0	7,187
1949	1,483	1,120	0	0	0	0	0	2,603
1950	2,109	1,613	461	0	0	0	101	4,284
1951	1,127	1,509	0	0	0	0	58	2,694
1952	5,493	5,933	3,113	199	0	0	76	14,814
1953	1,326	1,796	1,427	0	0	0	91	4,640
1954	2,849	1,289	0	0	0	0	37	4,175
Total		**58,007**	**25,112**	**1,111**	**0**	**0**	**679**	**159,176**
Average		**1,871**	**810**	**36**	**0**	**0**	**22**	**5,135**
Number of Deficient Months	**2**	**5**	**13**	**27**	**31**	**31**	**22**	**131**

[1] Includes satisfaction of all assumed Riparian and Appropriative and Other Rights water users along the Sacramento River above Sacramento and in the Delta Uplands and Lowlands with priorities prior to January 1, 1954, including the assumed 1927 and 1938 Rights of the United States at Shasta Dam and in the Delta and water quality requirements, to the extent of the available supply.

[2] Denotes Critical Year.

Table J – Water Remaining in the Delta after Satisfaction of all Pre-1955 Appropriative and Other Rights and Water Quality Requirements [1]

(In **thousands** of acre-feet)

Year	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
1924[2]	0	0	0	0	0	0	0	0
1925	2,904	2,347	459	0	0	0	0	5,710
1926	3,059	552	0	0	0	0	0	3,611
1927	3,933	2,453	1,317	0	0	0	0	7,703
1928	3,190	1,189	0	0	0	0	0	4,379
1929	448	448	0	0	0	0	0	896
1930	1,296	662	0	0	0	0	0	1,958
1931[2]	0	0	0	0	0	0	0	0
1932[2]	1,249	2,082	1,223	0	0	0	0	4,554
1933[2]	601	502	346	0	0	0	0	1,449
1934[2]	379	0	0	0	0	0	0	379
1935	5,183	3,064	1,349	0	0	0	0	9,596
1936	2,784	2,157	941	0	0	0	0	5,882
1937	2,873	2,908	1,048	0	0	0	0	6,829
1938	6,241	6,061	3,940	491	0	0	94	16,827
1939	575	0	0	0	0	0	0	575
1940	6,261	2,059	500	0	0	0	0	8,820
1941	5,096	4,145	1,934	0	0	0	0	11,175
1942	3,766	3,264	2,493	0	0	0	0	9,523
1943	3,255	2,016	880	0	0	0	0	6,151
1944	765	1,019	0	0	0	0	0	1,784
1945	1,707	1,981	795	0	0	0	40	4,523
1946	1,735	1,829	105	0	0	0	0	3,669
1947	897	0	0	0	0	0	27	924
1948	2,736	2,790	1,523	0	0	0	0	7,049
1949	1,533	1,064	0	0	0	0	0	2,597
1950	2,159	1,564	377	0	0	0	53	4,153
1951	1,179	1,464	0	0	0	0	12	2,655
1952	5,535	5,862	3,044	0	0	0	28	14,469
1953	1,376	1,746	1,356	0	0	0	43	4,521
1954	2,891	1,218	0	0	0	0	0	4,109
Total		**56,446**	**23,630**	**491**	**0**	**0**	**297**	**156,470**
Average		**1,821**	**762**	**16**	**0**	**0**	**10**	**5,047**
Number of Deficient Months	**2**	**5**	**13**	**30**	**31**	**31**	**24**	**136**

[1] Includes satisfaction of all assumed water rights of local water users along the Sacramento River above Sacramento and in the Delta Uplands and Lowlands, and the United States at Shasta Dam and in the Delta with priorities prior to January 1, 1955 to the extent of the available supply before water quality requirements are met.

[2] Denotes Critical Year.

EXHIBITS

LIST OF EXHIBITS

Exhibit I – North Delta Water Agency Contract

CONTRACT
BETWEEN
STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES
AND
NORTH DELTA WATER AGENCY

FOR THE ASSURANCE
OF A DEPENDABLE WATER SUPPLY OF SUITABLE QUALITY

TABLE OF CONTENTS

CONTRACT BETWEEN THE STATE OF CALIFORNIA DEPARTMENT OF WATER RESOURCES AND THE NORTH DELTA WATER AGENCY FOR THE ASSURANCE OF A DEPENDABLE WATER SUPPLY OF SUITABLE QUALITY

THIS CONTRACT, made this 28 day of Jan., 1981, between the STATE OF CALIFORNIA, acting by and through its DEPARTMENT OF WATER RESOURCES (State), and the NORTH DELTA WATER AGENCY (Agency), a political subdivision of the State of California, duly organized and existing pursuant to the laws thereof, with its principal place of business in Sacramento, California.

RECITALS

(a) The purpose of this contract is to assure that the State will maintain within the Agency a dependable water supply of adequate quantity and quality for agricultural uses and, consistent with the water quality standards of Attachment A, for municipal and industrial uses, that the State will recognize the right to the use of water for agricultural, municipal, and industrial uses within the Agency, and that the Agency will pay compensation for any reimbursable benefits allocated to water users within the Agency resulting from the Federal Central Valley Project and the State Water Project, and offset by any detriments caused thereby.

(b) The United States, acting through its Department of the Interior, has under construction and is operating the Federal Central Valley Project (FCVP).

(c) The State has under construction and is operating the State Water Project (SWP).

(d) The construction and operation of the FCVP and SWP at times have changed and will further change the regimen of rivers tributary to the Sacramento-San Joaquin Delta (Delta) and the regimen of the Delta channels from unregulated flow to regulated flow. This regulation at times improves the quality of water in the Delta and at times diminishes the quality from that which would exist in the absence of the FCVP and SWP. The regulation at times also alters the elevation of water in some Delta channels.

(e) Water problems within the Delta are unique within the State of California. As a result of the geographical location of the lands of the Delta and tidal influences, there is no physical shortage of water. Intrusion of saline ocean water and municipal, industrial and agricultural discharges and return flows, tend, however, to deteriorate the quality.

(f) The general welfare, as well as the rights and requirements of the water users in the Delta, require that there be maintained in the Delta an adequate supply of good quality water for agricultural, municipal and industrial uses.

(g) The law of the State of California requires protection of the areas within which water originates and the watersheds in which water is developed. The Delta is such an area and within such a watershed. Part 4.5 of Division 6 of the California Water Code affords a first priority to provision of salinity control and maintenance of an adequate water supply in the Delta for reasonable and beneficial uses of water and relegates to lesser priority all exports of water from the Delta to other areas for any purpose.

(h) The Agency asserts that water users within the Agency have the right to divert, are diverting, and will continue to divert, for reasonable beneficial use, water from the Delta that would have been available therein if the FCVP and SWP were not in existence, together with the right to enjoy or acquire such benefits to which the water users may be entitled as a result of the FCVP and SWP.

(i) Section 4.4 of the North Delta Water Agency Act, Chapter 283, Statutes of 1973, as amended, provides that the Agency has no authority or power to affect, bind, prejudice, impair, restrict, or limit vested water rights within the Agency.

(j) The State asserts that it has the right to divert, is diverting, and will continue to divert water from the Delta in connection with the operation of the SWP.

(k) Operation of SWP to provide the water quality and quantity described in this contract constitutes a reasonable and beneficial use of water.

(l) The Delta has an existing gradient or relationship in quality between the westerly portion most seriously affected by ocean salinity intrusion and the interior portions of the Delta where the effect of ocean salinity intrusion is diminished. The water quality criteria set forth in this contract establishes minimum water qualities at various monitoring locations. Although the water quality criteria at upstream locations is shown as equal in some periods of some years to the water quality at the downstream locations, a better quality will in fact exist at the upstream locations at almost all times. Similarly, a better water quality than that shown for any given monitoring location will also exist at interior points upstream from that location at almost all times.

(m) It is not the intention of the State to acquire by purchase or by proceeding in eminent domain or by any other manner the water rights of water users within the Agency, including rights acquired under this contract.

(n) The parties desire that the United States become an additional party to this contract.

AGREEMENTS

1. **Definitions.** When used herein, the term:

(a) "Agency" shall mean the North Delta Water Agency and shall include all of the lands within the boundaries at the time the contract is executed as described in Section 9.1 of the North Delta Water Agency Act, Chapter 283, Statutes of 1973, as amended.

(b) "Calendar year" shall mean the period January 1 through December 31.

(c) "Delta" shall mean the Sacramento-San Joaquin Delta as defined in Section 12220 of the California Water Code as of the date of the execution of the contract.

(d) "Electrical Conductivity" (EC) shall mean the electrical conductivity of a water sample measured in millimhos per centimeter per square centimeter corrected to a standard temperature of 25° Celsius determined in accordance with procedures set forth in the publication entitled "Standard Methods of Examination of Water and Waste Water", published jointly by the American Public Health Association, the American Water Works Association, and the Water Pollution Control Federation, 13th Edition, 1971, including such revisions thereof as may be made subsequent to the date of this contract which are approved in writing by the State and the Agency.

(e) "Federal Central Valley Project" (FCVP) shall mean the Central Valley Project of the United States.

(f) "Four-River Basin Index" shall mean the most current forecast of Sacramento Valley unimpaired runoff as presently published in the California Department of Water Resources Bulletin 120 for the sum of the flows of the following: Sacramento River above Bend Bridge near Red Bluff; Feather River, total inflow to Oroville Reservoir; Yuba River at Smartville; American River, total inflow to Folsom Reservoir. The May 1 forecast shall continue in effect until the February 1 forecast of the next succeeding year.

(g) "State Water Project" (SWP) shall mean the State Water Resources Development System as defined in Section 12931 of the Water Code of the State of California.

(h) "SWRCB" shall mean the State Water Resources Control Board.

(i) "Water year" shall mean the period October 1 of any year through September 30 of the following year.

2. **Water Quality.**

(a) (i) The State will operate the SWP to provide water qualities at least equal to the better of: (1) the standards adopted by the SWRCB as they may be established from time to time; or (2) the criteria established in this contract as identified on the graphs included as Attachment A.

(ii) The 14-day running average of the mean daily EC at the identified location shall not exceed the values determined from the Attachment A graphs using the Four-River Basin Index except for the period February through March of each year at the location in the Sacramento River at Emmaton for which the lower value of the 80 percent probability range shall be used.

(iii) The quality criteria described herein shall be met at all times except for a transition period beginning one week before and extending one week after the date of change in periods as shown on the graphs of Attachment A. During this transition period, the SWP will be operated to provide as uniform a transition as possible over the two-week period from one set of criteria to the next so as to arrive at the new criteria one week after the date of change in period as shown on the graphs of Attachment A.

(b) While not committed affirmatively to achieving a better water quality at interior points upstream from Emmaton than those set forth on Attachment A, the State agrees not to alter the Delta hydraulics in such manner as to cause a measurable adverse change in the ocean salinity gradient or relationship among the various monitoring locations shown on Attachment B and interior points upstream from those locations, with any particular flow past Emmaton.

(c) Whenever the recorded 14-day running average of mean daily EC of water in the Sacramento River at Sacramento exceeds 0.25 mmhos, the quality criteria indicated on the graphs of Attachment A may be adjusted by adding to the value taken therefrom the product of 1.5 times the amount that the recorded EC of the Sacramento River at Sacramento exceeds 0.25 mmhos.

3. **Monitoring.** The quality of water shall be measured by the State as needed to monitor performance pursuant to Article 2 hereof with equipment installed, operated, and maintained by the State, at locations indicated on "Attachment B". Records of such measurements shall at regular intervals be furnished to the Agency. All monitoring costs at North Fork Mokelumne River near Walnut Grove, Sacramento River at Walnut Grove, and Steamboat Slough at Sutter Slough incurred by the State solely for this contract shall be shared equally by the Agency and the State. All monitoring costs to be borne by the Agency for monitoring at the above locations are included in the payment under Article 10.

4. **Emergency Provisions.**

(a) If a structural emergency occurs such as a levee failure or a failure of an SWP facility, which results in the State's failure to meet the water quality criteria, the State shall not be in breach of this contract if it makes all reasonable efforts to operate SWP facilities so that the water quality criteria will be met again as soon as possible. For any period in which SWP failure results in failure of the State to meet the water quality criteria, the State shall waive payment under Article 10, prorated for that period, and the amount shall be deducted from the next payment due.

(b) (i) A drought emergency shall exist when all of the following occur:

(1) The Four-River Basin Index is less than an average of 9,000,000 acre feet in two consecutive years (which occurred in 1933-4 and 1976-7); and

(2) An SWRCB emergency regulation is in effect providing for the operation of the SWP to maintain water quality different from that provided in this contract; and

(3) The water supplied to meet annual entitlements of SWP agricultural contractors in the San Joaquin Valley is being reduced by at least 50 percent of these agricultural entitlements (it being the objective of the SWP to avoid agricultural deficiencies in excess of 25 percent) or the total of water supplied to meet annual entitlements of all SWP contractors is being reduced by at least 15 percent of all entitlements, whichever results in the greater reduction in acre feet delivered.

(ii) A drought emergency shall terminate if any of the conditions in (b) (i) of this Article ceases to exist or if the flow past Sacramento after October 1 exceeds 20,000 cubic feet per second each day for a period of 30 days.

(iii) Notwithstanding the provisions of Article 2 (a), when a drought emergency exists, the emergency water quality criteria of the SWRCB shall supersede the water quality requirements of this contract to the extent of any inconsistency; provided, however, that the State shall use all reasonable efforts to preserve Delta water quality, taking into consideration both the limited water supply available for that purpose and recognizing the priority established for Delta protection referred to in Recital (g).

(iv) When a drought emergency exists, and an overland supply is not available to an individual water user comparable in quality and quantity to the water which would have been available to the user under Attachment A, the State shall compensate the user for loss of net income for each acre either (A) planted to a more salt-tolerant crop in the current year, (B) not planted to any crop in the current year provided such determination not to plant was reasonable based on the drought emergency, or (C) which had a reduced yield due to the drought emergency, calculated on the basis of the user's average net income for any three of the prior five years for each such acre. A special contract claims procedure shall be estalished by the State to expedite and facilitate the payment of such compensation.

5. **Overland Water Supply Facilities.**

(a) Within the general objectives of protecting the western Delta areas against the destruction of agricultural productivity as a result of the increased salinity of waters in the Delta channels resulting in part from SWP operation, the State may provide diversion and overland facilities to supply and distribute water to Sherman Island as described in the report entitled "Overland Agricultural Water Facilities Sherman Island" dated January 1980. Final design and operating specifications shall be subject to approval of the Agency and Reclamation District No. 341. The Agency or its transferee will assume full ownership, operation, and maintenance responsibility for such facilities after successful operation as specified. After the facilities are constructed and operating, the water qualitry criteria for the Sacramento River at Emmaton shall apply at the intake of the facilities in Three Mile Slough.

(b) The State and the Agency may agree to the construction and operation of additional overland water supply facilities within the Agency, so long as each landowner served by the overland facilities receives a quality of water not less than that specified in Attachment A for the upstream location nearest to his original point of diversion. The design and operation of such facilities and the cost sharing thereof are subject to approval of any reclamation district which includes within its boundaries the area to be served. The ownership, operation, and maintenance of diversion works and overland facilities shall be the subject of a separate agreement between the Agency or its transferees and the State.

6. **Flow Impact.** The State shall not convey SWP water so as to cause a decrease or increase in the natural flow, or reversal of the natural flow direction, or to cause the water surface elevation in Delta channels to be altered, to the detriment of Delta channels or water users within the Agency. If lands, levees, embankments, or revetments adjacent to Delta channels within the Agency incur seepage or erosion damage or if diversion facilities must be modi-

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fied as a result of altered water surface elevations as a result of the conveyance of water from the SWP to lands outside the Agency after the date of this contract, the State shall repair or alleviate the damage, shall improve the channels as necessary, and shall be responsible for all diversion facility modifications required.

7. **Place of Use of Water.**

(a) Any subcontract entered into pursuant to Article 18 shall provide that water diverted under this contract for use within the Agency shall not be used or otherwise disposed of outside the boundaries of the Agency by the subcontractor.

(b) Any subcontract shall provide that all return flow water from water diverted within the Agency under this contract shall be returned to the Delta channels. Subject to the provisions of this contract concerning the quality and quantity of water to be made available to water users within the Agency, and to any reuse or recapture by water users within the Agency, the subcontractor relinquishes any right to such return flow, and as to any portion thereof which may be attributable to the SWP, the subcontractor recognizes that the State has not abandoned such water.

(c) If water is attempted to be used or otherwise disposed of outside the boundaries of the Agency so that the State's rights to return flow are interfered with, the State may seek appropriate administrative or judicial action against such use or disposal.

(d) This article shall not relieve any water user of the responsibility to meet discharge regulations legally imposed.

8. **Scope of Contract.**

(a) During the term of this contract:

(i) This contract shall constitute the full and sole agreement between the State and the Agency as to (1) the quality of water which shall be in the Delta channels, and (2) the payment for the assurance given that water of such quality shall be in the Delta channels for reasonable and beneficial uses on lands within the Agency, and said diversions and uses shall not be disturbed or challenged by the State so long as this contract is in full force and effect.

(ii) The State recognizes the right of the water users of the Agency to divert from the Delta channels for reasonable and beneficial uses for agricultural, municipal and industrial purposes on lands within the Agency, and said diversions and uses shall not be disturbed or challenged by the State so long as this contract is in full force and effect, and the State shall furnish such water as may be required within the Agency to the extent not otherwise available under the water rights of water users.

(iii) The Agency shall not claim any right against the State in conflict with the provisions hereof so long as this contract remains in full force and effect.

(b) Nothing herein contained is intended to or does limit rights of the Agency against others than the State, or the State against any person other than the Agency and water users within the Agency.

(c) This contract shall not affect, bind, prejudice, impair, restrict, or limit vested water rights within the Agency.

(d) The Agency agrees to defend affirmatively as reasonable and beneficial the water qualities established in this contract. The State agrees to defend affirmatively as reasonable and beneficial the use of water required to provide and sustain the qualities established in this contract. The State agrees that such use should be examined only after determination by a court of competent jurisdiction that all uses of water exported from the Delta by the State and by the United States, for agricultural, municipal, and industrial purposes are reasonable and beneficial, and that irrigation practices, conservation efforts, and groundwater management within areas served by such exported water should be examined in particular.

(e) The Agency consents to the State's export of water from the Delta so long as this contract remains in full force and effect and the State is in compliance herewith.

9. **Term of Contract.**

(a) This contract shall continue in full force and effect until such time as it may be terminated by the written consent and agreement of the parties hereto, provided that 40 years after execution of this contract and every 40 years thereafter, there shall be a six-month period of adjustment during which any party to this contract can negotiate with the other parties to revise the contract as to the provisions set out in Article 10. If, during this period, agreement as to a requested revision cannot be achieved, the parties shall petition a court of competent jurisdiction to resolve the issue as to the appropriate payment to be made under Article 10. In revising Article 10, the court shall review water quality and supply conditions within the Agency under operation of the FCVP and SWP, and identify any reimbursable benefits allocated to water users within the Agency resulting from operation of the FCVP and SWP, offset by any detriments caused thereby. Until such time as any revision is final, including appeal from any ruling of the court, the contract shall remain in effect as without such revision.

(b) In the event this contract terminates, the parties' water rights to quality and quantity shall exist as if this contract had not been entered into.

10. **Amount and Method of Payment for Water.**

(a) The Agency shall pay each year as consideration for the assurance that an adequate water supply and the specific water quality set forth in this contract will be maintained and monitored, the sum of one hundred seventy thousand dollars ($170,000.00). The annual payments shall be made to the State one-half on or before January 1 and one-half on or before July 1 of each year commencing with January 1, 1982.

(b) The payment established in (a) above shall be subject to adjustment as of January 1, 1987, and every fifth year thereafter. The adjusted payment shall bear the same relation to the payment specified in (a) above that the mean of the State's latest projected Delta Water Rate for the five years beginning with the year of adjustment bears to $10.00 per acre foot; provided that, no adjusted payment shall exceed the previous payment by more than 25 percent.

(c) The payments provided for in this article shall be deposited by the State in trust in the California Water Resources Development System Revenue Account in the California Water Resources Development Bond Fund. The trust shall continue for five years (or such longer period as the State may determine) but shall be terminated when the United States executes a contract as provided in Article 11 with the State and the Agency at which time the proportion of the trust fund that reflects the degree to which the operation of the FCVP has contributed to meeting the water quality standard under this contract as determined solely by the State shall be paid to the United States (with a pro rata share of interest). In the event that the United States has not entered into such a contract before the termination of the trust, the trust fund shall become the sole property of the State.

11. **Participation of the United States.** The Agency will exercice its best efforts to secure United States joinder and concurrence with the terms of this contract and the State will diligently attempt to obtain the joinder and concurrence of the United States with the terms of this contract and its participation as a party hereto. Such concurrence and participation by the United States in this contract shall include a recognition ratified by the Congress that the excess land provisions of Federal reclamation law shall not apply to this contract.

12. **Remedies.**

(a) The Agency shall be entitled to obtain specific perfor-

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mance of the provisions of this contract by a decree of the Superior Court in Sacramento County requiring the State to meet the standards set forth in this contract. If the water quality in Delta channels falls below that provided in this contract, then, at the request of the Agency, the State shall cease all diversions to torage in SWP reservoirs or release stored water from SWP reservoirs or cease all export by the SWP from Delta channels, or any combination of these, to the extent that such action will further State compliance with the water quality standards set forth in this contract, except that the State may continue to export from Delta channels to the extent required to meet water quality requirements in contracts with the Delta agencies specified in Section 11456 of the California Water code.

(b) To the extent permitted by law, the State agrees to forego the use of eminent domain proceedings to acquire water rights of water users within the Agency or any rights acquired under this contract for water or water quality maintenance for the purpose of exporting such water from the Delta. This provision shall not be construed to prohibit the utilization of eminent domain proceedings for the purpose of acquiring land or any other rights necessary for the construction of water facilities.

(c) Except as provided in the water quality assurances in Article 2 and the provisions of Article 6 and Article 8, neither the State nor its officers, agents, or employees shall be liable for or on account of:

(i) The control, carriage, handling, use, disposal, or distribution of any water outside the facilities constructed, operated and maintained by the State.

(ii) Claims of damage of any nature whatsoever, including but not limited to property loss or damage, personal injury or death arising out of or connected with the control, carriage, handling, use, disposal or distribution of any water outside of the facilities constructed, operated and maintained by the State.

(d) The use by the Agency or the State of any remedy specified herein for the enforcement of this contract is not exclusive and shall not deprive either from using any other remedy provided by law.

13. **Comparable Treatment.** In the event that the State gives on the whole substantially more favorable treatment to any other Delta entity under similar circumstances than that accorded under this contract to the Agency, the State agrees to renegotiate this contract to provide comparable treatment to the Agency under this contract.

GENERAL PROVISIONS

14. **Amendments.** This contract may be amended or terminated at any time by mutual agreement of the State and the Agency.

15. **Reservation With Respect to State Laws.** Nothing herein contained shall be construed as estopping or otherwise preventing the Agency, or any person, firm, association, corporation, or public body claiming by, through, or under the Agency, from contesting by litigation or other lawful means, the validity, constitutionality, construction or application of any law of the State of California.

16. **Opinions and Determinations.** Where the terms of this contract provide for action to be based upon the opinion, judgment, approval, review, or determination of either party hereto, such terms are not intended to be and shall never be construed as permitting such opinion, judgment, approval, review, or determination to be arbitrary, capricious, or unreasonable.

17. **Successors and Assigns Obligated.** This contract and all of its provisions shall apply to and bind the successors and assigns of the parties hereto.

18. **Assignment and Subcontract.** The Agency may enter into subcontracts with water users within the Agency boundaries in which the assurances and obligations provided in this contract as to such water user or users are assigned to the area covered by the subcontract. The Agency shall remain primarily liable and shall make all payments required under this contract. No assignment or transfer of this contract, or any part hereof, rights hereunder, or interest herein by the Agency, other than a subcontract containing the same terms and conditions, shall be valid unless and until it is approved by the State and made subject to such reasonable terms and conditions as the State may impose. No assignment or transfer of this contract or any part hereof, rights hereunder, or interest herein by the State shall be valid except as such assignment or transfer is made pursuant to and in conformity with applicable law.

19. **Books, Records, Reports, and Inspections Thereof.** Subject to applicable State laws and regulations, the Agency shall have full and free access at all reasonable times to the SWP account books and official records of the State insofar as the same pertain to the matters and things provided for in this contract, with the right at any time during office hours to make copies thereof, and the proper representatives of the State shall have similar rights with respect to the account books and records of the Agency.

20. **Waiver of Rights.** Any waiver at any time by either party hereto of its rights with respect to a default, or any other matter arising in connection with this contract, shall not be deemed to be a waiver with respect to any other default or matter.

21. **Assurance Relating to Validity of Contract.** This contract shall be effective after its execution by the Agency and the State. Promptly after the execution and delivery of this contract, the Agency shall file and prosecute to a final decree, including any appeal therefrom to the highest court of the State of California, in a court of competent jurisdiction a special proceeding for the judicial examination, approval, and confirmation of the proceedings of the Agency's Board of Directors and of the Agency leading up to and including the making of this contract and the validity of the provisions thereof as a binding and enforceable obligation upon the State and the Agency. If, in this proceeding or other proceeding before a court of competent jurisdiction, any portion of this contract should be determined to be constitutionally invalid, then the remaining portions of this contract shall remain in full force and effect unless modified by mutual consent of the parties.

22. **Notices.** All notices that are required either expressly or by implication to be given by one party to the other shall be deemed to have been given if delivered personally or if enclosed in a properly addressed, postage prepaid, envelope and deposited in a United States Post Office. Unless or until formally notified otherwise, the Agency shall address all notices to the State as follows:

Director, Department of Water Resources
P.O. Box 388
Sacramento, California 95802

and the State shall address all notices to the Agency as follows:

North Delta Water Agency
921 - 11th St., Rm. 703
Sacramento, California 95814

IN WITNESS WHEREOF, the parties hereto have executed this contract on the date first above written.

Approved as to legal form and sufficiency:	STATE OF CALIFORNIA
By /s/ P. A. TOWNER Chief Counsel Dept. of Water Resources	By /s/ RONALD B. ROBIE Dept. of Water Resources
Approved as to legal form and sufficiency:	NORTH DELTA WATER AGENCY
By /s/ GEORGE BASYE General Counsel North Delta Water Agency	By /s/ W. R. DARSIE Chairman Board of Directors

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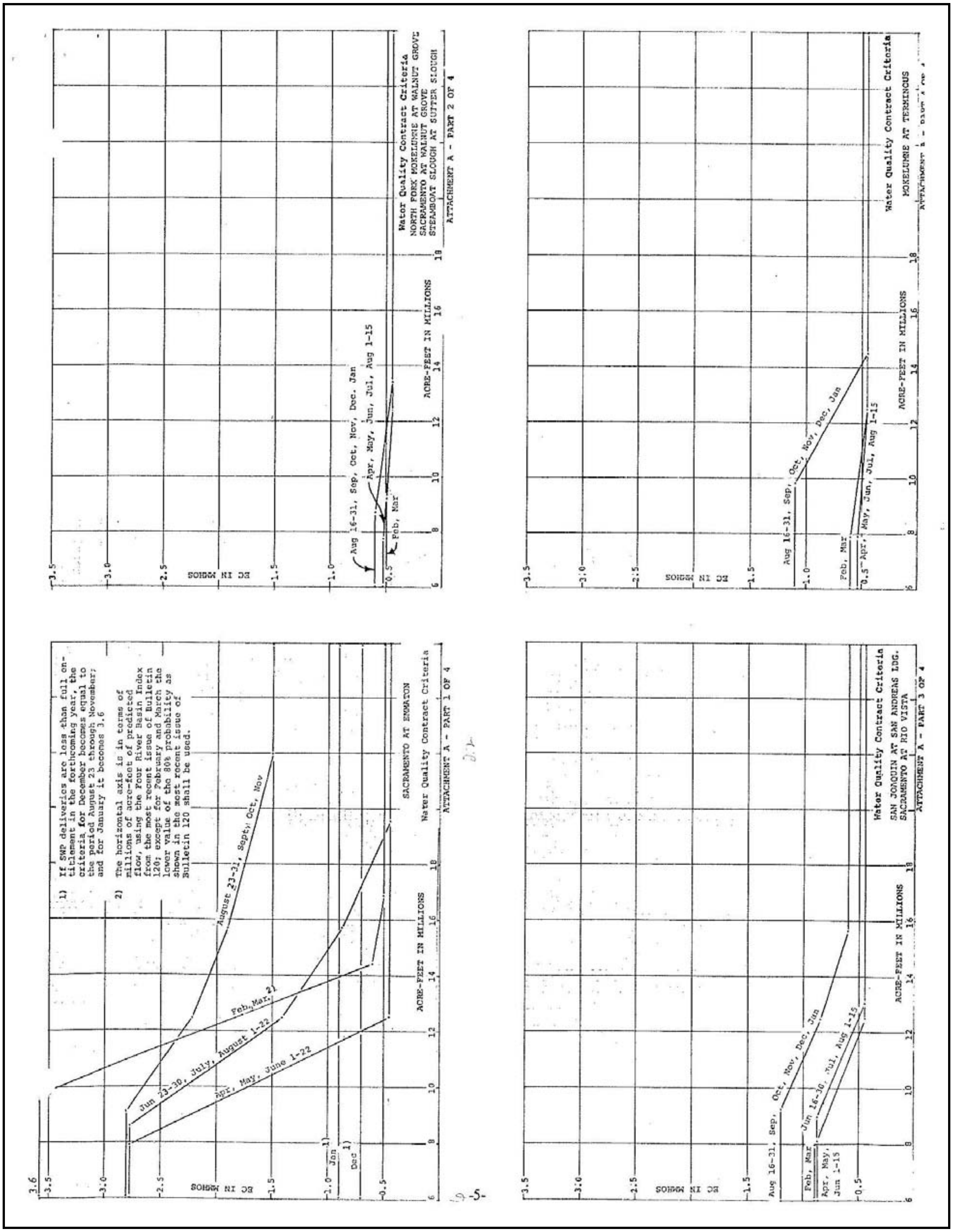

Water Quality Contract Criteria
SACRAMENTO AT EMMATON
ATTACHMENT A - PART 1 OF 4
1) If SWP deliveries are less than full entitlement in the forthcoming year, the criteria for December becomes equal to the period August 23 through November; and for January it becomes 3.6
2) The horizontal axis is in terms of millions of acre-feet of predicted flow, using the Four River Basin Index from the most recent issue of Bulletin 120; except for February and March the lower value of the 80% probability as shown in the most recent issue of Bulletin 120 shall be used.
Water Quality Contract Criteria
NORTH FORK MOKELUMNE AT WALNUT GROVE
SACRAMENTO AT WALNUT GROVE
STEAMBOAT SLOUGH AT SUTTER SLOUGH
ATTACHMENT A - PART 2 OF 4
Water Quality Contract Criteria
SAN JOAQUIN AT SAN ANDREAS LDG.
SACRAMENTO AT RIO VISTA
ATTACHMENT A - PART 3 OF 4
Water Quality Contract Criteria
MOKELUMNE AT TERMINOUS
ACRE-FEET IN MILLIONS
EC IN MMHOS
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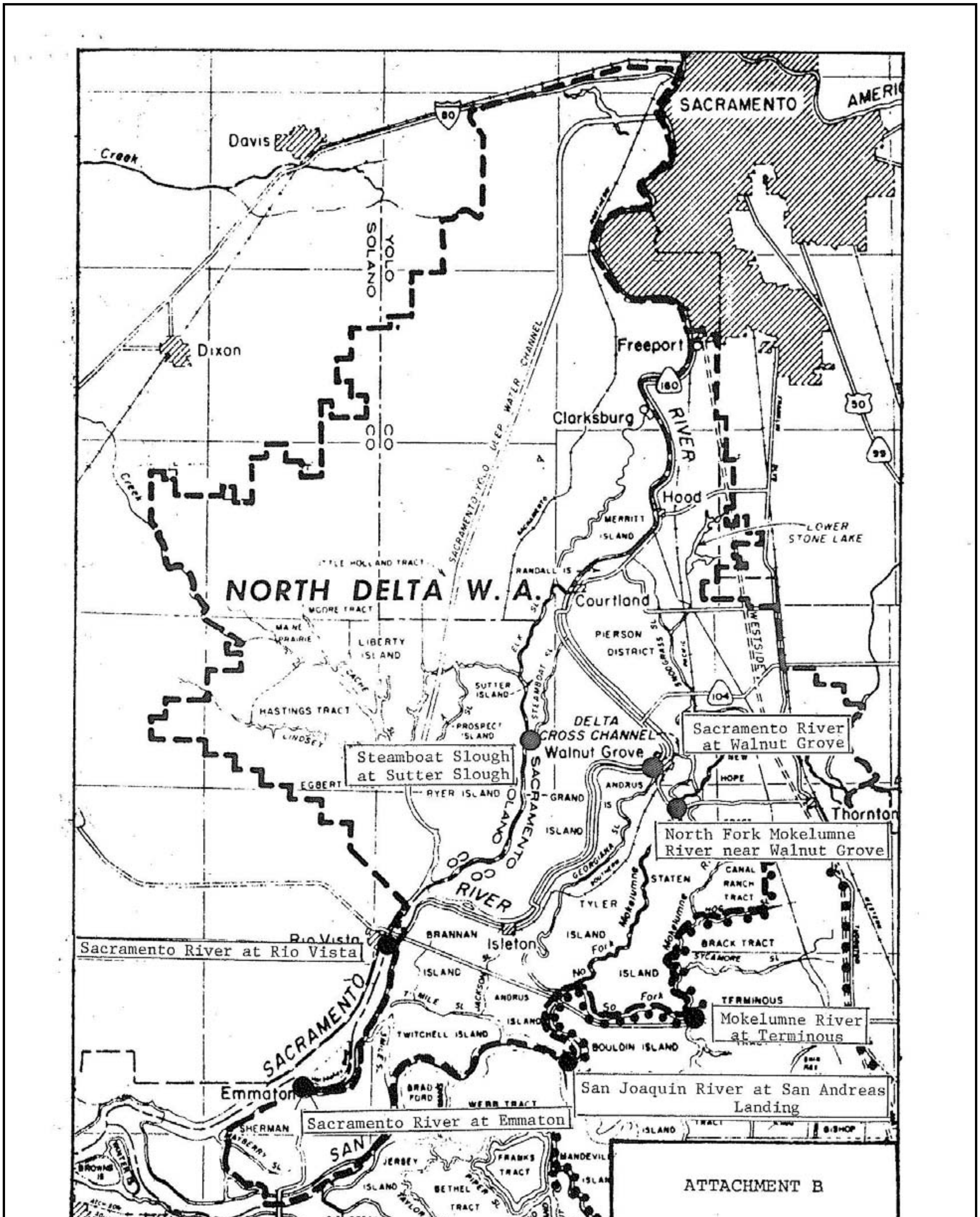
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Davis
YOLO
SOLANO
Dixon
Freeport
Clarksburg
RIVER
Hood
LOWER STONE LAKE
NORTH DELTA W. A.
Courtland
PIERSON DISTRICT
LIBERTY ISLAND
HASTINGS TRACT
SUTTER ISLAND
PROSPECT ISLAND
DELTA CROSS CHANNEL
Walnut Grove
Sacramento River at Walnut Grove
Steamboat Slough at Sutter Slough
RYER ISLAND
GRAND ISLAND
ANDRUS
Thornton
North Fork Mokelumne River near Walnut Grove
STATEN
TYLER ISLAND
SACRAMENTO
RIVER
Rio Vista
Sacramento River at Rio Vista
BRANNAN
Isleton
ISLAND
ANDRUS ISLAND
BRACK TRACT
TERMINOUS
Mokelumne River at Terminous
TWITCHELL ISLAND
BOULDIN ISLAND
San Joaquin River at San Andreas Landing
SACRAMENTO
Emmaton
Sacramento River at Emmaton
SHERMAN
WEBB TRACT
JERSEY
BETHEL TRACT
FRANKS TRACT
ATTACHMENT B

-6-

Exhibit II – 1979 Memorandum

NDWA Directors November 2, 1979

D. E. Kienlen

Water Quality Criteria Graphs and Ramping

In accordance with your request during your meeting on October 3, I am submitting further information on the use of graphs to define the water quality criteria for the NDWA and the suggested ramping criteria under the proposed contract with the State.

Water Quality Criteria Graphs

The water quality criteria set forth in Table A (1)* provides for substantial changes in water quality at some locations between different types of years. Since the year type forecast (2) is an estimate of runoff based on prior precipitation, snow pack, and future precipitation, a small difference can change the type of year and can result in substantial changes in water quality. In order to eliminate any pressure in making the forecast and also to eliminate the large water quality changes, DWR has developed a set of graphs to define the quality within the NDWA. These graphs are based on the Table A water quality criteria but provide for a uniform change depending on the estimated runoff.

The attached set of graphs (3) shows the proposed criteria as developed by DWR on which the divisions between the type of years corresponding to Table A are shown. In order to illustrate the procedure used to develop the graphs two additional graphs for Emmaton are attached (4) and (5).

Graph (4) is for the period June 23 through August 15. (Note that June 23-30 has been included with July and August but June 1-22 has been included with April and May. This reduces the June variations and simplifies the criteria. The dashed stepped line on (4) shows the criteria given in Table A for this period. The hatched triangles above the solid line show improved water quality from that given in Table A and the shadded triangles below the solid line show reduced water quality from that given in Table A.

---

* Number in parenthesis refers to attachment.

Memorandum to NDWA Directors November 2, 1979
Re: Water Quality Criteria Graphs and Ramping.

-2-

As may be seen, there is a good balance between the areas indicating a nearly equal split between improvements and detriments. However, improvements result in reducing the flow at the point of the poorest water quality. For example, an EC of 2.78 under Table A occurs at a flow of 10,200,000 AF (10.2 MAF) but with the graph this value is not reached until 8.9 MAF.

Graph (5) shows similar results for the period August 16 through November 30. All other graphs were prepared in a similar manner and provide equivalent results.

In my opinion, the graphs are an improvement over Table A and the elimination of the pressure to define the type of year is important for future operation. In addition, the poorest quality is not reached until there is lower runoff or flow. Therefore I recommend that you accept the graphs to define water quality criteria within NDWA.

There will be an additional advantage in using the graphs. The contract as presently drafted indicates that the best quality will prevail as either established by the contract criteria or Decision 1485 of the State Water Resources Control Board. This means that until the Board modifies Decision 1485, during the period April 1 through August 15 NDWA would receive the improvements shown by the hatched triangles above the solid line but would not receive the reduced quality shown by the shaded triangles below the solid line on Graphs (4) and (5).

Ramping

The water quality criteria can result in a substantial change from one day to the next. From a practical operation standpoint this is impossible to obtain. To overcome this point DWR is proposing a ramping criteria which will provide for a uniform transition from one criteria to the next. The proposal originally was for a four-week period which we said was unacceptable. We finally arrived at a two-week period beginning one week before the date of change and ending one week later. Graph (6) shows an example of ramping with an assumed four river runoff of 13.0 MAF. The dashed line shows the criteria from the graphs on sheet 1 of (3). The solid lines show the uniform transition brought about by ramping over a two-week period.

Without a ramping criteria the 14-day average will permit some flexibility to DWR but most of the change or ramping will have to occur before and after the better quality criteria. There is no

Memorandum to NDWA Directors November 2, 1979
Re: Water Quality Criteria Graphs and Ramping.

-3-

doubt that the ramping both reduces and improves quality in equal amounts and in that respect is fair. A more important point, however, is what effect it may have during the growing season. If there may be an effect, the ramping should not be accepted. An alternative may be to accept ramping outside of the main growing season of April through August.

D. E. Kienlen

cc: Mr. G. L. Renoud
Mr. George Basye

(1)

TABLE A

NORTH DELTA WATER AGENCY
AGRICULTURAL WATER QUALITY STANDARDS

Maximum 14-day running average of mean daily EC in mmhos.

Period	Wet	Above Normal	Below Normal	Dry	Critical
	Type of Year1/				
Sacramento River at Emmaton					
Feb. 1 to Apr. 1 2/	0.5	0.5	0.6	3.0	3.6
Apr. 1 to June 1	0.45	0.45	0.45	0.45	2.78
June 1 to July 1	0.45	0.45	--	--	2.78
July 1 to Aug. 15	0.45	0.63	--	--	2.78
June 1 to June 20	--	--	0.45	--	--
June 20 to Aug. 15	--	--	1.14	--	--
June 1 to June 15	--	--	--	0.45	--
June 15 to Aug. 15	--	--	--	1.67	--
Aug. 15 to Dec. 1	1.5	1.8	2.0	2.4	2.8
Dec. 1 to Jan. 1 3/	0.7	0.7	0.7	0.7	0.7
Jan. 1 to Feb. 1 3/	0.9	0.9	0.9	0.9	0.9
San Joaquin River at San Andreas Landing; Sacramento River at Rio Vista					
Feb. 1 to Apr. 1	0.45	0.45	0.45	0.45	0.6
Apr. 1 to Aug. 15	0.45	0.45	0.45	--	0.87
Apr. 1 to June 25	--	--	--	0.45	--
June 25 to Aug. 15	--	--	--	0.58	--
Aug. 15 to Feb. 1	0.6	0.6	0.7	1.0	1.2
Mokelumne River at Terminous					
Feb. 1 to Apr. 1	0.45	0.45	0.45	0.45	0.6
Apr. 1 to Aug. 15	0.45	0.45	0.45	0.45	0.54
Aug. 15 to Feb. 1	0.45	0.45	0.45	1.0	1.1
North Fork Mokelumne River near Walnut Grove; Sacramento River at Walnut Grove; Steamboat Slough at Sutter Slough					
Feb. 1 to Apr. 1	0.45	0.45	0.45	0.45	0.5
Apr. 1 to Aug. 15	0.45	0.45	0.45	0.45	0.54
Aug. 15 to Feb. 1	0.45	0.45	0.45	0.5	0.6

1/ Type of year determined by the forecast of unimpaired runoff as published in DWR Bulletin 120 assuming normal precipitation to follow except for February and March at Emmaton. (see footnote 2)

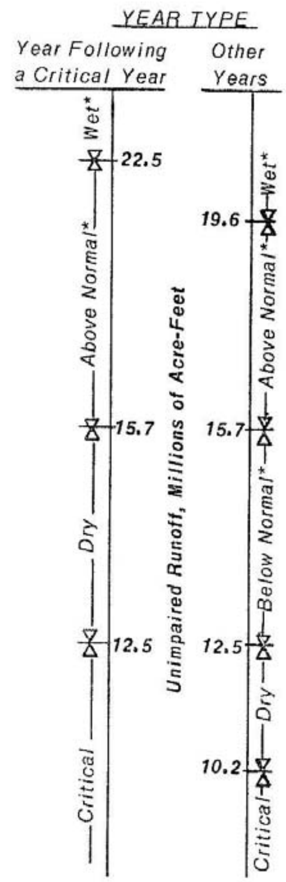
2/ Type of year determined by the forecast of unimpaired runoff using lower value of the 80% probability range from DWR Bulletin 120.

3/ If SWP deliveries are to be less than full entitlement in forthcoming year, the criteria becomes:

	Wet	Above Normal	Below Normal	Dry	Critical
Dec. 1 to Jan. 1	~~1.5~~	~~1.8~~	~~2.0~~	~~2.4~~	~~2.8~~
Jan. 1 to Feb. 1	3.6	3.6	3.6	3.6	3.6

(2)

Year classification shall be determined by the forecast of Sacramento Valley unimpaired runoff for the current water year *(October 1 of the preceding calendar year through September 30 of the current calendar year)* as published in California Department of Water Resources Bulletin 120 for the sum of the following locations: Sacramento River above Bend Bridge, near Red Bluff; Feather River, total inflow to Oroville Reservoir; Yuba River at Smartville; American River, total inflow to Folsom Reservoir. Preliminary determinations of year classification shall be made in February, March and April with final determination in May.



YEAR TYPE	RUNOFF, MILLIONS OF ACRE-FEET
Wet*	equal to or greater than 19.6 except equal to or greater than 22.5 in a year following a critical year.
Above Normal*	greater than 15.7 and less than 19.6 except greater than 15.7 and less than 22.5 in a year following a critical year
Below Normal*	equal to or less than 15.7 and greater than 12.5 except in a year following a critical year.
Dry	equal to or less than 12.5 and greater than 10.2 except equal to or less than 15.7 and greater than 12.5 in a year following a critical year.
Critical	equal to or less than 10.2 except equal to or less than 12.5 in a year following a critical year.

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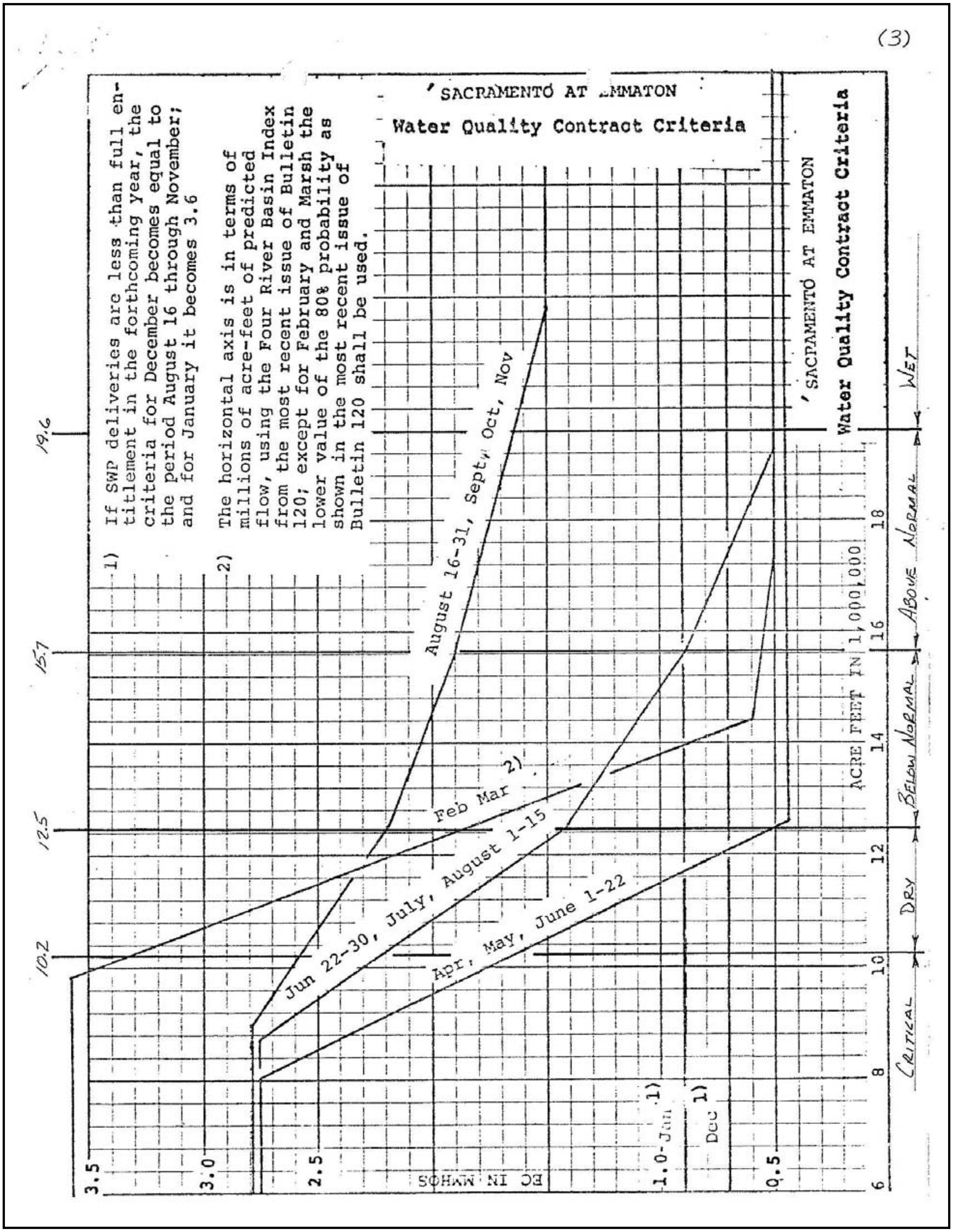
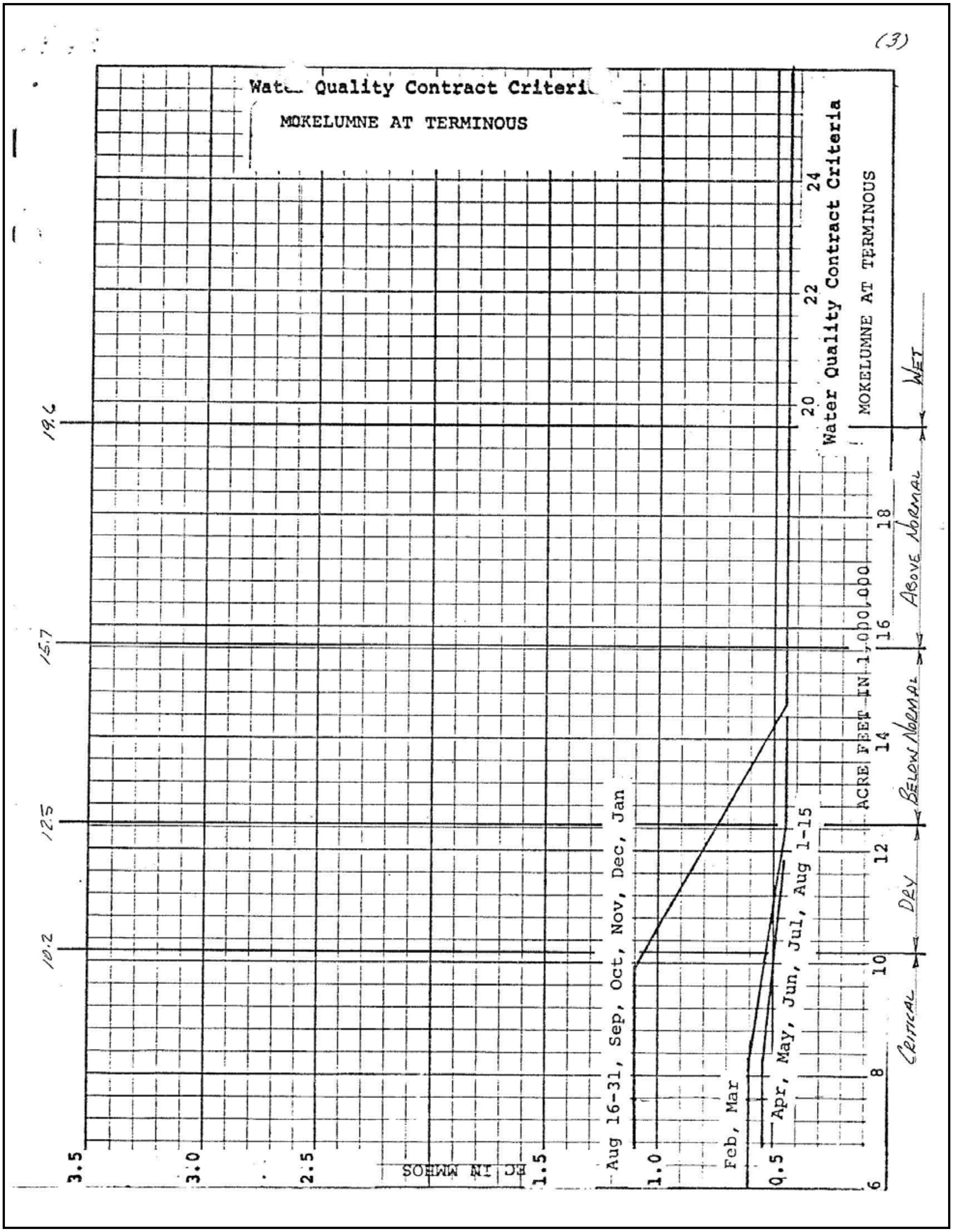
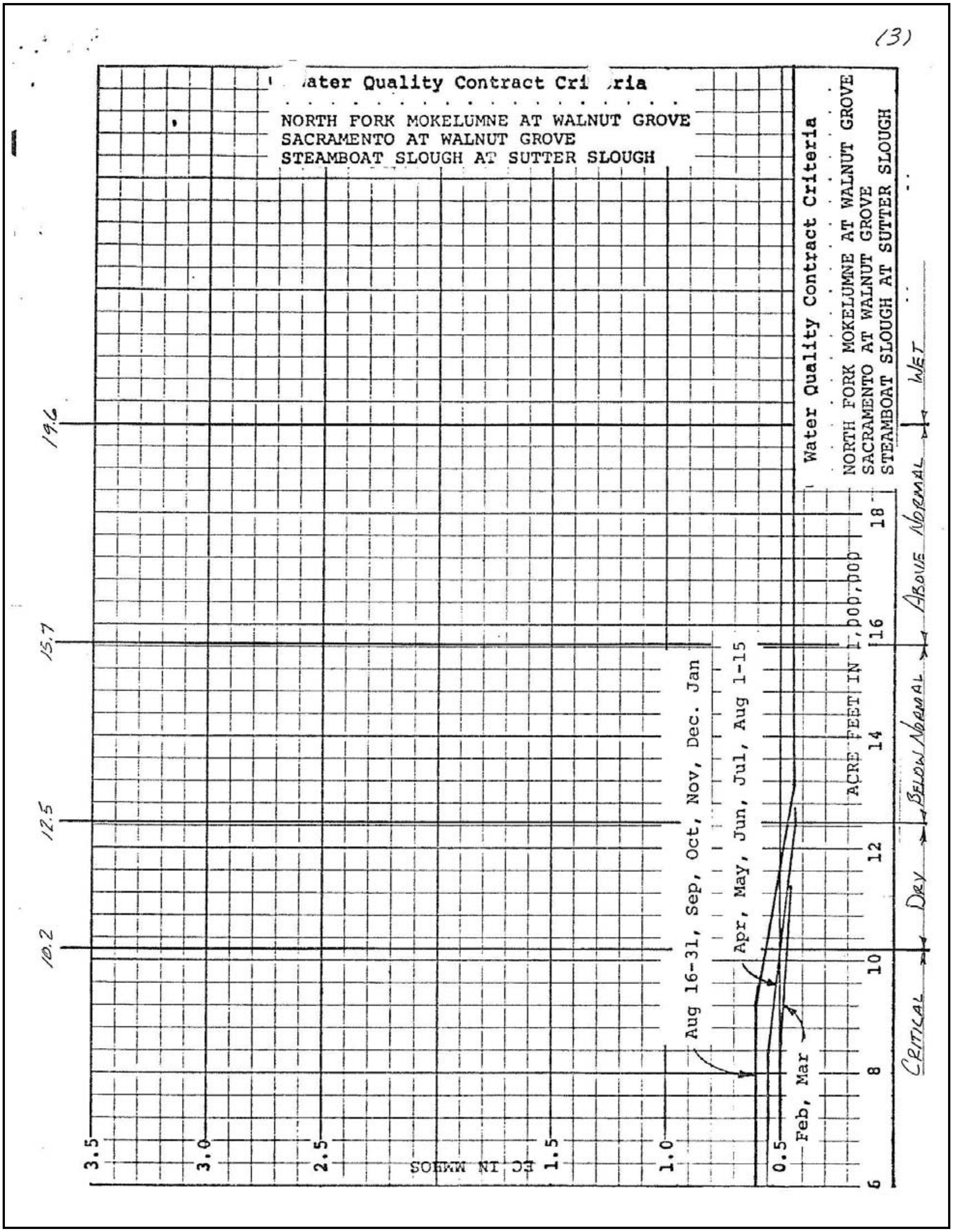
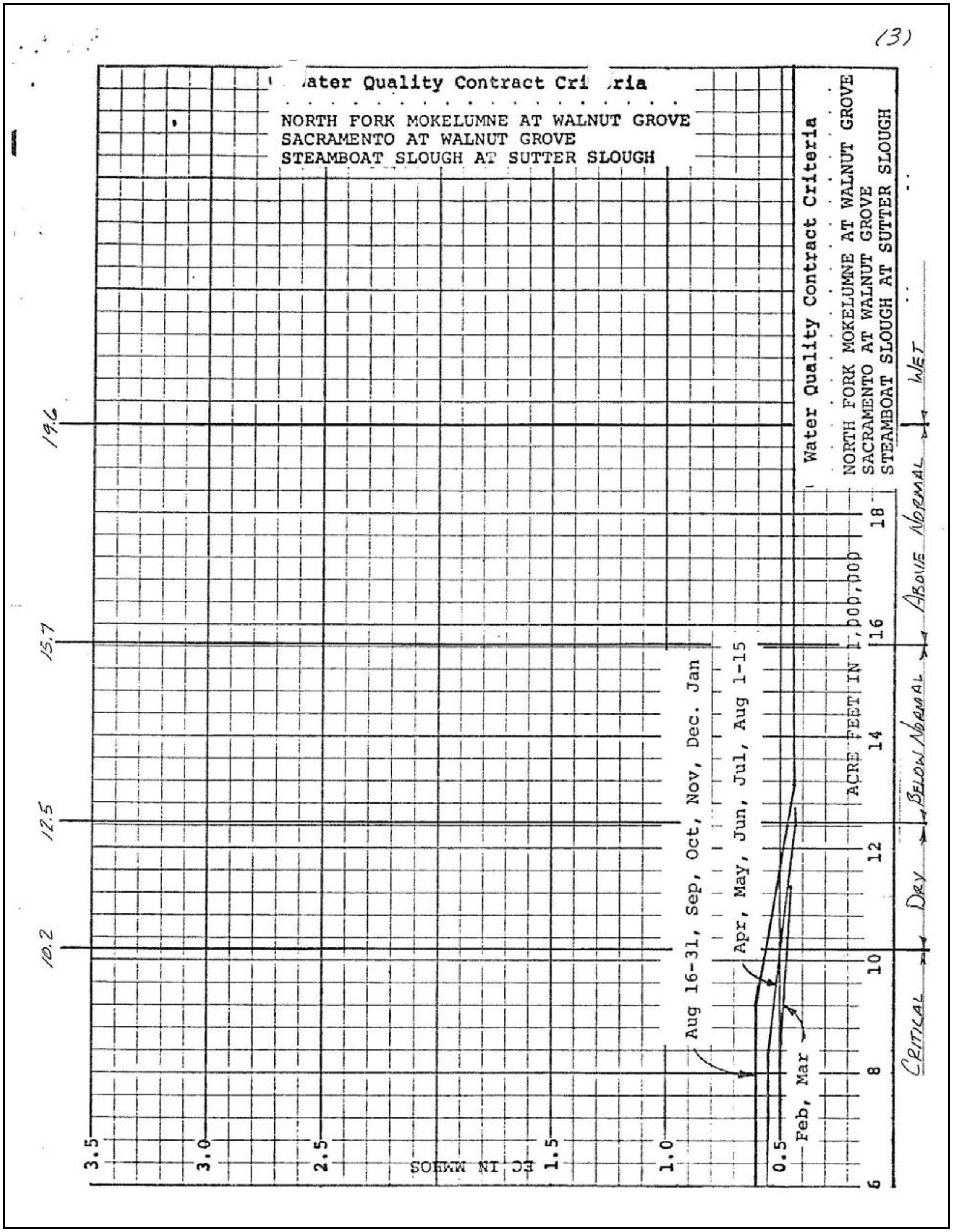
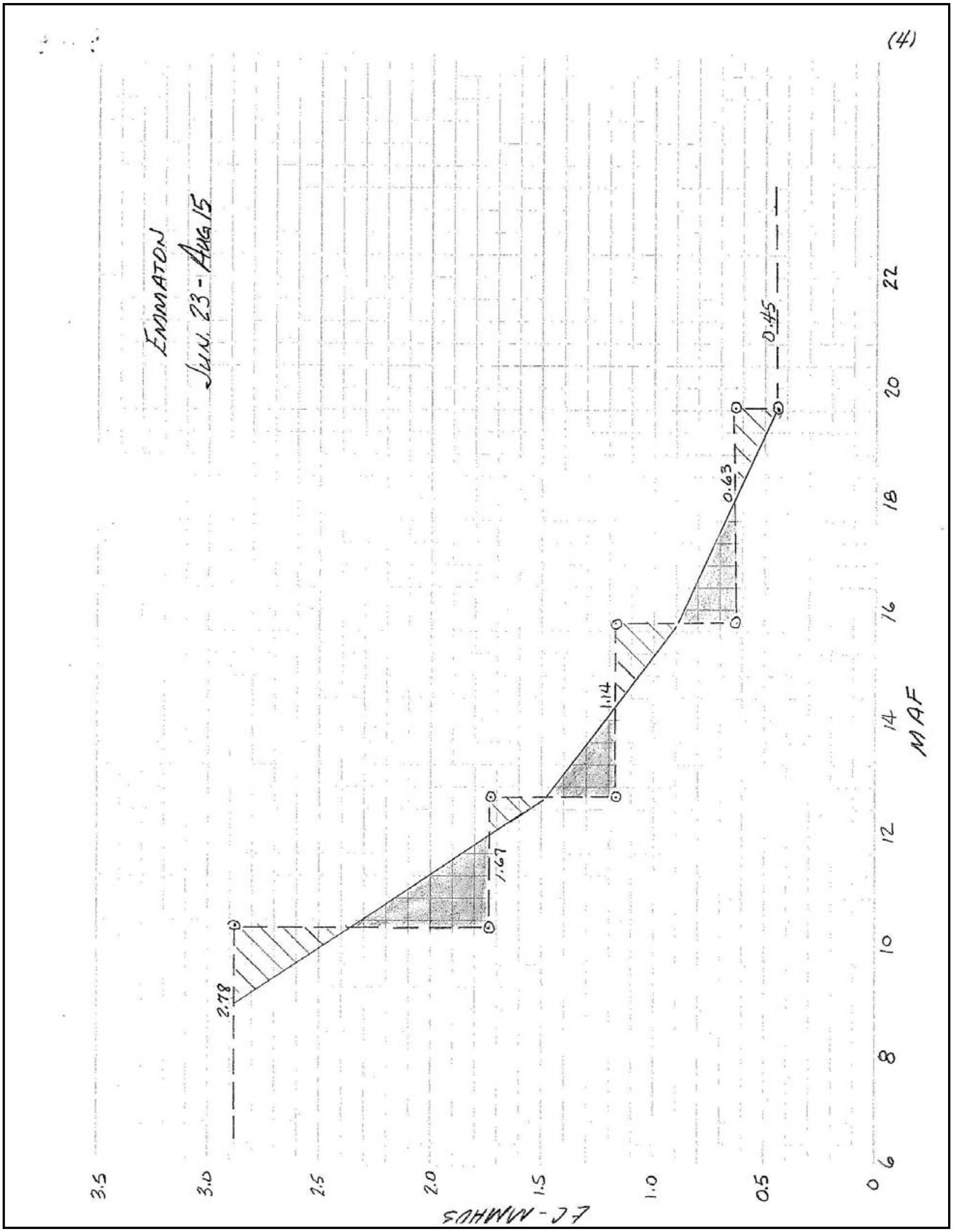
* *Any otherwise wet, above normal, or below normal year may be designated a subnormal snowmelt year whenever the forecast of April through July unimpaired runoff reported in the May issue of Bulletin 120 is less than 5.3 million acre-feet.*

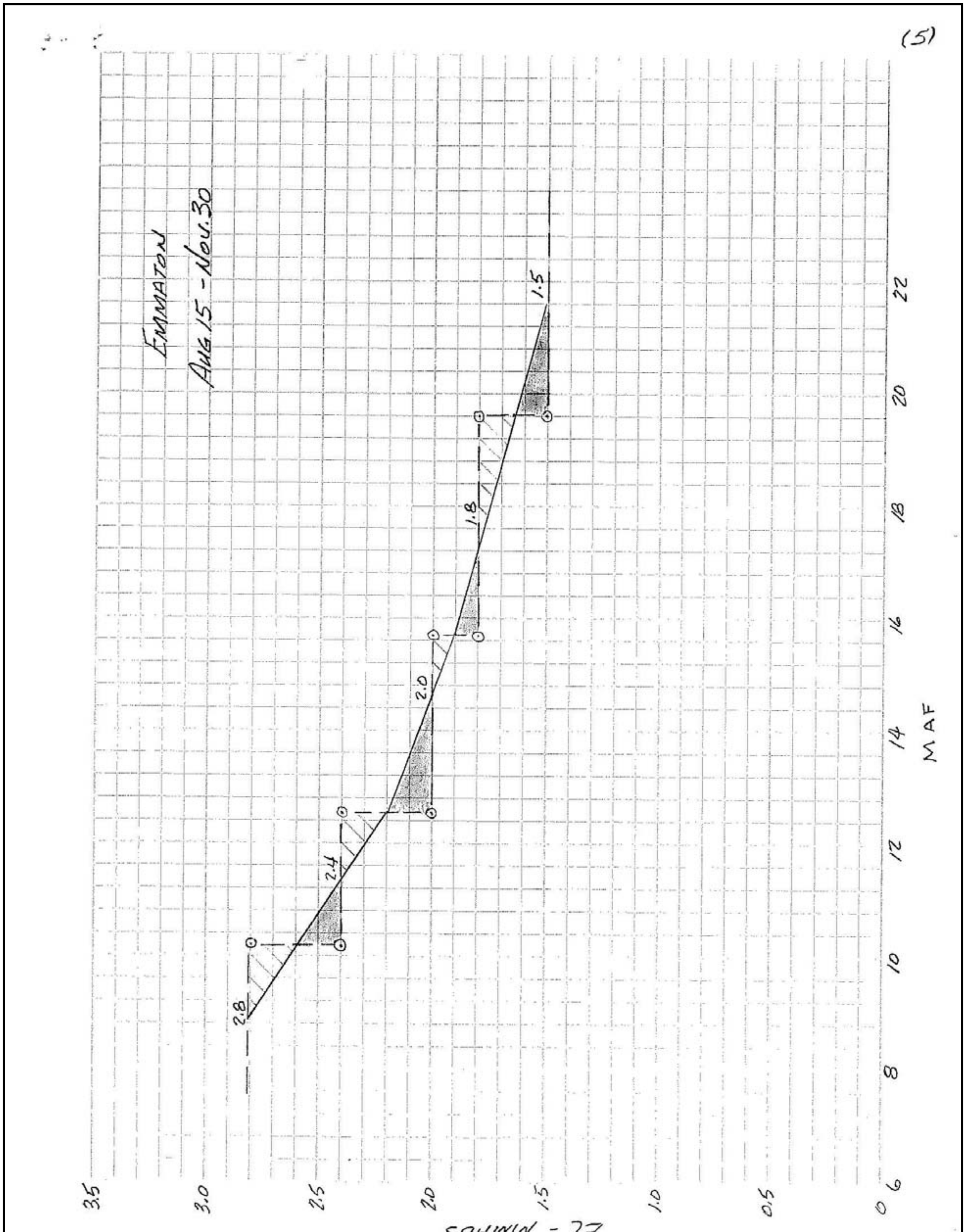

(3)
SACRAMENTO AT EMMATON
Water Quality Contract Criteria
1) If SWP deliveries are less than full entitlement in the forthcoming year, the criteria for December becomes equal to the period August 16 through November; and for January it becomes 3.6
2) The horizontal axis is in terms of millions of acre-feet of predicted flow, using the Four River Basin Index from the most recent issue of Bulletin 120; except for February and March the lower value of the 80% probability as shown in the most recent issue of Bulletin 120 shall be used.
August 16-31, Sept, Oct, Nov
Feb Mar 2)
Jun 22-30, July, August 1-15
Apr, May, June 1-22
1.0-Jan 1)
Dec 1)
EC IN MMHOS
3.5
3.0
2.5
0.5
ACRE FEET IN 1,000,000
6
8
10
12
14
16
18
10.2
12.5
15.7
19.6
CRITICAL
DRY
BELOW NORMAL
ABOVE NORMAL
WET


(3)
Water Quality Contract Criteria
MOKELUMNE AT TERMINOUS
ACRE FEET IN 1,000,000
EC IN MMHOS
Aug 16-31, Sep, Oct, Nov, Dec, Jan
Feb, Mar
Apr, May, Jun, Jul, Aug 1-15
WET
ABOVE NORMAL
BELOW NORMAL
DRY
CRITICAL
19.6
15.7
12.5
10.2
3.5
3.0
2.5
1.5
1.0
0.5
6
8
10
12
14
16
18
20
22
24


(3)
Water Quality Contract Criteria
NORTH FORK MOKELUMNE AT WALNUT GROVE
SACRAMENTO AT WALNUT GROVE
STEAMBOAT SLOUGH AT SUTTER SLOUGH
Aug 16-31, Sep, Oct, Nov, Dec. Jan
Apr, May, Jun, Jul, Aug 1-15
Feb, Mar
EC IN MMHOS
3.5
3.0
2.5
1.5
1.0
0.5
ACRE FEET IN 1,000,000
6
8
10
12
14
16
18
19.6
15.7
12.5
10.2
CRITICAL
DRY
BELOW NORMAL
ABOVE NORMAL
WET


(3)
Water Quality Contract Criteria
NORTH FORK MOKELUMNE AT WALNUT GROVE
SACRAMENTO AT WALNUT GROVE
STEAMBOAT SLOUGH AT SUTTER SLOUGH
ACRE FEET IN 1,000,000
6
8
10
12
14
16
18
EC IN MMHOS
0.5
1.0
1.5
2.5
3.0
3.5
19.6
15.7
12.5
10.2
Aug 16-31, Sep, Oct, Nov, Dec, Jan
Apr, May, Jun, Jul, Aug 1-15
Feb, Mar
CRITICAL
DRY
BELOW NORMAL
ABOVE NORMAL
WET


(4)
EMMATON
JUN. 23 - AUG 15
MAF
EC - MMHOS
2.78
1.67
1.14
0.63
0.45
6
8
10
12
14
16
18
20
22
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5


(5)
EMMATON
AUG 15 - NOV 30
2.8
2.4
2.0
1.8
1.5
6
8
10
12
14
16
18
20
22
MAF
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
EC - MMHOS

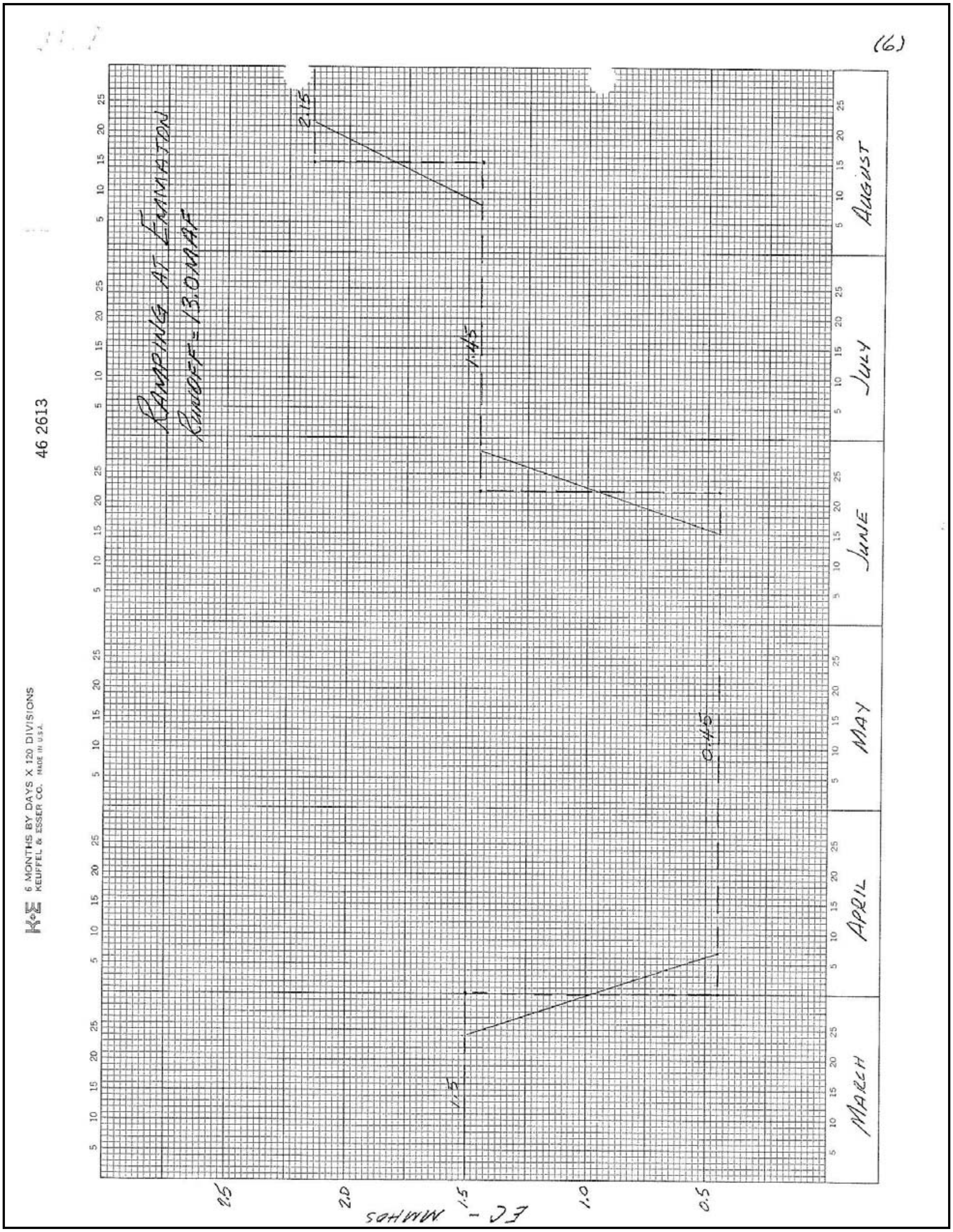

(6)
46 2613
K+E 6 MONTHS BY DAYS X 120 DIVISIONS
KEUFFEL & ESSER CO.
RAMPING AT EMMATON
RUNOFF = 13.0 MAF
2.15
1.45
0.45
1.5
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
2.5
2.0
1.5
1.0
0.5
EC - MMHOS

Exhibit III – Map of Historic Salinity Intrusion

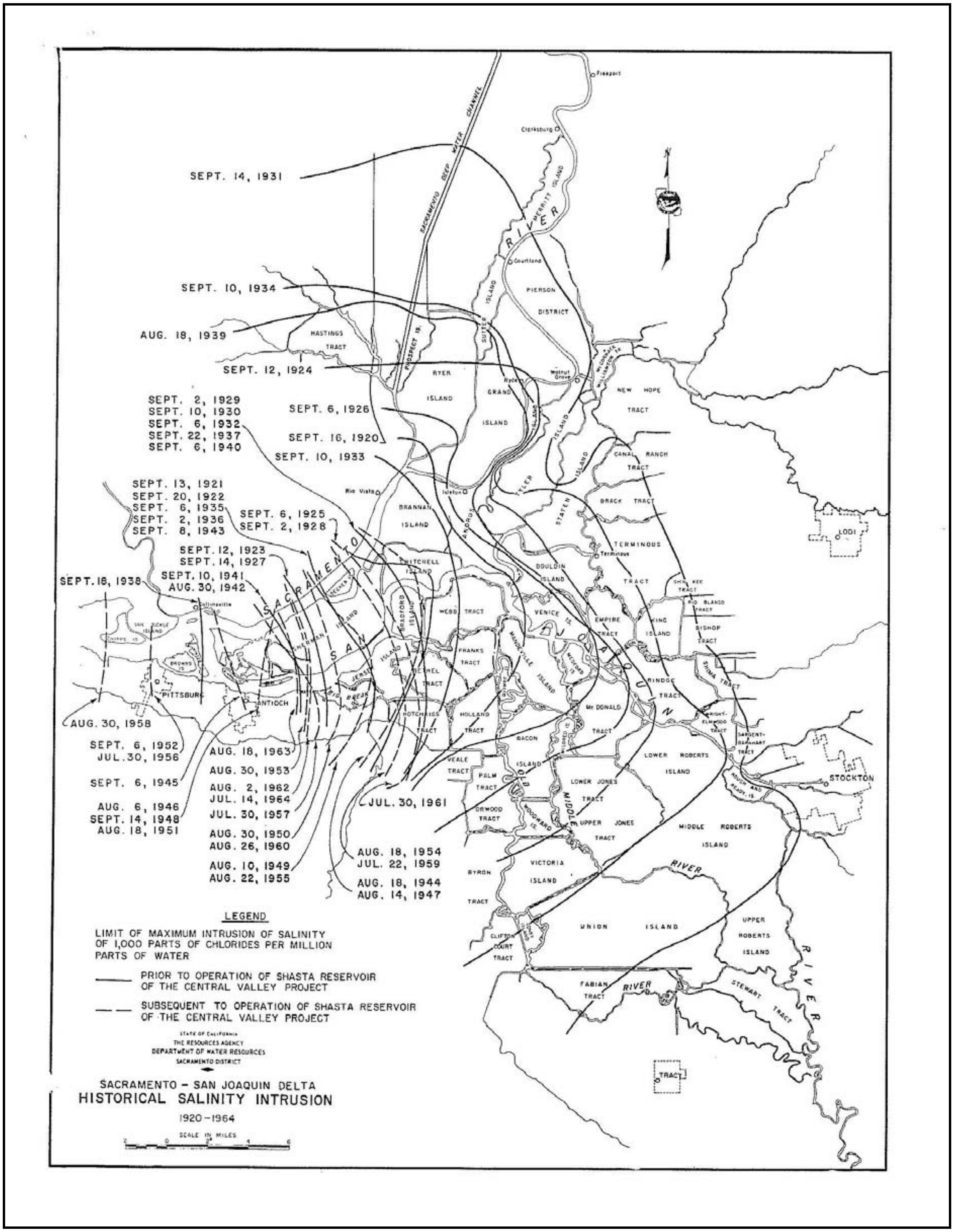
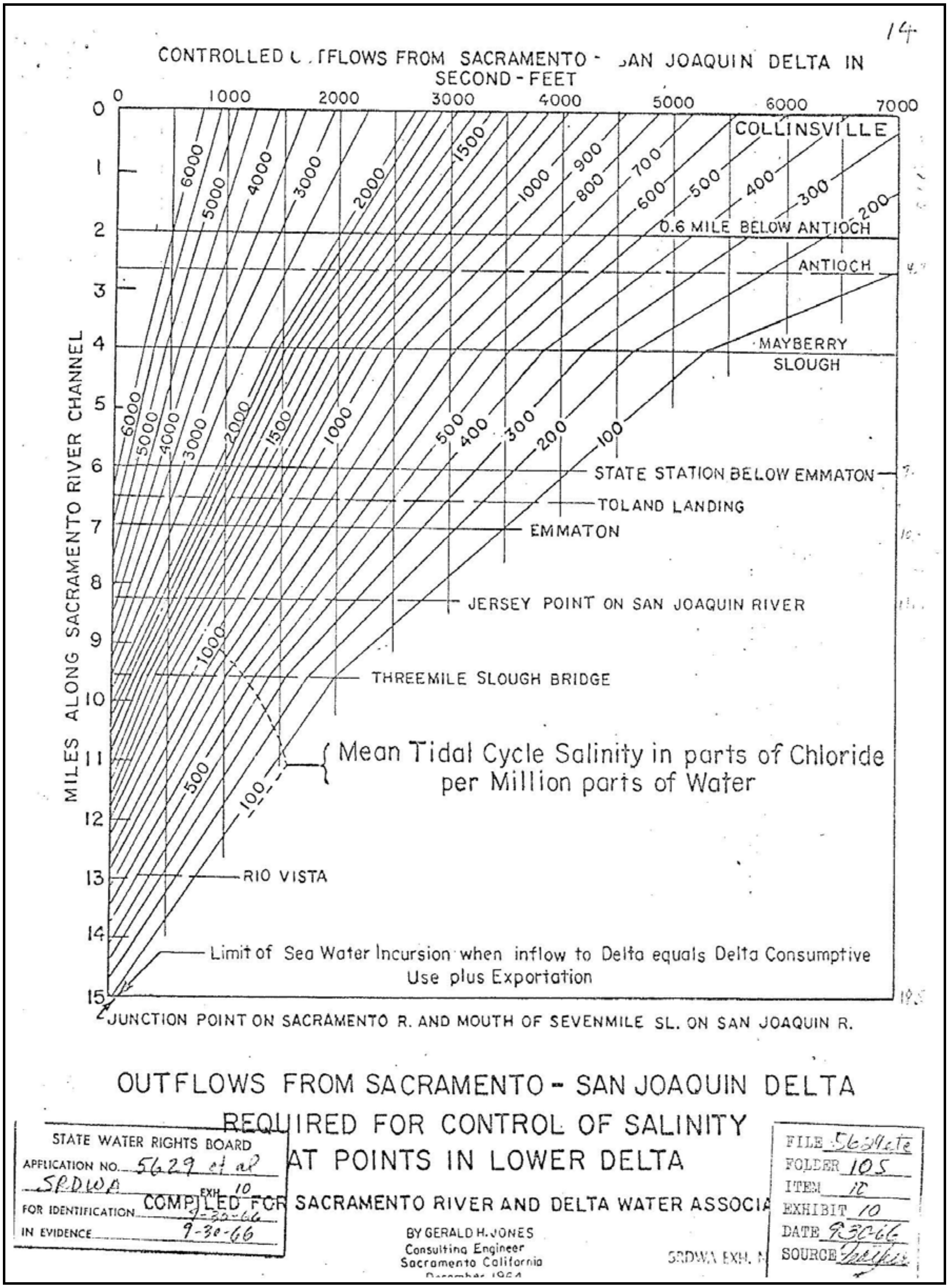
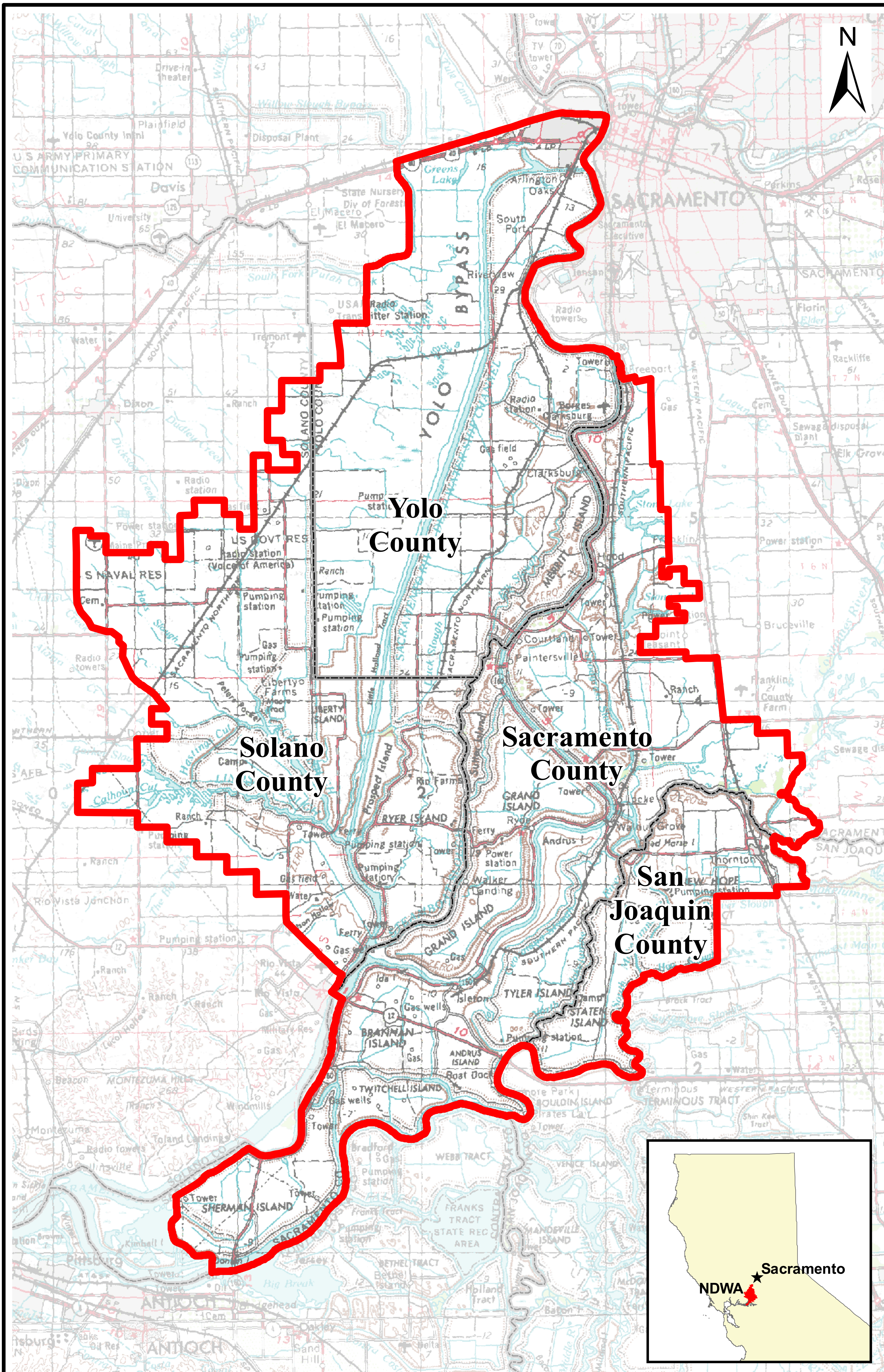


Exhibit IV – Outflow from Sacramento-San Joaquin Delta for Control of Salinity at Points in Lower Delta



MAPS

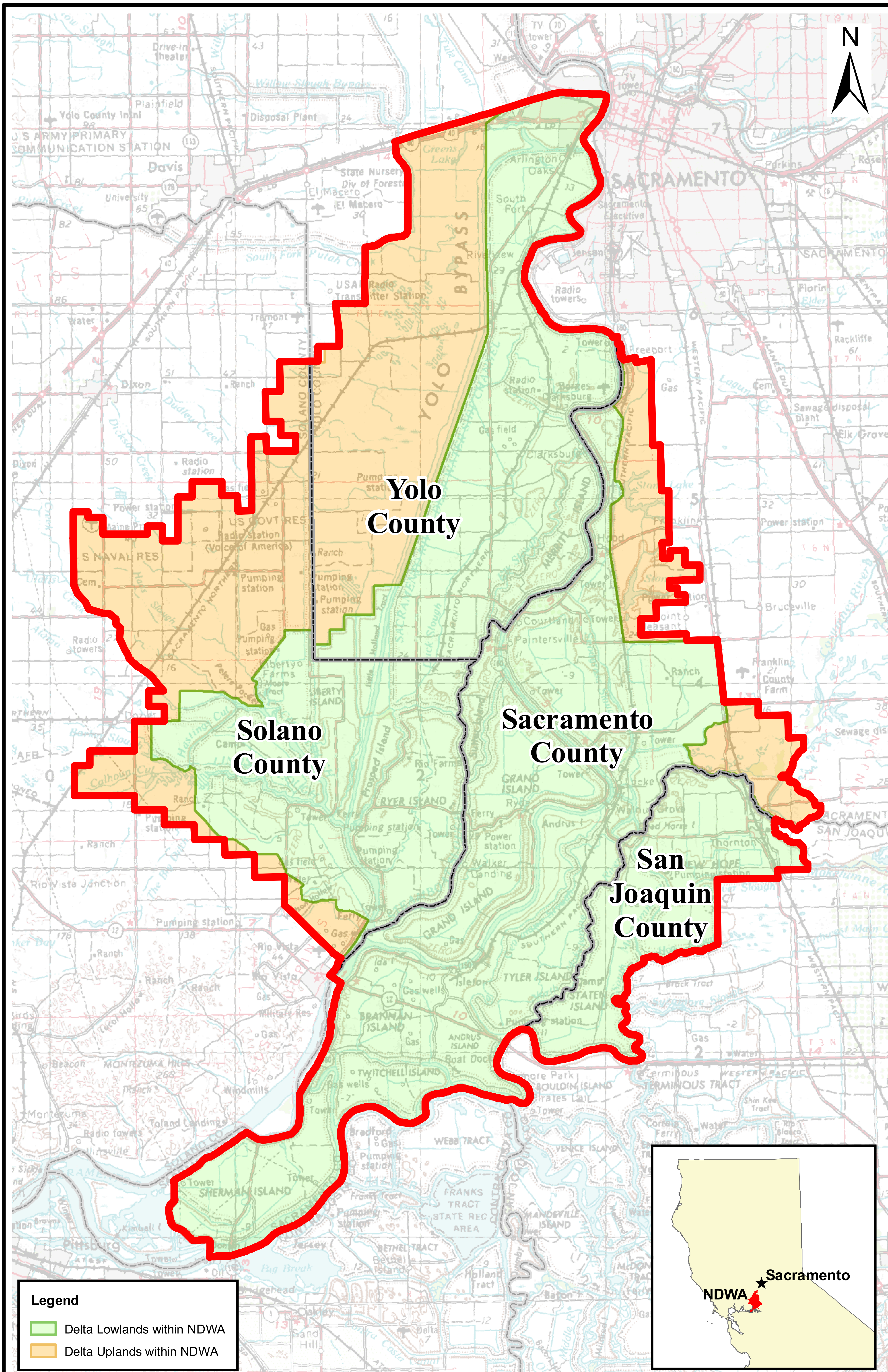
LIST OF MAPS



MBK ENGINEERS
1771 Tribute Road, Suite A
Sacramento, California 95815-4401
(916) 456-4400

Map 1 - Boundary of North Delta Water Agency

0 1.5 3
Scale in Miles



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Map 2 - Delta Upland and Lowland Areas within the North Delta Water Agency

0 1.5 3
Scale in Miles

WATER AND ENERGY SECTOR VULNERABILITY TO CLIMATE WARMING IN THE SIERRA NEVADA: Water Year Classification in Non-Stationary Climates

A White Paper from the California Energy Commission's California Climate Change Center

Prepared for: California Energy Commission

Prepared by: University of California, Davis

JULY 2012

CEC-500-2012-015

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Davis, California, 95616 USA

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ABSTRACT

This paper explores the sensitivity of water indexing methods to climate change scenarios to better understand how water management decisions and allocations will be affected by climate change. Many water management decisions, such as environmental flow requirements and water supply allocations, are based on numerical "water year type" designations. Water year type designations vary by region and index, but most are defined by some measure of runoff in the current water year compared to average historical runoff, with numerical thresholds categorizing year types. Climate change is anticipated to alter the timing and volume of runoff, and change the relative frequency of water year types as presently defined. California's Sacramento Valley and San Joaquin Valley Indices are used as a case study to examine climatic changes. These indices provide a framework for allocating and transferring water among users. Streamflow estimates for 1951–2099 from the climate-forced Variable Infiltration Capacity hydrologic model are used to estimate potential changes in runoff and water year type frequency, using six global circulation models for the A2 and B1 emissions scenarios. Results vary by emissions scenario and global circulation model, but indicate that critically dry water years in the Sacramento Valley and San Joaquin Valley are expected to be about 8 percent and 32 percent more likely by the latter half of the twenty-first century, respectively, if water year type definitions remain unchanged. If current water year type thresholds are maintained, more years will be classified as dry and less water will be allocated for environmental outflows, perhaps failing to provide adequate hydrologic variability to support species, habitats, and ecosystems. If thresholds are redefined to reflect the historical distribution of year types, the burden of climate change falls to consumptive users and water exporters. This case study illustrates how water policy and allocation frameworks were designed assuming climatic stationarity, and that adapting water policy (or maintaining the status quo) affects which users bear the burden of climate change.

Keywords: water year type, water management, climate change, water supply, environmental water

Please use the following citation for this paper:

Null, S. E., and J. H. Viers (Center for Watershed Sciences, University of California, Davis). 2012. ***Water and Energy Sector Vulnerability to Climate Warming in the Sierra Nevada: Water Year Classification in Non-Stationary Climates.*** California Energy Commission. Publication number: CEC-500-2012-015.

TABLE OF CONTENTS

List of Tables

List of Figures

Unless otherwise noted, all tables and figures are provided by the author.

Section 1: Introduction and Background

Water year classification systems and hydrologic indices are common for water planning and management because they simplify complex hydrology into a single, numerical metric that can be used in rule-based decision making. “Water years” avoid peak discharge during the start of a calendar year, typically beginning on October 1 in the northern hemisphere (Black 1996). Estimated unimpaired runoff for a water year is then further categorized by year type, such as wet, dry, or normal, compared to historical averages. Year type classification is tied to water resources planning, helping to answer the question of whether there is “enough” water (Redmond 2002), and allocations for various water uses are adjusted based on water year type (WYT). Water year type informs water allocation decisions for water supply, hydroelectric power generation, reservoir storage, and environmental protection (Simpson et al. 2004). Many drought and water year indices exist, including the Palmer Drought Severity Index (Palmer 1965), Standard Precipitation Index (McKee et al. 1993), Surface Water Supply Index (Shafer and Dezman 1982), Reclamation Drought Index (Weghorst 1996), and deciles (Gibbs and Maher 1967).

In California, the Sacramento Valley Index (SVI) and the San Joaquin Valley Index (SJI) are typically used to classify water years. They were designed with historical hydrology and are used in a complex and evolving water delivery allocation scheme shaped by operational constraints, regulatory restrictions, and objective demands (SWRCB 2000). Numerical thresholds separate each year type, set by winter and spring runoff volume for major rivers, as well as the previous year’s index (a proxy for carryover storage). Generally, the SVI and SJI (or the sum of both indices known as the “Eight River Index”) determine WYT for the State Water Project (SWP) and the federal Central Valley Project (CVP) to allocate water for out-of-stream users in the Bay Delta, environmental flows, and export limits to water users south of the Bay Delta (SWRCB 2000). Environmental flow objectives for the region include Bay Delta outflow, flow-dependent salinity and water temperature objectives, environmental flows for rivers in the Sacramento and San Joaquin watersheds, and salinity objectives in the San Joaquin River. The SVI and SJI directly influence water policy in the state through regulatory restrictions and directly affect dozens of federal, state, and local agencies (Simpson et al. 2004).

Global circulation models (GCMs) indicate that California’s climate is expected to become warmer in the next century, although no clear trend exists for precipitation volume (Dettinger 2005; Cayan et al. 2008). The hydrology of coming decades will deviate from historical observations in terms of volume, magnitude, and timing (Milly et al. 2008). Results of climate-forced hydrological models indicate that climate change will shift snowfall to rainfall, resulting in earlier runoff with more winter runoff flooding and longer summer drought, and may further impair water quality (Null et al. 2010; Null et al. in review; Cayan et al. 2008; Barnett et al. 2008; VanRheenen et al. 2004). This may alter California’s water allocation framework, which is determined by WYT compared to historical averages, and thus assumes climatic stationarity.

Previous research has indicated that the distribution of WYT is not stationary through time. Booth et al. (2006) showed the first and second half of a 100-year daily discharge dataset for California’s Cosumnes River were significantly different. VanRheenen et al. (2004) and Vicuña (2006) noted that the distribution of WYTs shift with climate change. VanRheenen et al. (2004) modeled a shift in WYT thresholds to maintain the historical distribution for analyzing climate change impacts on the combined SWP/CVP system. Their work focused on human impacts and did not consider changes to flow objectives or whether their new thresholds provided enough water to sustain ecological integrity and function. Vicuña (2006) suggested changing the weights of seasons in the water year index to reflect changes in inflow timing. Other research has focused on improving understanding of the effects of El Niño-Southern Oscillation events or including the paleoclimate record to improve understanding of how runoff and WYT designations change through space and time (Anderson et al. 2001; Verdon-Kidd and Kiem 2010). There has been little research on climate change impacts to environmental flows, except for general agreement that competition could increase for minimum instream flow allocations (VanRheenen et al. 2004; Meyer et al. 1999), also increasing the economic costs of environmental requirements (Tanaka et al. 2006).

This paper evaluates the response of water year indices that were designed assuming climatic stationarity to climate change scenarios using a multiple model, multiple emissions scenario approach. It starts with a brief description of California's Sacramento and San Joaquin watersheds and Bay Delta. California's SVI and SJI are used as case studies with data from the climate-forced Variable Infiltration Capacity (VIC) model (Maurer et al. 2002; Liang et al. 1994). The SVI and SJI indices are fully described, as are climate projections from two commonly used emissions scenarios, the SRESA2 and SRESB1 and six GCMs from a relatively dry group of climate model results.[1] Limitations of water year indices and typing frameworks are briefly discussed. Results compare modeled historical 1951–2000 index means from the 12 runs (6 GCMs and 2 emissions scenarios) with observed data to test if the differences in mean flow are statistically significant between datasets. Next, simulated 1951–2000 runoff is compared with climate forced runoff projections for 2001–2050 and 2051–2099 to test for statistically significant change. Relative frequency histograms by WYT for the SVI and SJI demonstrate anticipated changes for California. Discussion focuses on alternative methods for adapting WYT indices to climate change, showing how methods affect water users differently. This paper highlights how water dedications, WYT classification, and climate are interrelated.

Study Area

California's west-slope Sierra Nevada rivers flow generally westward to their confluence with the Sacramento or San Joaquin Rivers, which merge and flow through the Bay Delta to the Pacific Ocean (Figure 1). The Sacramento and San Joaquin basins provide approximately 43 percent of California's total average annual surface runoff and are a source of drinking water for about two-thirds of the state's 35 million residents. Historical average annual flow is 18.2 million acre feet (maf) for the four northern SVI watersheds and 5.9 maf for the four southern SJI watersheds. However, California's hydrology is notably variable, and interannual variability is less predictable than seasonal or geographic variability. The driest year on record was 1977 with statewide annual runoff of 15 maf, while the wettest year was 1983 with annual runoff of 135 maf.

The CVP and SWP have pumps in the Sacramento-San Joaquin Bay Delta to divert water to southern California, portions of the Bay Area, and the western San Joaquin Valley. Following

[1] Models and climate scenarios were chosen to coincide with those used for the California Energy Commission's California Climate Change Research Center (www.climatechange.ca.gov/research/).

water development, environmental minimum flows are now mandated in some river reaches to protect biological diversity, habitat complexity, and ecosystem services. In addition, the Bay Delta is an environmentally sensitive area, providing habitat for fish and wildlife (some species are protected under the state and federal Endangered Species Acts), and holding public trust value for common use (SWRCB 2000). Water year indices are used to establish operational rules by the State Water Resources Control Board (SWRCB) for regulating water quantity and quality through the Bay Delta (SWRCB 2000), by the Federal Energy Regulatory Commission (FERC) for hydropower relicensing (Viers 2011), and by the National Marine Fisheries Service (NMFS) and the U.S. Fish and Wildlife Service (USFWS) for their Biological Opinions (USFWS 2008; NMFS 2009). Thus, WYT designations directly affect environmental flow dedications and water quality, as well as local diversions and water exports from the Bay Delta.

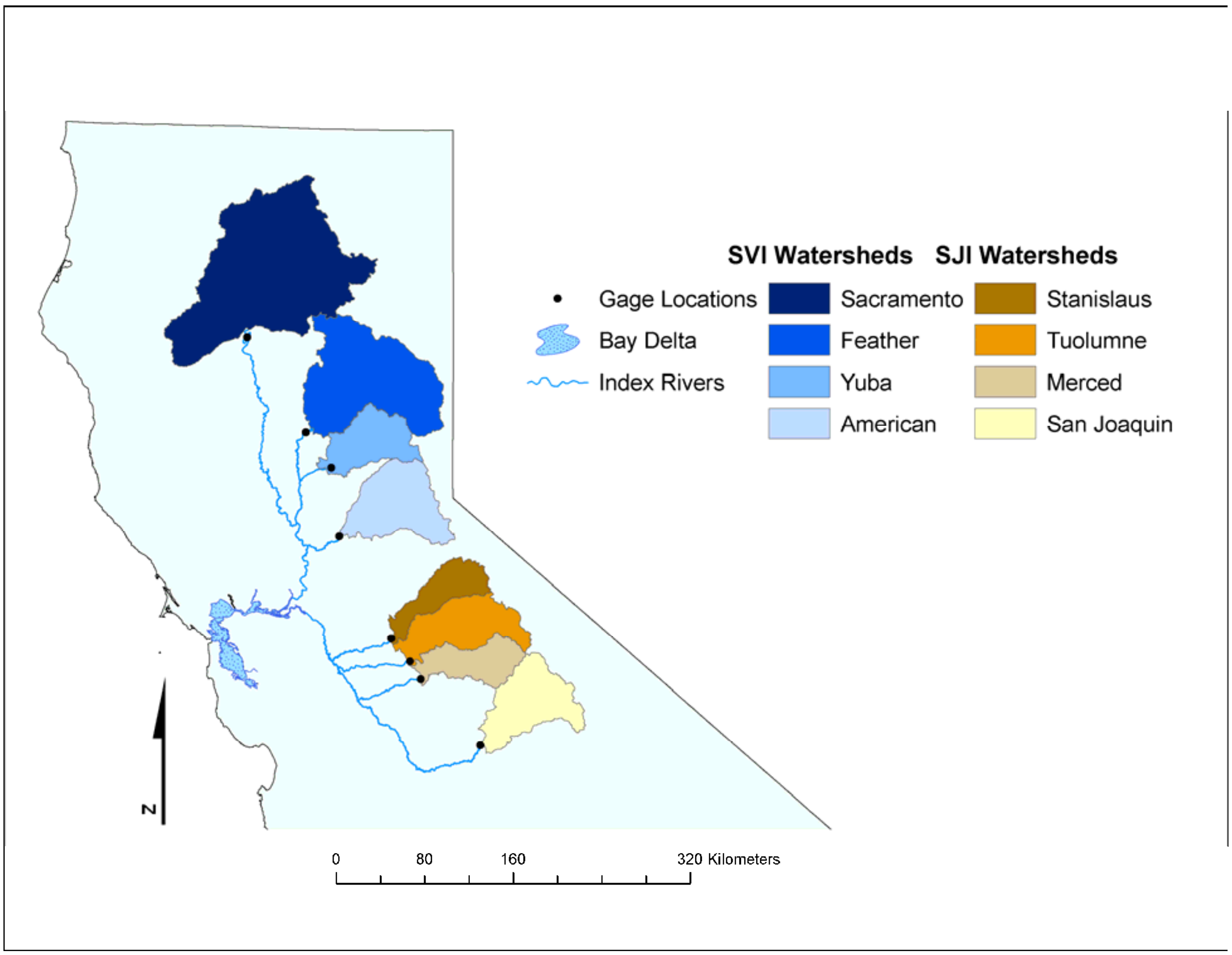


Figure 1. Sacramento and San Joaquin Watersheds with Gage Locations for Water Year Type Indexing

The SVI was developed by the SWRCB in 1989 (from a previously existing Sacramento River classification scheme), and the SJI was developed in 1991 (CDWR 1989, CDWR 1991). The general concept was to divide runoff into wet, near-normal (above normal and below normal), dry, and critical categories (weighted approximately 30 percent, 20 percent, 20 percent, 15 percent, and 15 percent), respectively, of the historic record to aid management of the water projects and provide an index of water supply for the public (CDWR 1989). Water shortages were expected during critical years (Roos, pers. comm. 2011). In practice, insufficient water is available for water export demands south of the Bay Delta pumps in critical, dry, and below-normal years for August, September, and October (SWRCB 2000). The SVI is the most important for managing the Bay Delta, although the SJI impacts environmental flow objectives and the "Eight River Index" uses both Sacramento and San Joaquin system runoff to determine salinity in Suisun Bay.

Sacramento Valley Index (SVI)

The SVI (also known as the "Four River Index" and the "40-30-30 Index") uses the sum of estimated unimpaired runoff from the following gages: Sacramento River above Bend Bridge, Feather River at Oroville, Yuba River near Smartsville, and American River below Folsom Lake (CDEC 2010) (Figure 1). It is calculated using Equation 1, and year type classification is based on the thresholds in Table 1. The term for the previous year's index is a proxy for the effect of carryover storage on system capability (CDWR 1989).

SVI = (0.4*current Apr–Jul runoff)+(0.3*current Oct–Mar runoff)+(0.3*previous year's index)[2] **(1)**

Table 1. Sacramento Valley Index and San Joaquin Valley Index Year Type Classification Thresholds

Water Year Type	Sacramento Valley Index (maf)	San Joaquin Valley Index (maf)
Wet	$\geq$9.2	$\geq$3.8
Above Normal	>7.8 and <9.2	>3.1 and <3.8
Below Normal	>6.5 and $\leq$7.8	>2.5 and $\leq$3.1
Dry	>5.4 and $\leq$6.5	>2.1 and $\leq$2.5
Critical	$\leq$5.4	$\leq$2.1

San Joaquin Valley Index (SJI)

The SVI and SJI were intentionally given different weights on each segment of the index to account for snowmelt-dominated runoff and occasional large winter floods that provide less water deliveries in the San Joaquin basin (CDWR 1991). The SJI (or the "60-20-20 Index") uses the sum of unimpaired runoff from Stanislaus River below Goodwin Dam, Tuolumne River below La Grange Dam, Merced River below Merced Falls, and San Joaquin River inflow to Millerton Lake (CDEC 2010) (Figure 1). It is calculated using Equation 2, and year type thresholds are based on the values in Table 1.

SJI = (0.6*current Apr–Jul runoff)+(0.2*current Oct–Mar runoff)+(0.2*previous year's index)[3] **(2)**

[2] Maximum of 10.0 maf for previous year's index term to account for required flood control reservoir releases.

Historical Water Year Thresholds

For planning purposes, year types are set by forecasts beginning in February (and updated monthly through May), although for this study we use estimated actual unimpaired runoff (CDEC 2010) or modeled data. Values of the SVI and SJI account for geographic variation in streamflow, so the SVI has greater thresholds than the SJI (Table 1). The historical relative frequency of year types also varies slightly between the SVI and SJI. For example, the threshold for critically dry year types falls at the 13th percentile of the observed period of record for Sacramento Valley streamflow, but at the 17th percentile for San Joaquin Valley streamflow. Operationally, this means there is a slightly higher chance that any year will be critically dry in the San Joaquin Valley, and more environmental flow is allocated from Sacramento Valley rivers than the San Joaquin rivers. The opposite is true for dry and below-normal year types.

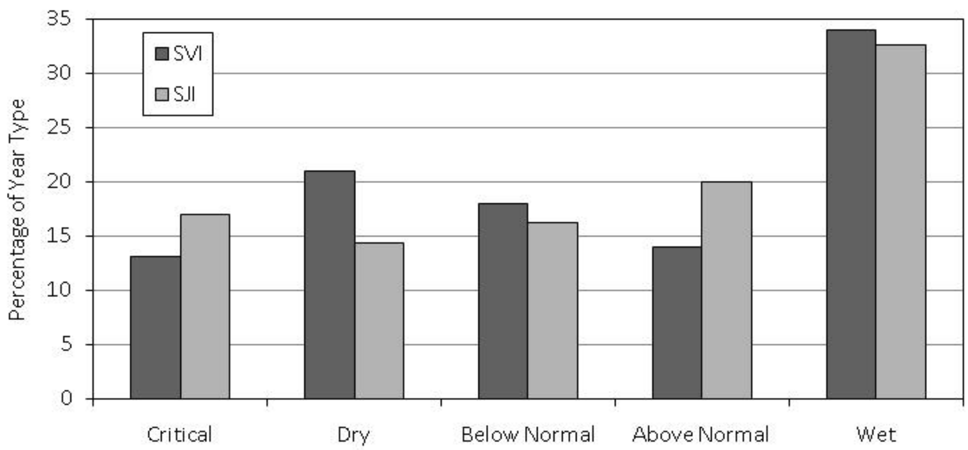


Figure 2. Current Water Year Type Variability Using Observed Historical Data (1905–2000)

Section 2: Methods

Modeled Hydrologic Data

A water year index framework was used to assess hydrologic response from the Sacramento and San Joaquin basins with climate change. Downscaled, climate-forced streamflow estimates were from the VIC model, a large-scale, distributed, physically based hydrologic model that balances surface energy and water over a grid (Liang et al. 1994; Maurer et al. 2002). VIC uses sub-grid representation for vegetation, soils, and topography to retain local variability for partitioning precipitation into runoff and infiltration, and uses non-linear representation for simulating baseflow. Data were downscaled using bias correction and spatial downscaling (BCSD), a statistical downscaling method that preserves monthly climate patterns between coarse and fine resolutions (Maurer and Hidalgo 2008). Water routing was post-processed to estimate streamflow at river outlets (using an algorithm developed by Lohmann et al. [1996] as

[3] Maximum of 4.5 maf for previous year's index term to account for required flood control reservoir releases.

cited in Cayan et al. 2008). Parameterization for deriving streamflow is identical to that used by VanRheenen et al. (2004) for the Sacramento–San Joaquin basin. VIC has previously been used to assess the hydrologic effects of climate change in the western United States (Cayan et al. 2008; VanRheenen et al. 2004; Maurer et al. 2002; Vicuña et al. 2007; and others).

This application of VIC used a 1/8° spatial grid and a daily timestep (later aggregated to a monthly timestep) for the 1951–2099 water years. Twelve VIC runs were analyzed, with climate input data from six GCMs for the A2 and B1 emissions scenarios (Table 2). Modeled water years were separated into three time periods: 1951–2000 constitutes the historical time period, and simulations of future years were split into two groups, 2001–2050 and 2051–2099 for near- and far-term estimates of runoff conditions. Water years (Oct–Sep) are used throughout this paper.

Table 2. Climate Scenarios, GCMs, and Modeled Time Periods

Climate Scenarios	Global Circulation Models	Time Periods
SRESA2	CNRM CM3	Historical (1951–2000)
SRESB1	GFDL CM2.1	Near-term (2001–2050)
	CCSR MIROC 3.2 medium resolution	Long-term (2051–2099)
	MPI-OM ECHAM5	
	NCAR CCSM3.0	
	NCAR PCM1	

Differences between emissions scenarios are due to uncertainty in human actions such as population growth and greenhouse gas (GHG) emissions, while differences in GCMs are due to uncertainty in climate models such as representation of physical processes and sensitivity to GHG forcings. The A2 scenario has more severe climate change, assuming maximum carbon dioxide (CO_2) emissions of 850 parts per million (ppm), continuously increasing global population, and slow economic growth. The B1 scenario is more moderate, assuming maximum carbon dioxide (CO_2) emissions of 550 ppm, global population that peaks mid-century and later declines, and global sustainability solutions that introduce resource-efficient technology (IPCC 2000).

Statistical Analysis

One-way ANOVA and Student's t-tests were used to analyze whether differences in mean runoff between modeled and observed data or between time periods are statistically significant. First, the means of the modeled historical 1951–2000 datasets (modeled A2 and B1 simulations) were tested against observed historical data for the same time period. (The six GCMs for each A2 or B1 emissions scenarios are grouped to reduce uncertainty associated with individual climate models.) The same tests were used to determine whether changes in the means of the SVI and SJI indices through time are statistically significant (simulated 1951–2000, 2001–2050, and 2051–2099). ANOVA was used to test the means of all three A2 and B1 time periods, reducing the risk of a type I error (which would show a difference in means when, in reality, none exists). Student's t-tests were used to assess whether the means of two groups are statistically different, so each time period can be compared to see when most change occurs. Mean cumulative frequency distributions for each emissions scenario illustrated how year type indices shift to represent drier conditions. All statistical analyses were completed using SAS's JMP v8.0.2 statistical software.

Limitations

Water year and drought indices are routinely used to assess meteorological, agricultural, hydrological, and socioeconomic drought. They are helpful for categorizing water years into similar types, allowing water managers and policymakers to quantify years, visualize variability, and guide water operations. However, they have inherent limitations. Water year indices can be used by policymakers who have poor understanding of the flaws and driving factors of the indices. Further, classifications of WYTs are typically arbitrary, with little scientific rigor (Goodrich and Ellis 2006). Quiring (2009) developed methods for objectively determining index thresholds and operational drought definitions, but discovered that few, if any, entities use objective methods for deciding on thresholds. By examining the magnitude and duration of flood pulse events, Booth et al. (2006) found that more inter-annual variability exists than is captured in WYT classifications. Water year indices focus on runoff volume, with less emphasis on timing (Vicuña 2006). Thus, they are poorly suited to evaluate intra-annual or seasonal shifts in runoff from climate change. Finally, more research is needed to accurately describe the ecological differences between year types, as well as determine how much water ecosystems need.

Section 3: Results

Water Year Index Means

For the SVI and SJI historical 1951–2000 datasets (comparing observed, modeled A2, and modeled B1), there is no significant difference between water year runoff means, October to March runoff means, or April to July runoff means using a 95 percent confidence level (Table 3).

Table 3. ANOVA and t-Test Significance for Historical Time Period, 1951–2000 (values < 0.05 are statistically significant at the 95 percent confidence level)

		ANOVA Significance (pr>F)	**Student's t-Test Significance (p-value)**	
Watershed		All GCMs (Observed, A2, □ B1)	Observed vs. A2	Observed vs. B1
Sacramento	SVI	0.65	0.36	0.41
	Oct□Mar Runoff	0.97	0.82	0.85
	Apr□Jul Runoff	0.38	0.17	0.19
San Joaquin	SJI	0.62	0.35	0.34
	Oct□Mar Runoff	0.47	0.23	0.25
	Apr□Jul Runoff	0.46	0.23	0.23

This indicates that the modeled hydrological data are representative of historical water year index values. Figure 3 shows the cumulative frequency distributions for observed and modeled SVI and SJI in the 1951–2000 historical period. The A2 family is shown with warm colors and the B1 with cool colors. For SVI, GCMs tend to over-predict index values in dry years when the historical index is less than approximately 8 maf (which includes the critical, dry, and below-normal year types). For SJI, GCMs typically slightly under-predict index values for all year types.

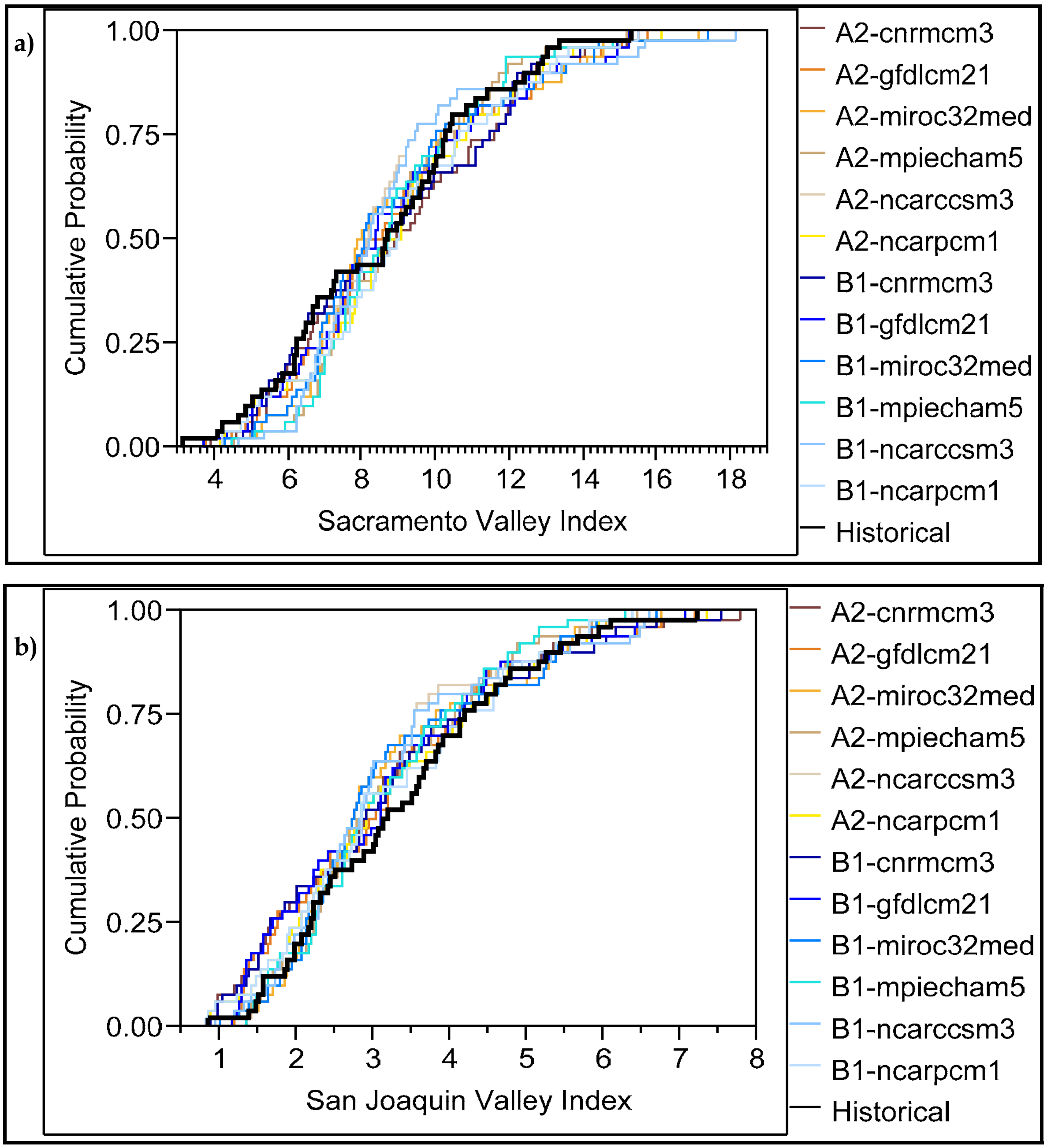


Figure 3. Cumulative Frequency Distributions for Observed vs. Modeled 1951–2000 Historical Time Period for (a) SVI and (b) SJI (note x-axis scale change between figures)

ANOVA and t-tests were again used to determine whether modeled mean SVI, SJI, October–March runoff, and April–July runoff are statistically different between modeled time periods (simulated 1951–2000, 2001–2050, 2051–2099, as shown in Table 4). ANOVA results indicate that SVI and SJI index means are statistically different between all time periods, as are April–July runoff means using a 95 percent confidence level (simulated average annual flow data are given in Table 5). When index means are compared between time periods using t-tests, SVI and SJI means are always statistically different between the first and third time period, and between the second and third time periods. However, only the means of the SJI A2 emissions scenario are significantly different between the first and second time period. This implies that for most simulations, changes in mean water year index values are most detectable in the latter half of the twenty-first century.

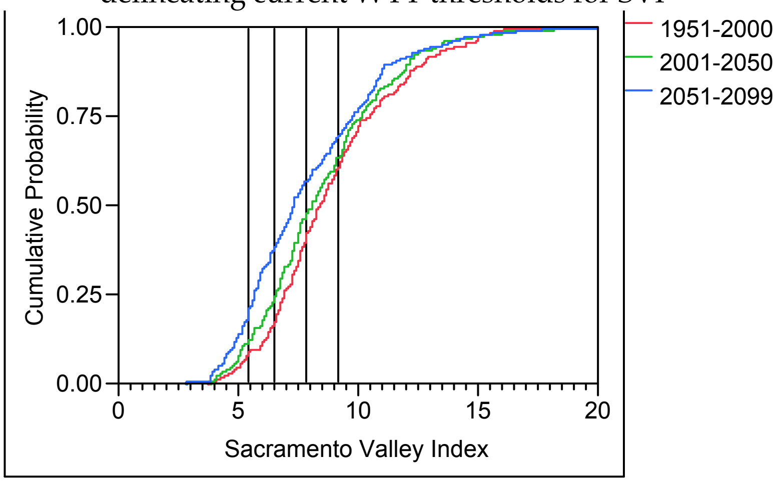
Table 4. ANOVA and t-Test Significance for the Modeled 1951–2000, 2001–2050, and 2051–2099 Time Periods. Black values indicate statistically different means ($p < 0.05$) between time periods.

			ANOVA Significance (pr>F)	Student's t-test Significance (p-value)		
	Index and Data	ES	All time periods	1951-2000 vs. 2001–2050	2001–2050 vs. 2051–2099	1951–2000 vs. 2051–2099
Sacramento	SVI	A2	0.0002	0.12	0.0109	<0.0001
		B1	<0.0001	0.84	<0.0001	0.0001
	Oct-Mar Runoff	A2	0.34	0.47	0.45	0.14
		B1	0.10	0.04	0.13	0.61
	Apr-Jul Runoff	A2	<0.0001	<0.0001	<0.0001	<0.0001
		B1	<0.0001	0.0013	<0.0001	<0.0001
San Joaquin	SJI	A2	<0.0001	0.0010	<0.0001	<0.0001
		B1	<0.0001	0.13	<0.0001	<0.0001
	Oct-Mar Runoff	A2	0.15	0.43	0.25	0.05
		B1	0.18	0.09	0.15	0.79
	Apr-Jul Runoff	A2	<0.0001	0.0002	<0.0001	<0.0001
		B1	<0.0001	0.0104	<0.0001	<0.0001

Table 5. Modeled average annual flow by time period (maf is millions of acre-feet)

			Average Annual Flow (maf)		
	Index and Data	ES	1951-2000	2001-2050	2051-2099
Sacramento	Annual Runoff	A2	20.09	19.38	18.29
		B1	20.02	20.29	18.23
	Oct-Mar Runoff	A2	11.70	12.08	12.50
		B1	11.66	12.68	11.92
	Apr-Jul Runoff	A2	7.34	6.31	4.91
		B1	7.31	6.60	5.39
San Joaquin	Annual Runoff	A2	6.03	5.50	4.79
		B1	6.02	5.81	4.83
	Oct-Mar Runoff	A2	2.24	2.35	2.50
		B1	2.24	2.45	2.27
	Apr-Jul Runoff	A2	3.48	2.91	2.08
		B1	3.48	3.09	2.33

Mean April–July runoff is statistically different between all time periods. Runoff volume change for April–July is given 40 percent and 60 percent weight for the SVI and SJI, respectively. Changes to this runoff season are likely driving mean index values. These findings underscore existing research demonstrating expected climate-induced changes to runoff timing (Cayan et al. 2008; Null et al. 2010; VanRheenen et al. 2004; Knowles and Cayan 2002). Cumulative frequency distributions show modeled shifts in index values by time period with vertical bars delineating current WYT thresholds for SVI



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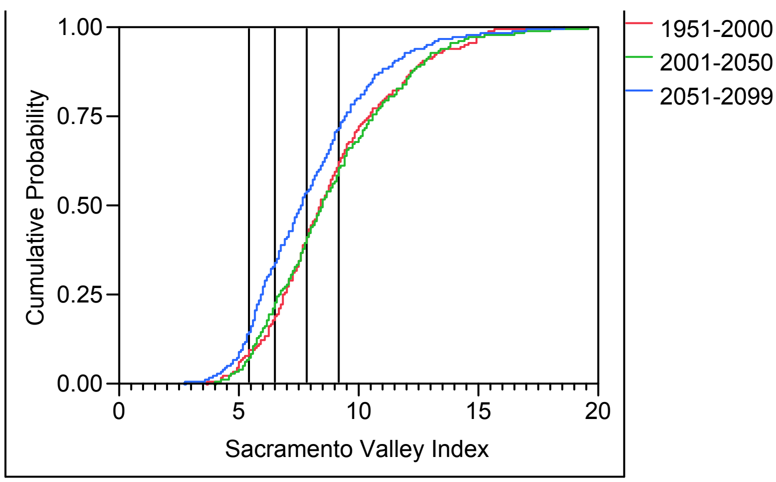

Figure 4) and SJI (Figure 5).

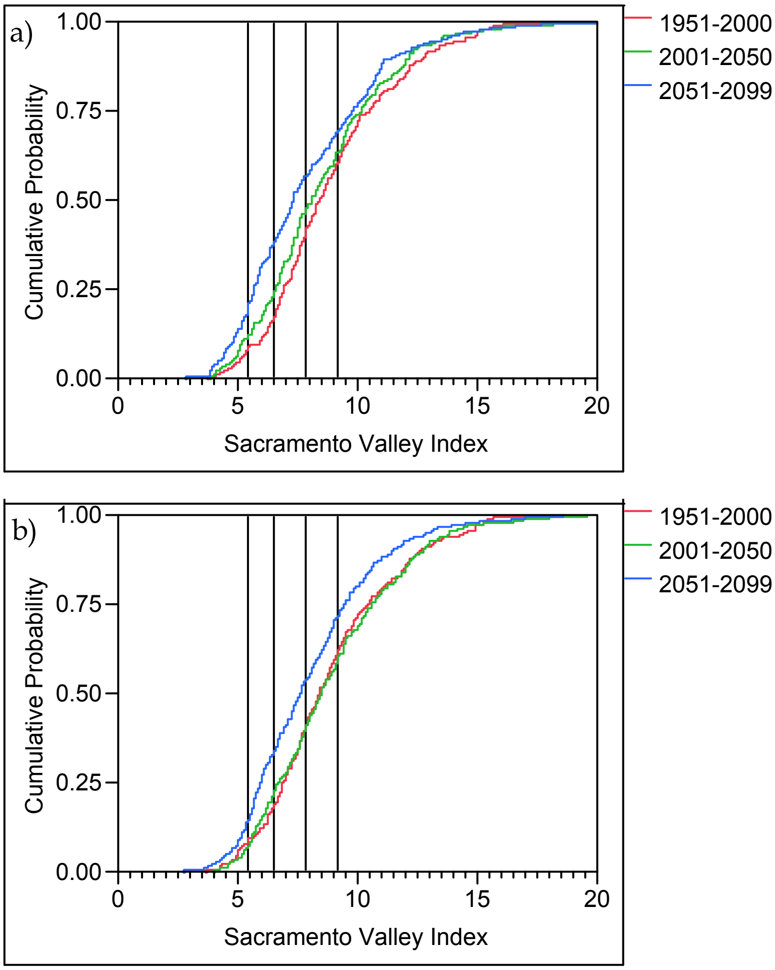

Figure 4. SVI Cumulative Frequency Distributions by Time Period for (a) A2 and (b) B1 (vertical bars show current WYT thresholds)

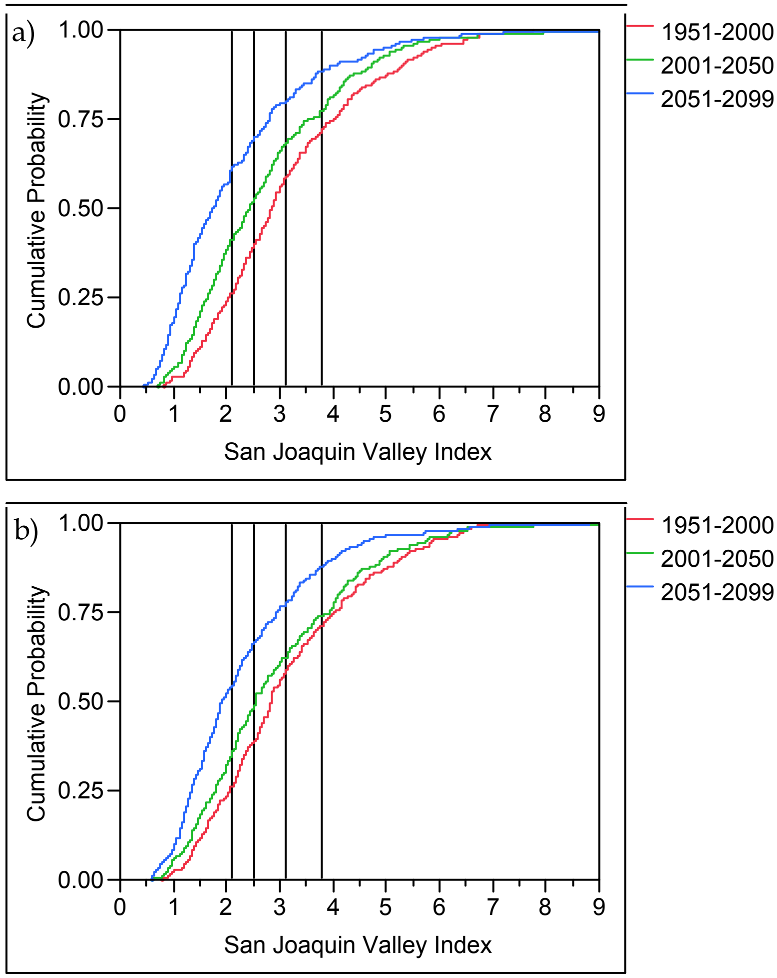

Figure 5. SJI Cumulative Frequency Distributions by Time Period for (a) A2 and (b) B1 (vertical bars show current WYT thresholds)

Water Year Types

If the hydroclimate changes in coming decades, then the relative frequency of WYTs will change, as will water allocations which are based on WYTs. The relative frequency that water years are classified as each year type is illustrated with histograms by modeled time period for SVI (Figure 6) and SJI (Figure 7) (note scale change between figures). Observed data are included for the 1951–2000 historical period (Figure 6a and Figure 7a) for visual corroboration of modeled and observed data. Differences between emissions scenarios (warm hues versus cool hues) are due to uncertainty in human actions such as population growth and GHG emissions, while differences in GCMs (variability within the warm hues or cool hues) are due to uncertainty in climate models, such as representation of physical processes and sensitivity to radiative forcings.

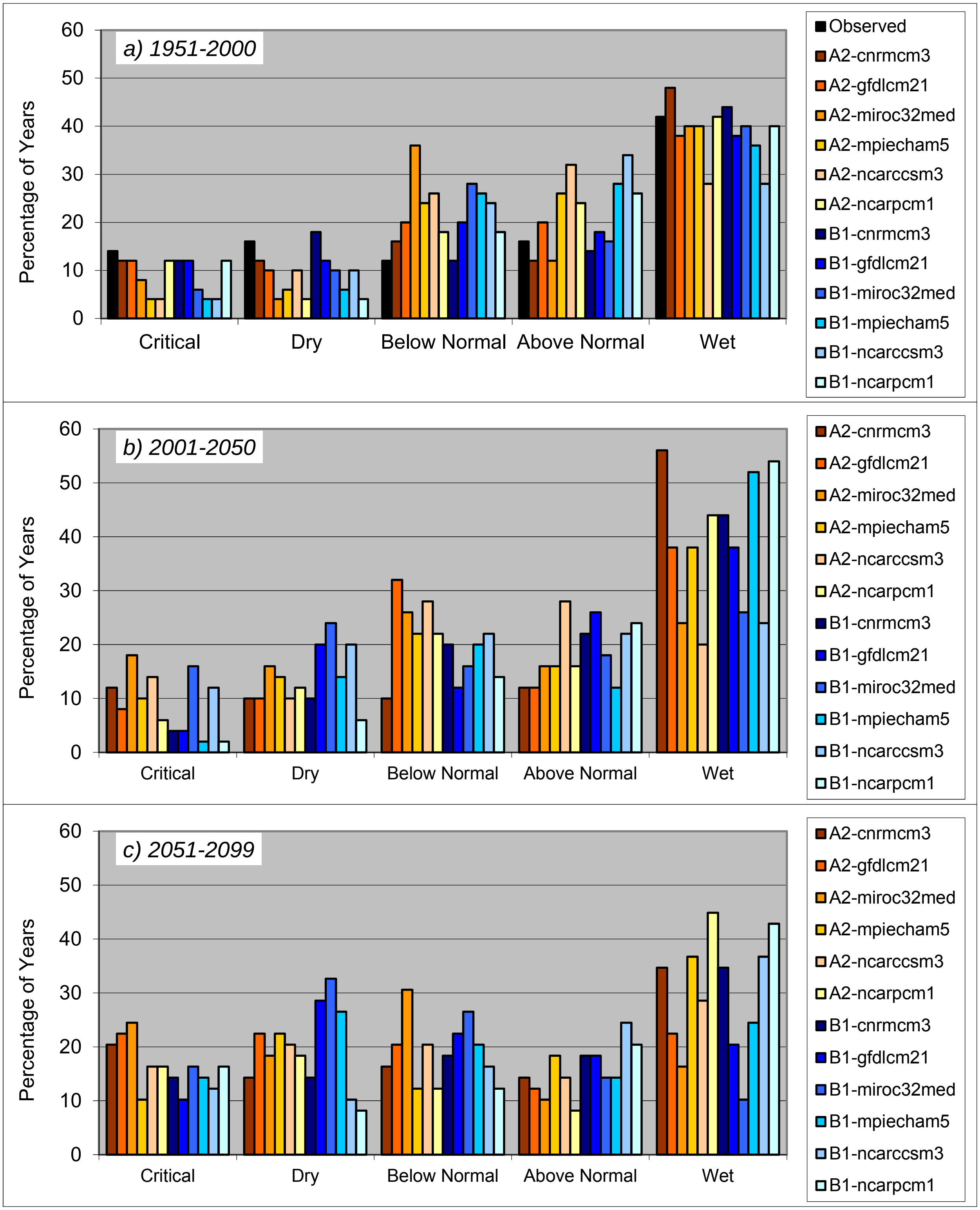

Figure 6. SVI Relative Frequency Histograms for (a) 1951–2000, (b) 2001–2050, and (c) 2051–2099

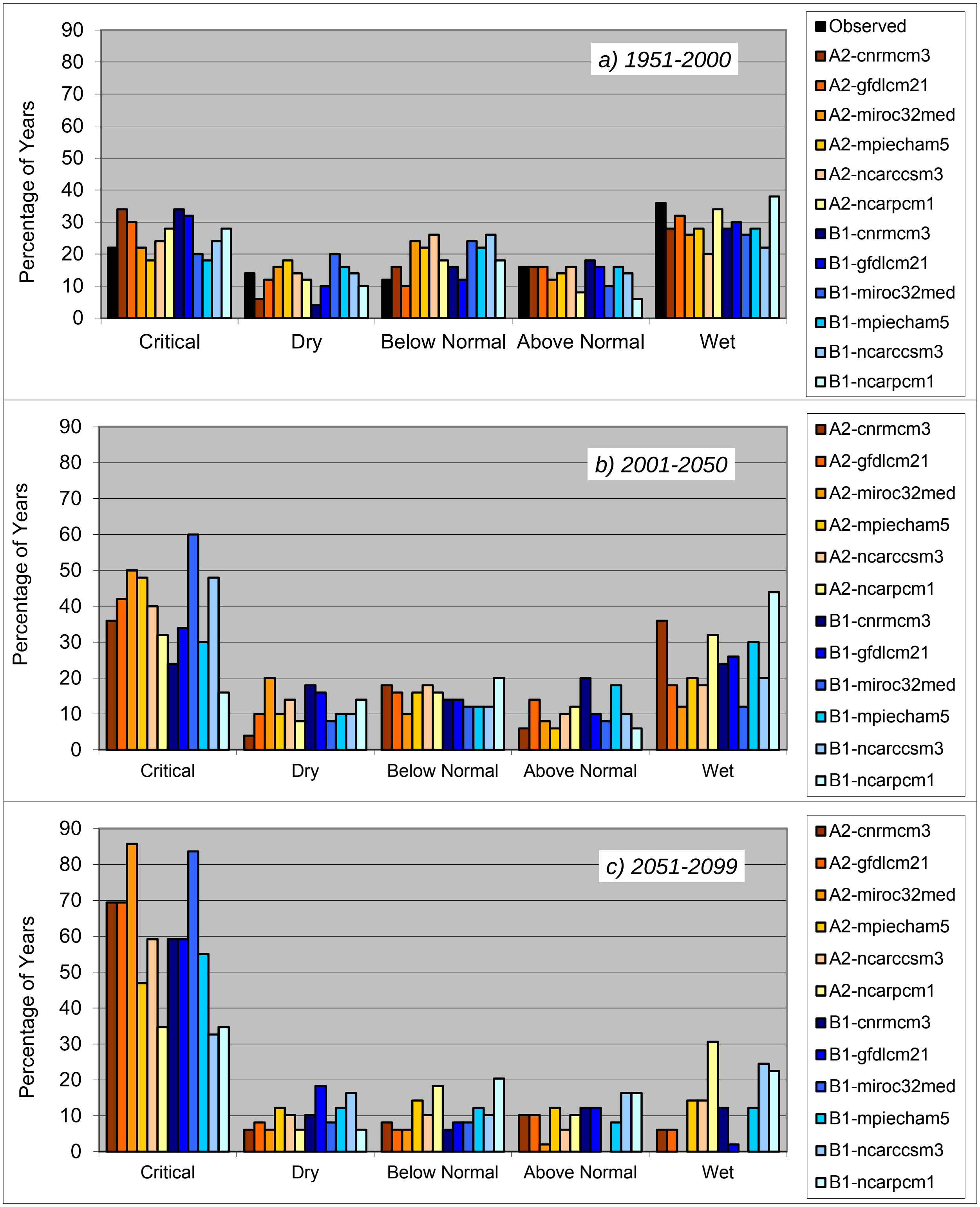

Figure 7. SJI Relative Frequency Histograms for (a) 1951–2000, (b) 2001–2050, and (c) 2051–2099

Results indicate the relative frequency of WYTs is expected to shift throughout the next century. For the SVI, modeling suggests a more even distribution of WYTs in each category by the end of the century (Figure 6). Projections from both the A2 and B1 emissions scenarios indicate the Sacramento Basin will likely have more dry and critical years, and fewer normal and wet years throughout the current century (Figure 6, Table 6). By the latter half of the twenty-first century (2051–2099), 6 to 10 percent more critical years and 10 to 12 percent more dry years could occur if water year thresholds remain the same. The more drastic changes could occur if the higher CO_2 emissions and increasing population assumptions of the A2 emissions scenarios are realized.

Table 6. Percentage of Years in Each Water Type by Modeled Time Period and Emissions Scenario (italicized values are percent change from historical period)

	SVI					
	1951-2000 (□)		2001-2050 (□)		2051-2099 (□)	
	A2	B1	A2	B1	A2	B1
Critical	8.7	8.3	11.3 *(2.7)*	6.7 *(-1.7)*	18.4 *(9.7)*	14.0 *(5.6)*
Dry	7.7	10.0	12.0 *(4.3)*	15.7 *(5.7)*	19.4 *(11.7)*	20.1 *(10.1)*
Below Normal	23.3	21.3	23.3 *(0.0)*	17.3 *(-4.0)*	18.7 *(-4.6)*	19.4 *(-1.9)*
Above Normal	21.0	22.7	16.7 *(-4.3)*	20.7 *(-2.0)*	12.9 *(-8.1)*	18.4 *(-4.3)*
Wet	39.3	37.7	36.7 *(-2.7)*	39.7 *(2.0)*	30.6 *(-8.7)*	28.2 *(-9.4)*
	SJI					
	1951-2000 (□)		2001-2050 (□)		2051-2099 (□)	
	A2	B1	A2	B1	A2	B1
Critical	26.0	26.0	41.3 *(15.3)*	35.3 *(9.3)*	60.9 *(34.9)*	54.1 *(28.1)*
Dry	13.0	12.3	11.0 *(-2.0)*	12.7 *(0.3)*	8.2 *(-4.8)*	11.9 *(-0.4)*
Below Normal	19.3	19.7	15.7 *(-3.7)*	14.0 *(-5.7)*	10.5 *(-8.8)*	10.9 *(-8.8)*
Above Normal	13.7	13.3	9.3 *(-4.3)*	12.0 *(-1.3)*	8.5 *(-5.2)*	10.9 *(-2.5)*
Wet	28.0	28.7	22.7 *(-5.3)*	26.0 *(-2.7)*	11.9 *(-16.1)*	12.2 *(-16.4)*

For the SJI, considerably more years fall into the critical category with fewer years in all other year types, particularly toward the end of this century (Figure 7). Results indicate a 28 to 35 percent increase in critical water years by the last half of this century, with the larger changes under A2 assumptions (Figure 7,

Table). The distribution of water years could go through a major shift toward the second half of the century. Changes to the relative frequency of SJI year types could affect water users in the Sacramento watershed when the eight-river index is used (as is the case for determining Bay Delta export limits as a percentage of Delta inflow) (SWRCB 2000). These findings reiterate results from VanRheenen et al. (2004), who also observed more severe streamflow volume reduction in the San Joaquin Basin than the Sacramento Basin.

Section 4: Discussion

Threshold-based water year classification forms the framework for flow objectives in the Bay Delta and Sierra Nevada rivers, consumptive water uses in the Bay Delta, and licensure rules for hydropower generation in the Sierra Nevada, and shapes water deliveries for much of

California's population. The SVI and SJI are numerical indices, so they can continue to be used with severe climatic change as they are. However, WYT classifications and threshold definitions will likely become less representative with climate change. By the end of this century the distribution of particular year types is anticipated to be significantly different from the historical record.

Previous work has indicated that average Bay Delta CVP/SWP exports are especially reduced during summer and fall from reduced snowpack, and that exports are most sensitive to climate change during very wet or very dry years (Anderson et al. 2008). This paper shows the frequency of very dry years is likely to increase significantly using data from a relatively dry group of climate models. More dry years may shift climate change–related impacts, altering the relative water use winners and losers, as well as shifting associated economic costs.

If current WYT thresholds are maintained, substantially more dry and critically dry years are anticipated to occur as explained in the results section above and further illustrated with the modeled distribution of WYT using historical thresholds (Figure 8; black bars show thresholds, and wider bars quantify uncertainty between the A2 and B1 runoff estimates). This would disproportionately impact environmental uses (for example, Bay Delta outflows are reduced by approximately 36 percent between wet and dry years), although deliveries to all water users would be reduced. With persistent dry conditions under this scenario, California risks failing to provide adequate baseflow and hydrologic variability to support various ecosystems, and failing to protect species and habitat as required by the state and federal Endangered Species Acts, the Natural Community Conservation Planning Act, and the Clean Water Act. Additional confounding regulatory drivers include, but are not limited to, regulatory oversight by the SWRCB to uphold public trust values and expanded water quality enforcement through the Porter-Cologne Water Quality Control Act (SWRCB 2011), hydropower relicensing through FERC (Viers 2011), or the emergence of state interest in safeguarding public trust values through Section 5937 of the California Department of Fish and Game code (Baiocchi 1980).

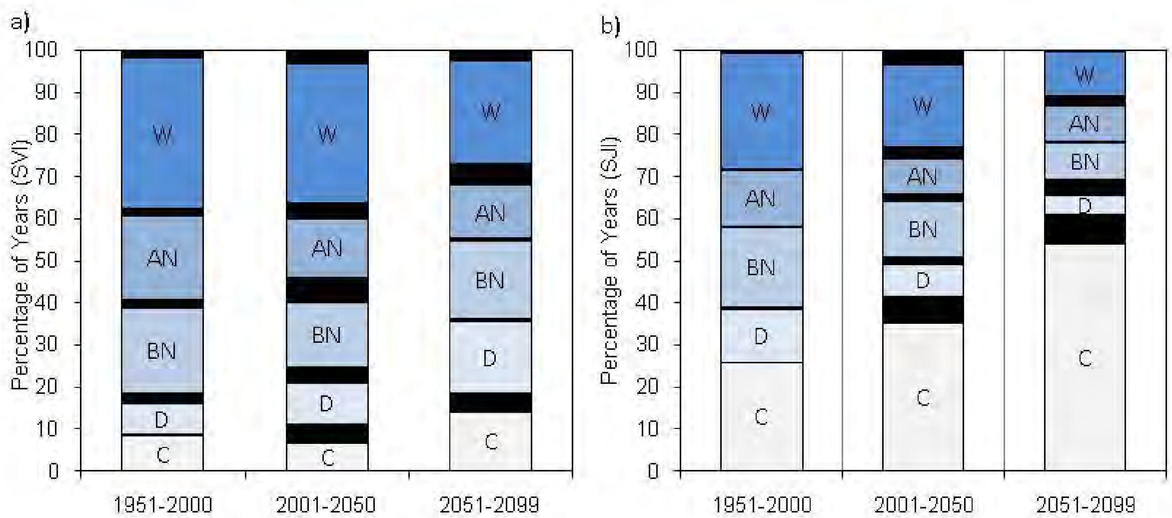

Figure 8. Modeled Distribution of Water Year Types Using Historical Thresholds Where Black Bands Show Uncertainty Between A2 and B1 Projections for (a) SVI and (b) SJI (Note scale change between figures. C is critically dry, D is dry, BN is below normal, AN is above normal, and W is wet.)

Conversely, WYT thresholds could be redefined to reflect changes in climate, recognizing that the normal years of the future may resemble the critical or dry years of the past century (Figure 9). The thresholds determining year types must be lowered to maintain the historical distribution of water years with climate-driven modeled data (CDWR 1989; CDWR 1991). For example, for modeled SJI 1951-2000 data, the threshold for critically dry year types should be set at about 1.7 maf for 17 percent of years to be in the critically dry year type, but the threshold would have to be reset between 0.9 to 1.1 maf for 17 percent of years to be in the critically dry category by 2051-2099. If volumetric environmental flow requirements tied to each WYT remain the same, much of the burden of climate change would fall on human water uses under this scenario and regulatory restrictions could increasingly drive water policy in California. If environmental flow allocations were altered to reflect overall drier conditions, the impacts of climate change would be shared more equitably among water uses (and water scarcity would be commonplace).

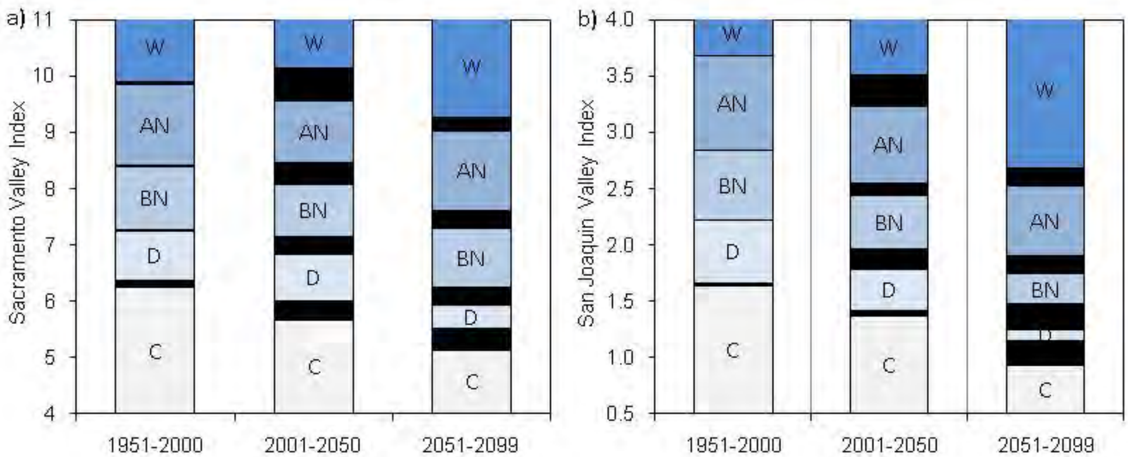

Figure 9. Modeled Water Year Classification Thresholds Using Historical Percentages of Years Per Category Where Black Bands Show Uncertainty Between A2 and B1 Projections for (a) SVI and (b) SJI (Note scale change between figures. C is critically dry, d is dry, BN is below normal, AN is above normal, and W is wet.)

Numerous peer-reviewed papers exist about developing environmental flows (Tharme 2003; Arthington et al. 2006; Acreman and Dunbar 2004), but the quality, accuracy, and utility of the SVI and SJI indices for these purposes have yet to be extensively studied. It is important to improve understanding of how much water is needed to maintain and enhance aquatic and riparian ecosystems in the Bay Delta, but it makes little sense to rigorously study environmental flow allocations, while arbitrarily setting water year classification thresholds. Failing to recognize how probabilities of year types may shift with climate change introduces error and uncertainty into the long-term regulatory stability emphasized by the SWRCB's flow decisions, FERC's relicensing, and NMFS's Biological Opinions. These mechanisms may not preserve the hydrologic variability needed to maintain ecosystem health with the potential of 16 to 21 percent more dry and critically dry years in the SVI, and 28 to 30 percent more dry and critically dry years in the SJI by the end of the twenty-first century. Quiring (2009) has described methods to develop objective index thresholds, and future research should focus on improving understanding of how much water is needed for environmental protection, while considering the WYT framework underpinning environmental flow objectives.

In a changing climate, attention should also be given to the relative frequency of each WYT and how that affects the hydrologic variability necessary to maintain aquatic ecosystems. Aquatic ecosystems depend on hydrologic variability to preserve function and integrity (Richter et al. 1997). In undeveloped river systems, aquatic and riparian ecosystems must respond to climate change. However, in developed systems, water managers have some responsibility to maintain ecological functions and health of downstream aquatic and riparian systems. In a future where more than half of all years are designated as critically dry, larger instream flows may be warranted to manage hydrologic variability if we are to maintain existing ecosystems. The listing of additional species as threatened or endangered could also increase environmental flow requirements.

However, preserving the historical distribution of species and ecosystems, for which environmental flow requirements were developed, may not be the ecosystems we choose to manage for in the future (Lund et al. 2010). As a society, we like to preserve ecosystems that we are accustomed to, although that may not be realistic in a future with severe climate change (Hanak et al. 2011). Future conditions, as well as unanticipated events such as invasions of exotic species, collapse of food webs, or changing migration barriers, could all threaten the historical distribution of ecosystems. Changing frequencies of WYTs may present an opportunity to openly recognize that ecosystems are already heavily managed and to more explicitly decide what ecosystems, functions, and species we opt to manage for.

Water resources will likely be managed more tightly in coming decades. It is in the interest of the public trust to implement a mechanism or formal process to adapt WYT classification and to promote flexibility in water policy for meeting environmental flow needs. In past years, the SWRCB has generally reopened hearings to revise Bay Delta quality standards every 15 to 20 years. This may provide a mechanism to revise WYT thresholds and environmental protection standards, and to correct water allocation imbalances between environmental flows, consumptive water users in the Bay Delta, and water exports south of the Bay Delta. This also implicitly hands these types of adaptive management decisions to SWRCB, perhaps without a more structured revision process. The SWRCB could also potentially review the timing of inflows with climate change and adjust seasonal weighting of runoff to preserve WYT integrity.

It makes little sense to rely on a water allocation framework that assumes climatic stationarity when research repeatedly indicates climatic and hydrologic change is anticipated for California (Cayan et al. 2008; Null et al. 2010; Knowles and Cayan 2002). Climate, WYT, and water allocation decision-making are interrelated. WYT thresholds should be reevaluated at SWRCB hearings (or a similar forum), and WYT thresholds should be periodically revised to maintain WYT classification integrity with the historic division of WYT. Infrastructure or policy improvements that reduce water demands, increase water reliability, or improve water quality (for both people and ecosystems) in light of anticipated hydroclimate changes should be made a priority today to hedge future water scarcity and environmental decline. Finally, in light of existing water scarcity (there is already not enough water to meet Bay Delta exports for the three driest year types), the state must commit to environmental protection while recognizing that the distribution of species, habitats, and ecosystem services may shift with climate change.

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Glossary

A2	A greenhouse gas emissions scenario set forth by the Intergovernmental Panel on Climate Change in its Special Report on Emissions Scenarios. A2 is characterized by a world of independently operating, self-reliant nations, continuously increasing population, and regionally oriented economic development.
ANOVA	Analysis of variance, a standard statistical analysis technique
B1	A greenhouse gas emissions scenario set forth by the Intergovernmental Panel on Climate Change in its Special Report on Emissions Scenarios, published in 2000. B1 depicts a more globally integrated and ecologically friendly world than A2.
CO_2	Carbon dioxide, a contributor to global climate change
CVP	Central Valley Project, the federal-level water project in California
FERC	Federal Energy Regulatory Commission
GCM	Global circulation model, also known as global climate model
GHG	Greenhouse gas—a gas such as carbon dioxide or methane that contributes to global climate change
maf	Million acre-feet, a unit of measure of water flow
NMFS	National Marine Fisheries Service
SJI	San Joaquin Valley Index, or the "60-20-20 Index"; used to quantify runoff in the San Joaquin Valley Basin
SRES	Special Report on Emissions Scenarios, a publication of the Intergovernmental Panel on Climate Change; see http://ipcc.ch/ipccreports/sres/emission/index.php?idp=0
SVI	Sacramento Valley Index, also known as the "Four River Index" and the "40-30-30 Index"; used to quantify runoff in the Sacramento Valley Basin

SWP	State Water Project
SWRCB	State Water Resources Control Board
USFWS	U.S. Fish and Wildlife Service
VIC	Variable Infiltration Capacity, the name of a hydrologic model used in this study
WYT	Water year type—classification of a 12-month period of precipitation as average, above-normal, below-normal, etc.

CLIMATE CHANGE IMPACTS ON WATER SUPPLY AND AGRICULTURAL WATER MANAGEMENT IN CALIFORNIA'S WESTERN SAN JOAQUIN VALLEY, AND POTENTIAL ADAPTATION STRATEGIES

A Paper From:
California Climate Change Center

Prepared By:
Brian A. Joyce, Vishal K. Mehta, David R. Purkey, Larry L. Dale, and Michael Hanemann

FINAL PAPER

DISCLAIMER

Arnold Schwarzenegger, *Governor*

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California's electricity and natural gas ratepayers. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts focus on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

In 2003, the California Energy Commission's PIER Program established the **California Climate Change Center** to document climate change research relevant to the states. This center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions. Priority research areas defined in PIER's five-year Climate Change Research Plan are: monitoring, analysis, and modeling of climate; analysis of options to reduce greenhouse gas emissions; assessment of physical impacts and of adaptation strategies; and analysis of the economic consequences of both climate change impacts and the efforts designed to reduce emissions.

The California Climate Change Center Report Series details ongoing center-sponsored research. As interim project results, the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the center seeks to inform the public and expand dissemination of climate change information, thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

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Abstract

Climate change impacts and potential adaptation strategies were assessed using an application of the Water Evaluation and Planning (WEAP) system developed for the Sacramento River basin and Delta export region of the San Joaquin Valley. WEAP is an integrated rainfall / runoff, water resources systems modeling framework that can be forced directly from time series of climatic input to estimate water supplies (watershed runoff) and demands (crop evapotranspiration). We applied the model to evaluate the hydrologic implications of 12 climate change scenarios as well as the water management ramifications of the implied hydrologic changes. In addition to evaluating the impacts of climate change with current operations, the model also assessed the impacts of changing agricultural management strategies in response to a changing climate. These adaptation strategies included improvements in irrigation technology and shifts in cropping patterns towards higher valued crops. Model simulations suggested that increasing agricultural demand under climate change brought on by increasing temperature will place additional stress on the water system, such that some water users will experience a decrease in water supply reliability. The study indicated that adaptation strategies may ease the burden on the water management system. However, offsetting water demands through these approaches will not be enough to fully combat the impacts of climate change on water management. To adequately address the impacts of climate change, adaptation strategies will have to include fundamental changes in the ways in which the water management system in operated.

Keywords: climate change, water management, crop water demand, irrigation, water resources modeling

1.0 Introduction

1.1. California Water Resources

One of the defining features of the California landscape is the Sierra Nevada mountain range that runs along much of the eastern part of the state (Figure 1). The rivers that run out of the Sierra provide drinking water for the state's large urban areas and provide irrigation for the state's vast agricultural land in the Central Valley. Precipitation, however, falls mainly in the fall and winter, so flows in these rivers are sustained throughout the year by melting snow. In fact, Sierra snowpack accounts for approximately half of the surface water storage in the state. Current projections forecast that this snowpack may decline by 70% to as much as 90% over the next 100 years, threatening California's water supply (California Climate Change Center 2006).

Figure 1. California geography

In addition to having to manage water supplies that are unequally distributed throughout the year and, indeed, vary considerably from year to year, the state also faces the challenge of moving water from the water-rich northern part of the state to support cities and agriculture in drier areas in the south. Left to flow naturally through the state's rivers, most of the precipitation that falls in the state would flow out to the Pacific Ocean either directly through the rivers of the North Coast or through the San Francisco Bay via the Sacramento and San Joaquin rivers. This would leave the southern part of the state—which contains roughly two-thirds of the state's population—with little of the state's available fresh water supplies. To address this imbalance, several local, state, and federal water projects have been built to deliver water from the water-rich parts of the state to the arid south (Figure 2).

Figure 2. Major state, federal, and local water projects in California
Courtesy of the California Department of Water Resources

Indeed, the state has made a fairly Herculean effort to transfer water between watersheds through a complex of canals and tunnels that have been built over the last century. Figure 3 shows average annual volumes of water that are transferred between the state's ten hydrologic regions. It is clear from this graphic that many parts of the state rely heavily upon water exports from the Sacramento River Basin. It is critical then for the viability of water management in California to understand how climate change may affect the sustainability of operating the water management system to deliver water throughout the state.

The importance of the Sacramento River as a source of water for the entire state led the research team, as part of the 2006 Scenarios Project reporting, to focus on that region when investigating the potential impacts of climate change on water management. In that work, possible changes in hydrology and water demand in the regions south of the Delta was not explicitly considered in the analysis. As part of the 2009 Scenarios Project reporting, an effort was made to extend the scope of the analysis to include the impact of climate change on water demand in the western San Joaquin Valley. This incremental expansion will allow for a more comprehensive assessment of climate change impacts, and possible management adaptations, in the California Water System, particularly since this area constitutes a major portion of the water demand that drives water exports from the Delta. While future work would logically include bringing the rest of system in to the model, the current expansion represents an important step in developing a tool for climate change assessment in California water management.

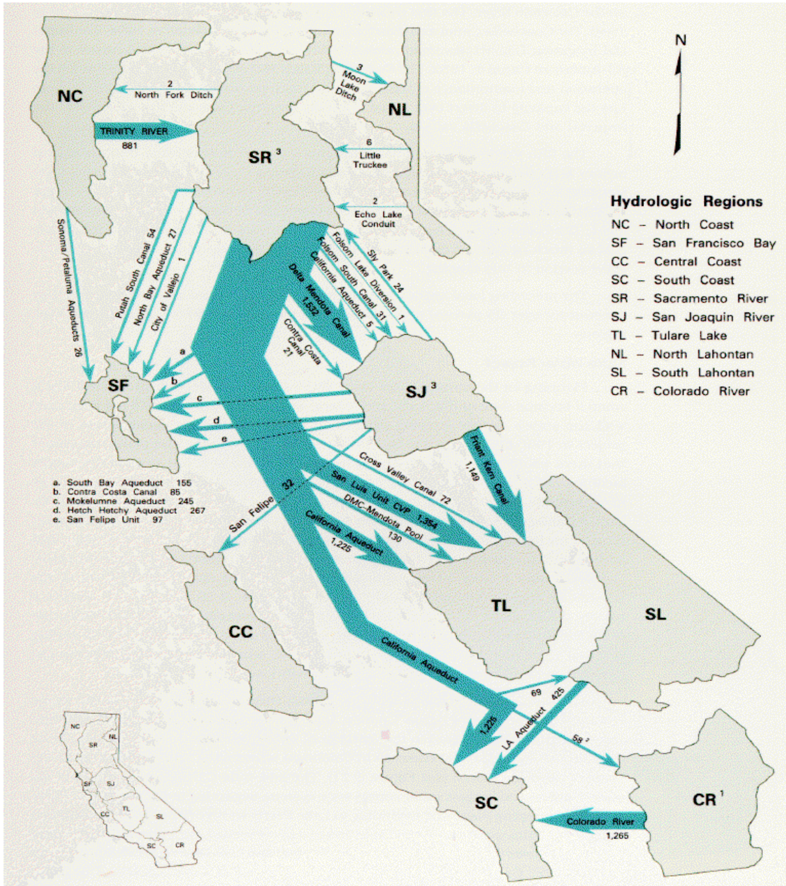


Figure 3. Interbasin Water Transfers
Courtesy of the California Department of Water Resources

1.2. Background

The 2006 edition of the report to the California governor and legislature on potential climate change impacts and adaptations (California Environmental Protection Agency 2006) included an annex report on potential impacts to Sacramento Valley agriculture (Joyce et al. 2006). This analysis was conducted using the Water Evaluation and Planning (WEAP) modeling system (Yates et al. 2005a; Yates et al. 2005b) developed by the Stockholm Environment Institute. While the technical aspects of the WEAP model and the Sacramento Valley application are presented later in this paper, it is worth mentioning that WEAP is an integrated rainfall/runoff, water resources systems modeling framework that can be forced directly from time series of climatic input. Within a single software package, the hydrologic implications of a climate change scenario as well as the water management ramifications of this hydrologic change can be assessed.

Using this WEAP application as part of CalEPA's 2006 report to the governor, it was possible to assess the implications of a limited set of future climatic sequences on water demand in the various sectors and to evaluate the availability of supplies to meet these demands. These future climate scenarios were developed based on downscaling of two general circulation models (GCMs)—the Geophysical Fluid Dynamic Laboratory model (GFDL) and the Parallel Climate

Model (PCM)—run under two emissions scenarios (A2 and B1). The results suggested that increasing agricultural demand under climate change due to increased evapotranspiration (ET) would place additional stress on the water system in the Sacramento Valley. The model was also used to assess the effectiveness of two agricultural adaptations, increasing on-farm efficiency and crop shifts toward lower consumption / higher value crops in times of shortage. These were found to be effective at reducing supply shortfalls in agriculture and other sectors.

The completeness of this analysis was limited somewhat, however, because the water demand within the region that depends upon water deliveries from the Sacramento-San Joaquin Delta was not adjusted according to the assumed climatic sequences, and was instead a composite of historic export demands. This demand is a critical driver of water operations in the Sacramento Valley and a major factor in characterizing the status of the Delta itself, a topic of increasing urgency. The current work attempts to resolve this issue by bring agricultural demand and water management in the western San Joaquin Valley into the WEAP application. This will include representing climatically driven water demand in the agricultural sector in this region along with the operations of state and federal conveyance and storage infrastructure. This expanded WEAP application, run under 12 climatic sequences using the same two adaptation strategies, will provide a much more complete assessment of the potential impact of climate change on agriculture in the Central Valley and the other users that depend on the waters of the Sacramento River Basin.

1.3. Paper Organization

This paper presents an analysis of climate change impacts on agricultural water management in California's Central Valley and is an extension of research conducted by Joyce et al. (2006) as part of the first report to the governor on climate change (California Environmental Protection Agency 2006). We begin the paper by briefly describing the main features of the water planning model that was used in our previous research and used here as a point of departure for the current effort. We then describe the modifications made to this model that were required to make it suitable for considering climate change impacts on a broader scale than was considered under the previous research effort. This is followed by a section describing the scope of the analyses conducted in the current effort. Specifically, it outlines how we used downscaled climate projections to estimate impacts on water management and then how we constructed hypothetical adaptation strategies that were geared toward offsetting anticipated water shortages. This is followed by a results section wherein we present the estimated impacts of the climate projections on water management and discuss the capacity of combating these impacts through demand reduction adaptation strategies. We end with some conclusions about our findings.

2.0 Project Approach

2.1. WEAP Model Description

The Water Evaluation and Planning (WEAP) system is a comprehensive, fully integrated water basin analysis tool. It is a simulation model that includes a robust and flexible representation of water demands from all sectors and flexible, programmable operating rules for infrastructure elements such as reservoirs, canals, and hydropower projects. Additionally, it has watershed rainfall-runoff modeling capabilities that allow all portions of the water infrastructure and demand to be dynamically nested within the underlying hydrological processes. In effect, it allows the modeler to analyze how specific configurations of infrastructure, operating rules, and priorities will affect water uses as diverse as in-stream flows, agricultural irrigation, and municipal water supply under the umbrella of input weather data and physical watershed conditions. This integration of watershed hydrology with a water systems planning model makes it ideally suited to studies of the impacts of climate change internal to watersheds.

2.1.1. Sacramento Valley WEAP Application

For a complete description of the Sacramento Valley WEAP application, the reader is strongly encouraged to refer to Yates et al. (2008). In summary, however, the WEAP application for the Sacramento Valley water system includes the major rivers; the major alluvial aquifers; the major trans-basin diversion from the Trinity River; the main reservoirs (Clair Engle, Shasta, Whiskeytown, Black Butte, Oroville, Almanor, Bullard's Bar, and Folsom); the major irrigation canals and their associated demand centers (e.g., Tehama-Colusa canal, the Glen-Colusa canal, and others); aggregated irrigation districts that draw water directly from rivers; and the principal urban water demand centers. Three flood conveyance systems included in the model are the Sacramento Weir and the Yolo and Sutter bypasses. A simplified schematic is presented in Figure 4.

The WEAP system allows the user to set priorities among different users, such as urban users and agriculture, to define the preference of a particular user for a particular source, such as surface water or groundwater, and to constrain the transmission of water between sources and users based on physical and or regulatory constraints. In formulating a WEAP application, the user describes the multi-objective nature of most engineered water systems.

This last point merits additional comment. The original EPA call for research proposals sought to develop a framework for climate change impact and adaptation analysis for water resources and aquatic ecosystems that could be used to investigate potential large-scale tradeoffs between various water management objectives. The goal was not to investigate future water supply reliability to individual water users but rather to assess whether the broad range of water uses might remain compatible under what are uncertain future climate scenarios, and if not, whether adaptations would be available to reduce potential conflicts.

The critical point to state here is that the WEAP application of the Sacramento River system includes the possibility of allowing users to tap groundwater in times of surface water scarcity and for allocation of water to urban uses in times of shortage. As such, the system can be used to explore the management tradeoffs intrinsic to the California water system that may accompany future climate change in the state.

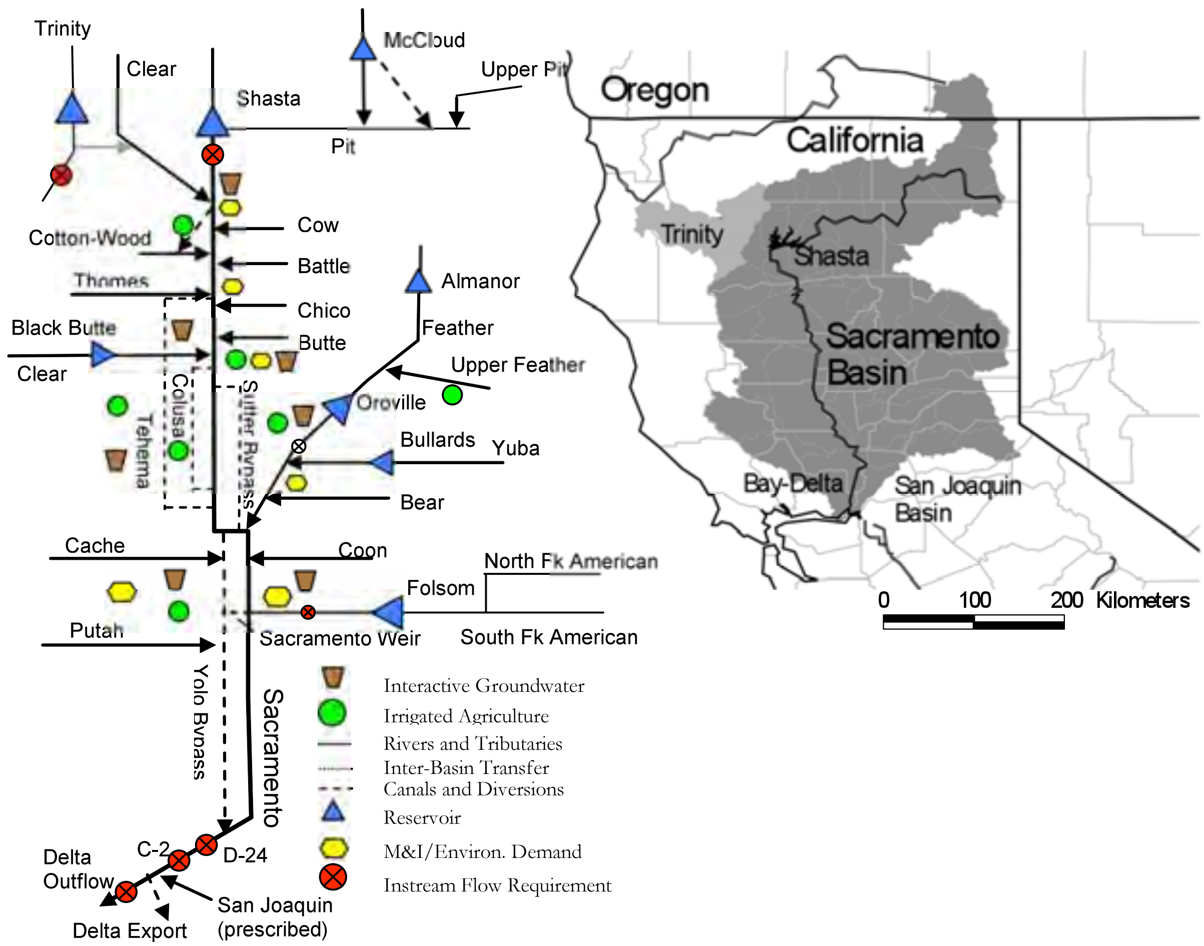


Figure 4. Simplified schematic of the water resources elements implemented in the Sacramento River WEAP model

2.1.2. WEAP Hydrology

The hydrology module in WEAP is spatially continuous, with a study area configured as a contiguous set of sub-catchments that cover the entire extent of the river basin in question. This continuous representation of the river basin is overlaid with a water management network topology of rivers, canals, reservoirs, demand centers, aquifers and other features (see Yates et al. 2005a and Yates et al. 2005b for details). Within each sub-catchment (SC), the entire area is fractionally subdivided into a unique set of independent land use/land cover classes that lack detail regarding their exact location within the SC, but which sum to 100% of the SC's area. A unique climate-forcing data set of precipitation, temperature, relative humidity, and wind speed is uniformly prescribed across each sub-catchment.

A one-dimensional, quasi-physical water balance model depicts the hydrologic response of each fractional area within an SC and partitions water into surface runoff, infiltration, evapotranspiration, interflow, percolation, and baseflow components. Values from each fractional area within the SC are then summed to represent the lumped hydrologic response, with the surface runoff, interflow and baseflow being linked to a river element; deep percolation being linked to a groundwater element where prescribed; and evapotranspiration being lost from the system. Where stream-aquifer interactions are significant, the two-store water balance representation within select SCs can be reformulated by recasting the lower store as a simplified groundwater element that has hydraulic connection to associated river reaches. The hydrology module also includes a snow accumulation / melt routine based on the use of an index temperature approach.

At each time step, WEAP first computes the hydrologic flux, which it passes to each river and groundwater object. The water allocation is then made for the given time step, where constraints related to the characteristics of reservoirs and the distribution network, environmental regulations, and the priorities and preferences assigned to points of demands are used to condition a linear programming optimization routine that maximizes the demand "satisfaction" to the greatest extent possible (see Yates et al. 2005a for details). All flows are assumed to occur instantaneously; thus a demand site can withdraw water from the river, consume some, and optionally return the remainder to a receiving water body in the same time step. As constrained by the network topology, the model can also allocate water to meet any specific demand in the system, without regard to travel time. Thus, the model time step should be at least as long as the residence time of the study area. For this reason, a monthly time step was adopted for this Sacramento Basin analysis.

2.1.3. Agricultural Water Demands

Irrigated crops can be one of many fractional areas within an SC and thus share the same surface hydrologic model as the natural and non-irrigated land covers. Irrigated land covers differ, however, in that the user can assign unique irrigation schedules and upper and lower thresholds for soil water storage, which together dictate the quantity, timing, and efficiency of applied irrigation. Irrigated areas require water sources to meet that demand and in WEAP the user associates surface and / or groundwater supplies to the appropriate catchments that contain irrigated land covers.

Meteorological drivers and crop coverage combine to uniquely define water demands for each sub-catchment. WEAP reads in monthly climate data—precipitation, temperature, relative humidity, and wind speed—to calculate reference evapotranspiration using a modified Penman-Montieth approach. Crop coefficients, characterized for six generalized crop types (row crops, oil crops, cereals, rice, orchards, and pasture), are applied to the reference evapotranspiration to determine crop water requirements, which are met from the soil water stores assigned to each crop type. Water deliveries for irrigation then are requested when soil water is drawn below a lower threshold. The volume of water requested depends upon the depth of the water needed to fill the soil to the upper threshold and the total acreage assigned to each crop type.

2.2. Model Refinements

2.2.1. Expanding the Model into the San Joaquin Valley

The Sacramento Valley WEAP application considered water demands outside of the Sacramento Basin that rely upon water transfers through the Delta (herein referred to as the *export zone*) to be unchanged from historical patterns. This assumption limited the scope of the analysis conducted, because it did not consider how shifting Delta exports could potentially affect the operations of the water system in the Sacramento Valley. The current effort addresses this issue by expanding the model domain such that it includes the agricultural areas in the western San Joaquin and Tulare Lake Basins.

Expanding WEAP to include the demands within the export zone requires the consideration of different demands types (agricultural, urban) and the major management authorities that serve them: the Central Valley Project (CVP), State Water Project (SWP), and the Contra Costa Water District (CCWD). Whereas the Sacramento Valley model lumped all exports from the Delta and did not follow them to their point of use, the revised model tracks exports from the main points of diversion—Jones Pumping Plant, Banks Pumping Plant, and the Contra Costa Canal—to the main areas of use: CVP agricultural contractors in the western San Joaquin and Tulare Lake Basin, SWP users south of the Delta, CCWD, and CVP water contractors in the Santa Clara Valley (herein referred to as *the San Felipe unit*). Additionally, because the demand for water in the export zone is out of phase with the available water supplies from the Delta, the revised model includes a representation of San Luis reservoir and its operations. The modified WEAP schematic of the area serviced by Delta exports is shown in Figure 5.

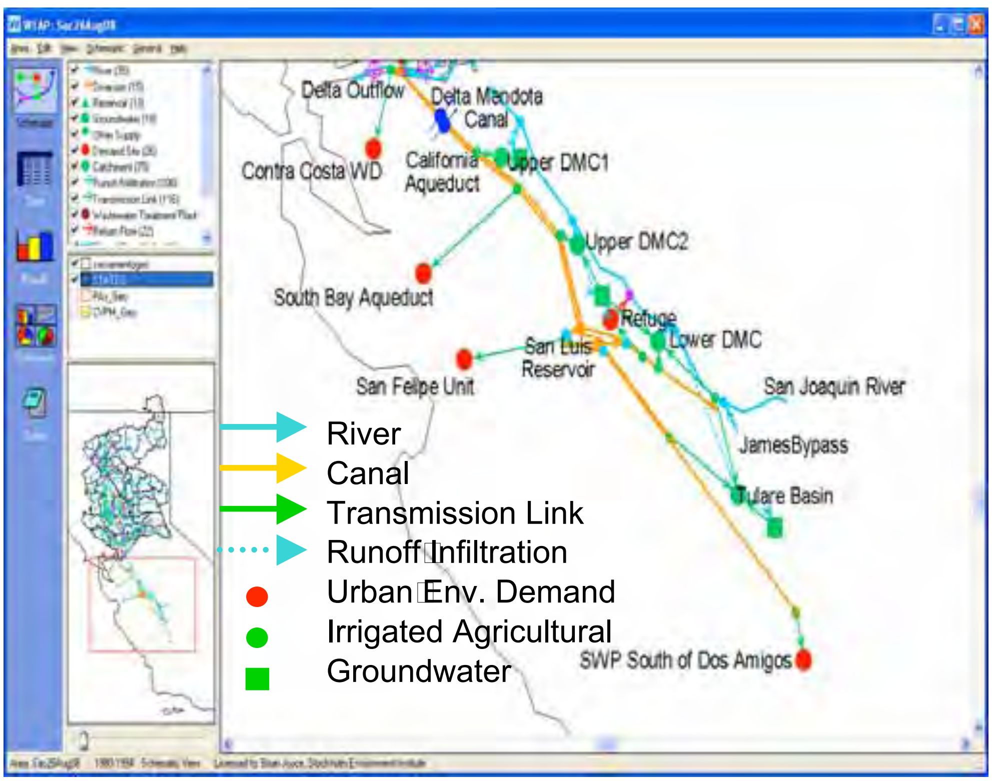


Figure 5. WEAP schematic of Delta export zone

The details of the model changes required to include the west side of the San Joaquin Valley and export zone are presented below. A description of the model recalibration to historical data is given in Appendix A: Model Calibration.

Agricultural and Urban Water Demands

The model was expanded to include agricultural areas in the western San Joaquin and Tulare Lake Basins that receive water pumped from the Delta. These irrigators contract water primarily with the CVP and are serviced by the Delta Mendota Canal (DMC) and San Luis Reservoir. These demand areas were divided into four general regions based upon water sources and, because this study linked with an economic model of changing cropping patterns, overlap with regions defined within the Central Valley Production Model, CVPM (U.S. Department of the Interior 1997). The demand areas are summarized in Table 1.

Table 1. Agricultural areas receiving Delta export water

WEAP demand	Water Users	Surface Water Source	CVPM Region
Upper DMC1	CVP contractors	DMC	Region 9
Upper DMC2	CVP contractors	DMC	Region 10
Lower DMC	CVP contractors, Exchange contractors	DMC, San Luis Reservoir, Mendota Pool	Region 10
Tulare Basin	CVP contractors	San Luis Canal, Mendota Pool	Region 14

For each of the four agricultural areas in the western San Joaquin and Tulare Lake Basins, irrigation schedules and cropped acreages were defined for thirteen irrigated and one non-irrigated land classes (Table 2). Unique irrigation schedules were defined for each commodity, while rice included an explicit representation of ponding to mimic its flood irrigation strategy and to represent the capture and storage of water by rice fields. Cropping patterns were fixed over the calibration period, 1993–2001 (see Appendix A: Model Calibration) and for base scenario runs, but they were allowed to change from year to year for other analyses (see Section 3.3 Demand Analysis) by linking WEAP to CVPM outputs (see Shifting Cropping Patterns in Section 2.3.2).

Table 2. Irrigated crops

Crop Type	Irrigation Schedule
Alfalfa	February–October
Cotton	May–October
Grain	November–May
Pasture	February–October
Rice	May–September
Sugar Beet	April–September
Tomato – Process	March–August
Tomato – Market	April–August
Vineyard	March–November
Orchard	March–October
Subtropical	March–October
Field crops	April–September
Truck crops	April–September
Fallow	N / A

The agricultural areas in the western San Joaquin and Tulare Lake Basins represent only part of the total demands within the export zone. Delta export water is delivered also to demand areas in the San Francisco Bay, the Central Coast, and the South Coast. These demand areas that lie outside of the geographic area covered by the WEAP model are summarized in Table 3. These demands are treated as boundary conditions to the current model. Two of these areas—the South Bay Aqueduct and the State Water Project south of Dos Amigos—receive surface water deliveries directly from the California Aqueduct; whereas, the Contra Costa Water District pumps from the Delta and the San Felipe Unit takes water from San Luis Reservoir.

For each of these areas, we used average historical monthly deliveries (1993–2001) to estimate their total annual demands and their monthly variation. For the calibration period, we applied a multiplier to adjust the annual demands to the observed historical record. For future scenarios, we assumed that these demands could be approximated by their observed 1993–2001 averages.

While it is reasonable to assume that water demands in these areas may increases in the future, we chose not to adjust these demands such that we could limit our analyses to evaluating the changes in demand and management that were driven by climate inputs to the model. Thus, our assessment focused on conducting a differential analysis of climate change impacts on agricultural water demand and the subsequent impacts on water management.

Table 3. Demand areas outside of the Sacramento and San Joaquin basins that receive Delta export water

WEAP Demand	Average Annual Demand (1993–2001)
Contra Costa Water District	0.109 million acre-feet
South Bay Aqueduct	0.102 million acre-feet
San Felipe Unit	0.128 million acre-feet
State Water Project south of Dos Amigos	2.245 million acre-feet

Delta Export Operations

Exports from the Delta at the Banks (SWP) and Jones (CVP) pumping plants are controlled by many regulatory rules and operational objectives. The regulatory rules include export restrictions during critical migration periods for anadromous fish called for under Section 3406b(2) of the Central Valley Project Improvement Act (CVPIA), flow objectives for the Bay-Delta estuary in accordance with SWRCB Decision 1641, and discretionary use of the environmental water account (EWA) to set limits on Delta exports. The operational objectives include delivery allocations to SWP and CVP contractors and sharing surplus and deficit flows within the Delta by the two projects under the Coordinated Operations Agreement (COA). The WEAP application was modified to include representations of regulatory guidelines that restrict Delta exports during periods deemed critical for supporting aquatic ecosystems and operational objectives that limit exports during dry periods when water supplies are insufficient to satisfy all consumptive water demands within the system.

The regulatory guidelines restricting Delta exports include aspects of the standards mentioned above. While the model does not perform a full accounting of b(2) or EWA operations, rules were added that curtail Delta exports during and following the critical April–May pulse period, during which extra releases are made on the San Joaquin River to facilitate juvenile salmon out-migration. Further, whereas b(2) and EWA restrictions are discretionary actions that vary in degree from year to year, we have added rules that are applied in each year, which capture average Delta operations over the calibration period, 1993–2001. First, between April 15 and May 15 the combined CVP and SWP Delta exports were limited to 1500 cubic feet per second (cfs). Following this period, separate restrictions were applied to Banks and Jones exports. For CVP Delta exports, the b(2) pulse period restrictions were extended to the end of May and ramped up to 3000 cfs for the month of June. For SWP, assumed EWA actions limited Delta pumping at Banks to 3000 cfs for the period May 16–June 30.

Inter-annual variability in water supply motivates many of the reservoir operating rules. These rules are intended to secure water for dry years by balancing current water demands against carryover storage for delivery in subsequent years. Currently, the WEAP model contains routines for tracking water year-types using the Sacramento Valley Index, the Eight River Index, and the Shasta Index. These routines are used within the model to adjust environmental flow requirements, but are not implemented to guide curtailment of deliveries to CVP and SWP water contractors. That is, the model does not calculate annual allocations for the two projects. Instead, the WEAP model imposes limits on the amount of water that can be released from reservoirs. When storage drops below certain thresholds (i.e., into the buffer storage zone) reservoir releases are limited to a fraction (or buffer coefficient) of remaining active storage. This limits the amount of surface water available that can be diverted from rivers and, ultimately, pumped from the Delta.

The Sacramento-western San Joaquin WEAP application has been developed to evaluate regional water supply and demand conditions. Therefore, analyses focus on water deliveries to different water use sectors (i.e., domestic, agriculture, and environment), but do not distinguish between all of the various users within a sector. The model, however, represents the major infrastructural components that influence the distribution of water through the system. Therefore, many of the principal water users are explicitly represented. For example, the main service areas of the Delta-Mendota Canal and the California Aqueduct are modeled as distinct demand areas because the magnitude and seasonal pattern of their demands affect Delta export and San Luis reservoir operations. However, for reporting purposes, we consider the aggregate of deliveries to water use sectors, and not to each project. This obviates the need to consider sharing of surplus Delta flows between the projects under COA. For sharing responsibility to satisfy Delta standards, reservoir storage priorities and buffer coefficients were used to train the model.

San Luis Reservoir

The San Luis Reservoir is an off-stream (or pump-storage) reservoir located in the eastern part of the Diablo Range, west of the San Joaquin Valley. Water from California's Sacramento-San Joaquin Delta is delivered to San Luis Reservoir via the California Aqueduct and Delta-Mendota Canal for temporary storage during the rainy season. During the dry season, this stored water is released for use by SWP and CVP water contractors located south of the Sacramento-San Joaquin Delta. San Luis Reservoir also provides water to the Santa Clara Valley Water District (SCVWD) and the San Benito County Water District (SBCWD). Water is delivered to these users through the CVP's San Felipe Division on the west side of the reservoir.

The San Luis Reservoir is set up within the WEAP model to fill in the fall and winter (Oct–Mar) and release in the spring and summer (Apr–Sep). This is accomplished by using a combination of priorities, target storages, and pumping limits. The priority for San Luis storage is set such that water is pumped into the reservoir only after all other demands (agricultural, urban, environmental) have been met, including meeting target storages for Sacramento Valley reservoirs. The target storage for San Luis is set to fill the reservoir from its low point – generally at the end of August—to its maximum capacity (2.04 million acre feet, or MAF) by the end of March. For the period April–September, pumping into the reservoir is turned off and releases are limited to a fraction of the available storage. This fraction increases as the irrigation season proceeds, such that all of the available storage in San Luis can be utilized (i.e., April = 1/6, May = 1/5, June = 1/4, July = 1/3, August = 1/2, and September = 1).

Other Water Sources

Many of the water users in the San Joaquin Valley receive their surface water deliveries out of the Mendota Pool, which lies at the confluence of the San Joaquin River with the Delta Mendota Canal (DMC) and Fresno Slough/James Bypass. Much of the water that flows into the Mendota Pool comes from the Delta Mendota Canal. In exceptionally wet years, however, a large fraction of the water that is delivered from the Mendota Pool may originate from the San Joaquin River and / or the Fresno Slough / James Bypass.

For the purposes of model calibration and baseline historical runs, we used observed (1922–2003) San Joaquin River and Fresno Slough / James Bypass inflows to Mendota Pool. While the San Joaquin River record showed a consistent seasonal pattern of flow, the Fresno Slough / James Bypass record demonstrated no such pattern. For future scenarios, we used average monthly inflows (omitting outlying peak events) from the San Joaquin River into the Mendota Pool, but did not construct a similar boundary condition for the Fresno Slough / James Bypass, because of the irregularity of flows. Thus, it should be noted that in the scenarios unmet demands and / or deliveries from other sources may be overestimated in wet years for Mendota Pool water users.

2.2.2. *Introducing Delta Water Quality Standards*

The previous version of the Sacramento Valley WEAP model included a schedule of minimum Delta outflow requirements, which were intended to support and protect estuarine habitat for anadromous fish and other estuarine-dependent species. Expanding the WEAP application to include a model of the western San Joaquin Valley and export zone decoupled a boundary condition of the model, which had included elements of both consumptive and non-consumptive water demands. This then necessitated the consideration of Delta water quality standards as a means of bounding Delta export operations. For this study, we included two Delta water quality standards—salinity and X2—that together with the Delta outflow requirement combine to determine the minimum required Delta outflow.

Outflow requirements to meet Delta salinity standards were determined by linking WEAP to the Contra Costa Water District's salinity-outflow model, commonly referred to as the "G-model" (Denton and Sullivan 1993). The G-model is based on a set of empirical equations, developed from the one-dimensional advection-dispersion equation. The model predicts the salinity caused by seawater intrusion at a number of key locations in Suisun Bay and the western Sacramento-San Joaquin Delta as a function of antecedent Delta outflow. This antecedent or effective Delta outflow incorporates the combined effect of all the previous Delta outflows. That is, the model acknowledges that today's salinity is not just a function of today's outflow but also the outflows going back at least three to six months. Because this salinity-outflow model was developed from the one-dimensional advection-dispersion equation, it accounts for the transport of salt by both mean flow (advection) and tidal mixing (dispersion).

In addition to setting flow requirements to meet Delta salinity standards, WEAP sets a Delta outflow standard to maintain the position of the two parts per thousand bottom isohaline, X2, which is applied as a habitat indicator for the Delta. For this, WEAP uses the Kimmerer-Monismith equation to compute the required net Delta outflow, based upon the position of X2 in the previous month (Kimmerer and Monismith 1992).

2.2.3. *Model Summary*

The WEAP application developed for this study covers much of the same area and water management features that are represented in other models used in water planning in California: mainly, CalSim-II and CALVIN. The WEAP model, however, differs from these tools in a couple of important respects. First, unlike standard water resource planning tools that rely on exogenous information on water supply and demand to simulate how available water should be allocated, WEAP has embedded a watershed hydrology module into a water resources modeling framework, such that climatic inputs can be used directly to drive the model. This integration of hydrologic processes into a water resources modeling framework allows for analysis of the future climate scenarios that are unbounded by a reliance on historical hydrologic patterns. That is, analysis in the WEAP framework flows directly from the future climate scenarios and not from a perturbation of the historic hydrology as is necessary in applying standard tools to the question of potential climate change impacts in the water sector.

The other important distinction to make about the WEAP application is that it contains a rather simplified representation of the rules that guide the operations of the CVP and SWP systems. As such, we have not entered all of the sharing agreements (e.g., Coordinated Operations Agreement), regulatory guidelines (e.g., CVPIA b(2) accounting), and other rules (e.g., project allocations) that are explicitly represented in other planning models. Rather, we have attempted to capture the main features that govern the operation of the system as a whole. This choice was made in response to the main research objective which was to develop a tool that could illuminate high level implication of climate change and potential adaptive responses. This is as against an objective which would focus on impacts that may be felt by individual water right and water contract holders in California.

Even though we have not focused on these individual water right and water contract impacts, we have captured enough of the details of the system to allow us, through this and other studies (Joyce et al. 2006; Yates et al. 2005b; Yates et al. 2008), to refine the representation of model features such that model simulations reliably recreate observed patterns in water supply (i.e., reservoir storage, unimpaired streamflow, groundwater elevation, snow pack), water demand (i.e., crop evapotranspiration of applied water, urban demand), and system operations (i.e., surface water deliveries, delta inflows, delta exports, delta outflows). This same type of calibration, it is argued by some, is impossible for other models that possess detailed regulations that have changed through time.

The successful calibration and validation of the model gives us confidence that WEAP can reliably simulate the water management system and, so, can be used to evaluate the impacts of changes in water management in response to changing water supply conditions. It should be understood, though, that the WEAP model is intended to complement the standard set of water planning tools. Given the simplifications made in describing project-specific operations, the WEAP model is directed towards evaluating broader-scale issues of water management. Its utility is mainly in evaluating high-level water management objectives and identifying the most promising set of strategies that may be used to optimally operate the system. Once identified, such strategies may require further investigation using standard tools, which can address management issues at a finer scale. Lastly, the integration of hydrological processes into the WEAP planning model make the tool particularly strong in evaluating proposed management alternatives in the context of climate change.

2.3. Analytical Approach

The WEAP model was used to evaluate the impact of twelve future climate scenarios on agricultural water management in the region, and to investigate whether water management adaptation could reduce potential impacts. Each of the twelve climate sequences was run for three management scenarios: one in which no changes in agricultural practices occurred (No Adaptation); a second in which improvements in irrigation efficiency occurred gradually until 2050 (Increased Irrigation Efficiency); and a third in which annual cropping patterns changed in response to water supply conditions (Shifting Cropping Patterns). All scenarios were run for an analysis period 2006–2099.

2.3.1. Future Climate Scenarios

The Intergovernmental Panel on Climate Change (IPCC) released a *Special Report on Emissions Scenarios* (SRES) that grouped future greenhouse gas emission scenarios into four separate "families" that depend upon the future developments in demography, economic development, and technological change (Nakicenovic and Swart 2000). Together they describe divergent futures that encompass a significant portion of the underlying uncertainties in the main driving force behind global climate change. These scenario families are summarized in Box 1. For the purposes of this study, outputs from six general circulation models (GCMs) were used to estimate future climate conditions under two SRES scenarios: A2 and B1. By choosing six GCM and two emission scenarios that would be applied to all investigations in response to the governor's executive order (S-3-05), the Climate Action Team hoped to create a consistent set of output that would represent the range of future climate conditions.

The six GCMs used to generate the future climate conditions for the current investigation are summarized in Table 4. Outputs from these models were downscaled by applying the methodology developed by Maurer et al. (2002) to create a 1/8 degree gridded data set for daily climate variables. These downscaled daily data were used to derive average monthly time-series of precipitation, temperature, wind speed, and relative humidity for each of the 75 sub-catchments in the WEAP model.

Table 4. General circulation models used in study

Developer	GCM	Study Code
Center for National Weather Research, CNRM (France)	CM3	GCM1
Geophysical Fluid Dynamics Laboratory, GFDL (US)	CM2.1	GCM2
Center for Climate System Research, CCSR (Japan)	MIROC 3.2	GCM3
Max Planck Institute, MPI (Germany)	ECHAM5	GCM4
National Center for Atmospheric Research, NCAR (US)	CCSM3.0	GCM5
National Center for Atmospheric Research, NCAR (US)	PCM1	GCM6

Box 1. Main Characteristics of the Four SRES Storylines
from Nakic´enovic and Swart (2000), *Special Report on Emissions Scenarios,* published by the Intergovernmental Panel on Climate Change.

- The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive sources (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).
- The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.
- The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.
- The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

2.3.2. Adaptation Strategies

Adaptation to climate change within the agricultural sector is likely to occur naturally in response to economic signals that are driven by public policy, market conditions, and, in a setting like California, the availability of irrigation water supply. Understanding the evolution of this last factor under future climate conditions requires the application of a water resources systems model that tracks the management of the available hydraulic infrastructure.

In the context of adaptations, WEAP allows the model user to represent dynamic changes in water management by programming in model parameters that vary over the course of a simulation. These parameter changes can be imposed as exogenous forces upon the model (e.g., as functions of the passage of time) or they can be expressed within the model as a function of the state of the system (e.g., water supply, crop yields, depth to groundwater). Both methods are used here separately to represent the adaptation strategies considered in this study.

Improving Irrigation Efficiency

With regard to improvements in irrigation efficiency, the research team believes that existing and anticipated future regulatory pressures for improved agricultural water use efficiency are likely to lead to increased efficiency such that most crops other than rice will employ drip irrigation by the middle of the century. For this study, it is assumed that these changes occur gradually over the first half of the century and reach a maximum level by 2050.

To represent these improvements in the WEAP model the parameters that determine the irrigation process in the model were modified. The first of these parameters called the lower irrigation threshold represents the soil moisture level at which irrigation will be required to increase the soil moisture up until it reaches an upper irrigation threshold. Considering that these two parameters were directly related to irrigation procedures they were chosen as parameters to be modified to represent improvements in irrigation efficiency.

Improvements in irrigation efficiency will generally be achieved through reductions in both the lower and upper irrigation thresholds. In practice, this means allowing soils to become dryer when managing irrigation scheduling. Reducing the lower threshold lowers supply requirements, because irrigation is called less frequently, so the level of soil moisture tolerance before external supplies of water are needed are increased. Similar reductions in the upper threshold imply that the same depth of water will be applied at each irrigation. However, as the soil moisture is reduced, irrigation losses to surface runoff and percolation are also reduced, thus improving the overall irrigation efficiency.

Shifting Cropping Patterns

Each agricultural demand unit in WEAP possesses a characterization of how crops are distributed across the land available for irrigation. These cropping patterns were initially estimated using historical land use surveys, which show only a snapshot in time of how crops are distributed. In actuality, cropping patterns change from year to year as farmers react to water supply conditions and economic and social factors. To capture this dynamic, we have included in WEAP cropping relationships, developed by the Lawrence Berkeley National Laboratory (L. Dale, personal communication), that relate the share of various crops within a command area to water supply conditions at the time of planting.

The share of crop acreage in each demand area varies as a function of changes in the supply of surface water and depth to groundwater. The function is derived from a multinomial logit regression analysis of synthetic data of crop shares generated by the Central Valley Production Model (CVPM) for 21 regions in the Central Valley (Figure 6). The data were generated from CVPM model runs assuming the base water supply and groundwater depth and perturbations from these base levels. These model runs provided a suite of synthetic estimates of crop shares across a range of different regional water supply and groundwater depth assumptions. These crop share equations were then used by WEAP to show changes in crop acreage and water use over time.

Figure 6. CVPM regions

3.0 Results

This section shows some results of the WEAP model simulations for each of the 12 climate change scenarios. We begin by evaluating the projected climate data for each of the scenarios used as input to the WEAP model. We then discuss the implication of these projected climate sequences by following their impacts downward through the watershed. First, we evaluate the projected changes in reservoir inflows. This includes an assessment of the changes in timing and magnitude of inflows, as well as a look at the relative magnitude and duration of future droughts. In addition to evaluating the impacts of changing climate on water supply, we also look at how climate change may affect crop water demands. We then evaluate the combined impact of these changes on water management in the Sacramento Valley and Delta export zone. Here we consider the ability of the water resources system to deliver water to satisfy future demands and evaluate the impact of water management on resources protection. This is followed by an evaluation of water management strategies that are expected to offset some of the anticipated consequences of climate change by reducing stressors on California's water resources. We considered separately two "adaptation" strategies: improvements in irrigation efficiency through investments in technology and a shift toward less water-intensive crops as farmers react to changes in water supply conditions.

3.1. Climatic Analysis

In the following analysis, precipitation and temperature data are presented for 12 climate projections. Precipitation and temperature data are presented as averages of 56 climate locations used as inputs to WEAP, aggregated into three regions—Central Valley, Coastal Range and Sierra. Figure 7 and Figure 8 respectively plot the annual precipitation and average annual temperature time series from 2006–2099 for all climate projections. While the data exhibits considerable inter-annual and inter-model variability, there is no apparent change in annual precipitation for either emission scenario (Figure 7). By contrast, a warming trend is discernible in all climate projections across models and emissions scenarios, in all three regions. Further, Figure 8 also shows that, as expected, the rate of warming is higher in the medium-high emissions scenario A2 than in the low emissions scenario B1.

A clearer picture of precipitation changes emerges when comparing across three distinct periods: 2006–2034, 2035–2064, and 2065–2099. Figure 9 shows boxplots of period-averaged annual precipitation across all climate projections. These plots suggest that there is generally a decreasing trend in precipitation from the first third of the century to the latter part of the century, when considering all 12 scenarios. Comparing between emission scenarios, precipitation projections tend to be lower in the A2 scenarios compared to the B1 scenarios, with CNRM-CM3 A2 for 2006–2034 being the exception.

Temperature projections suggested a much stronger trend than that seen with the precipitation data. Figure 10 shows a boxplot for temperature that consistently indicates warming across all projections.

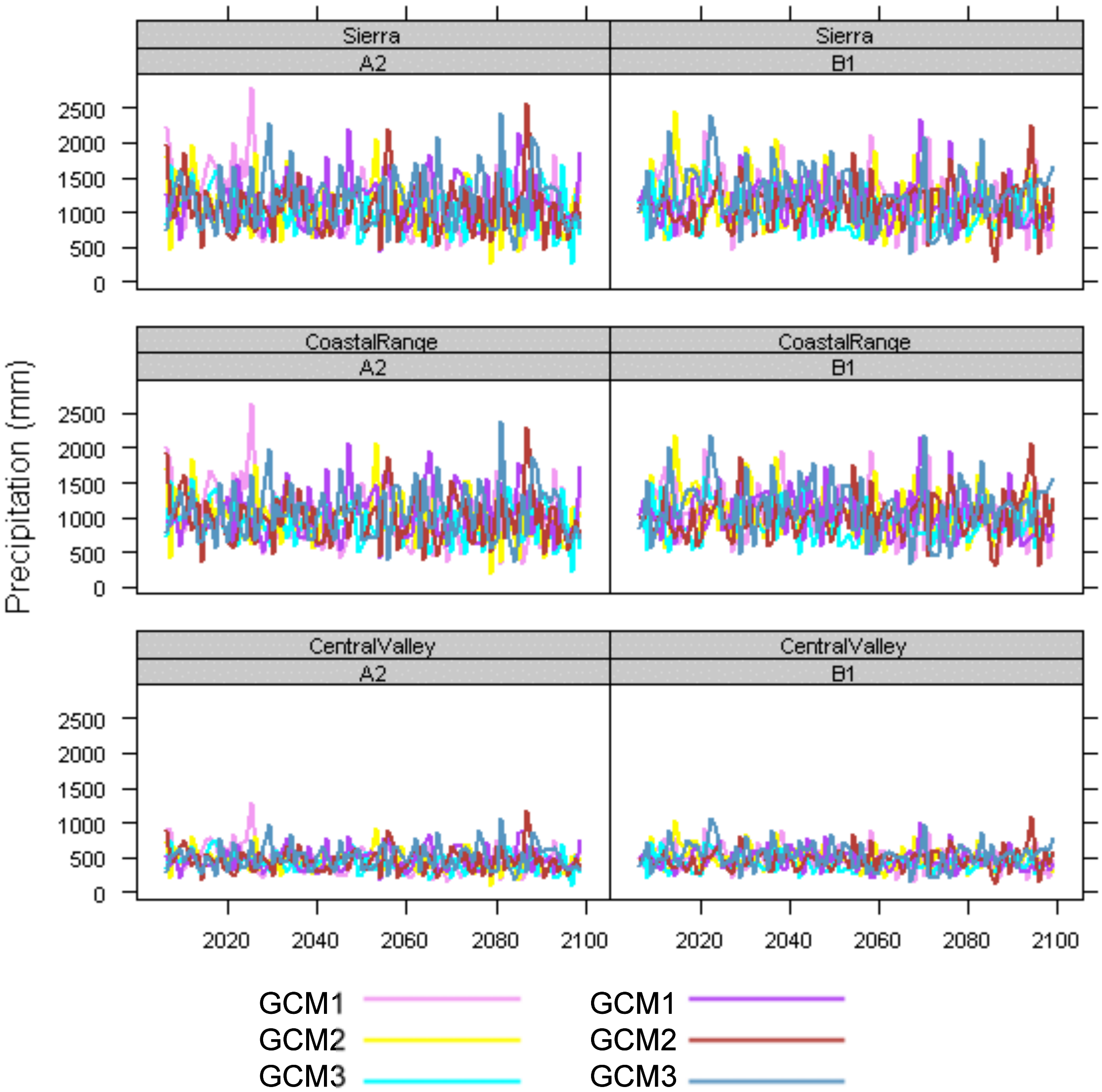


Figure 7. Annual precipitation (2006–2099)

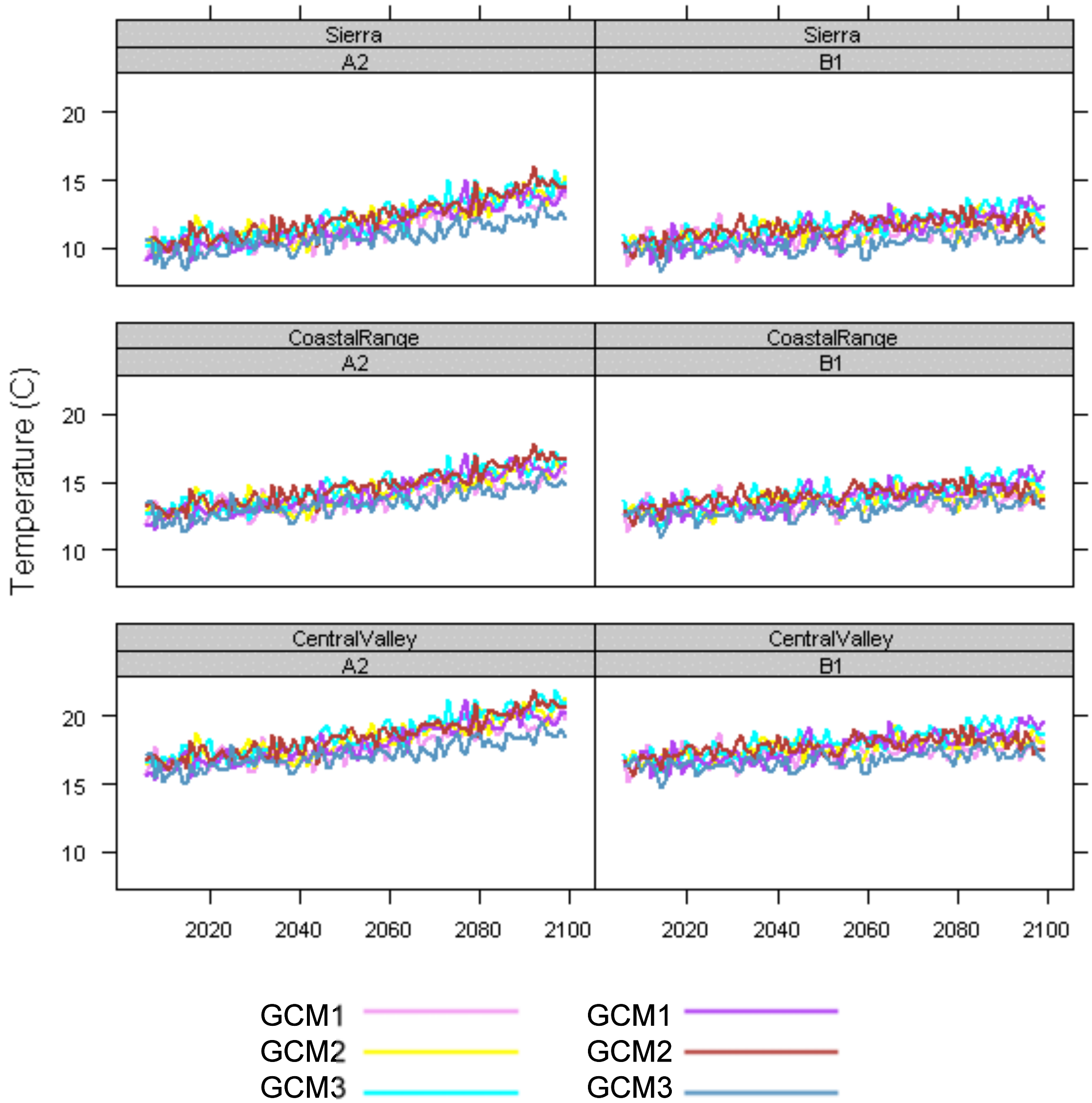


Figure 8. Annual average temperature (2006–2099)

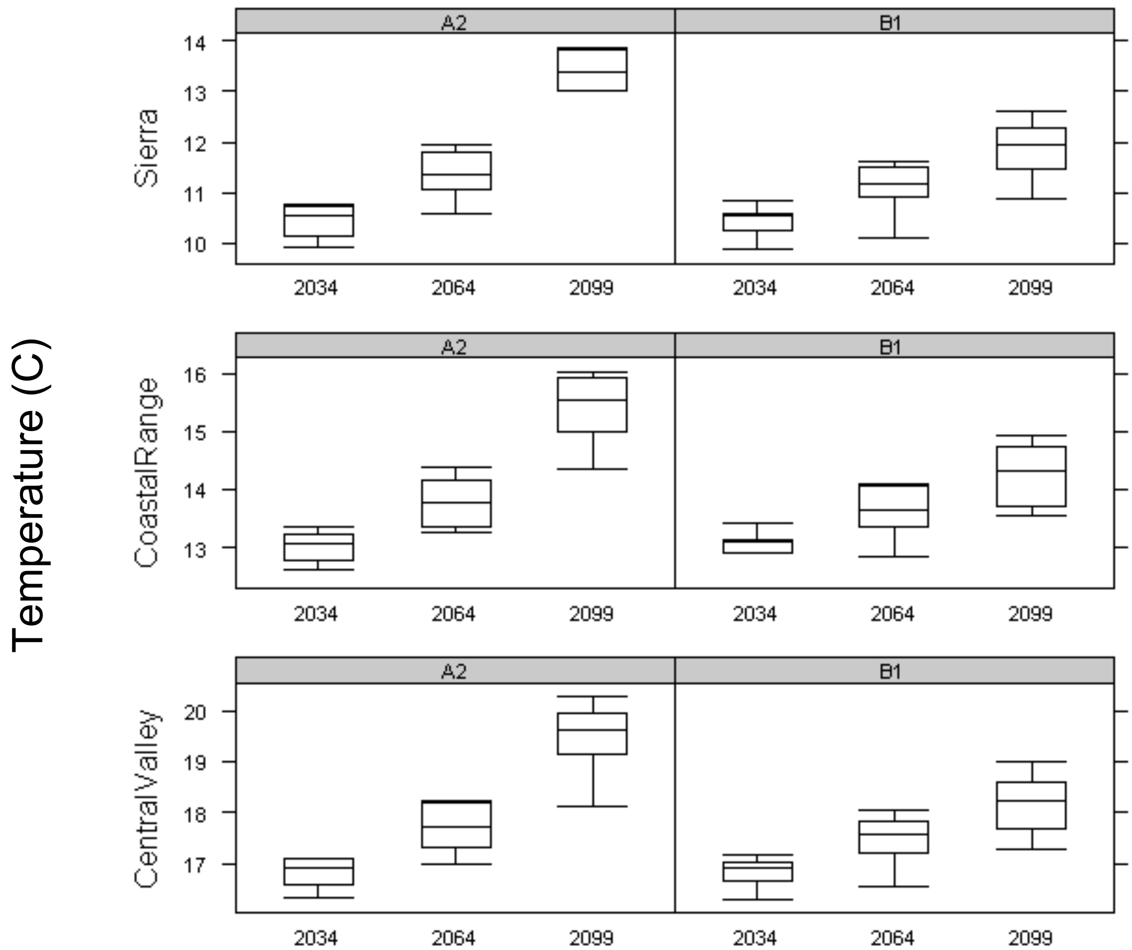


Figure 10. Boxplots[2] of average annual temperature (°C) for three periods (2006–2034, 2035–2064, and 2065–2099)

3.2. Hydrologic Analysis

3.2.1. Reservoir inflows

Figure 11 shows changes in monthly average inflows to the major reservoirs in the Sacramento Basin (Shasta, Folsom, and Oroville) for the end-of-century period 2065–2099. While neither emission scenario showed a statistically significant difference in annual volume of inflow to the three reservoirs as compared to the historic (1950–2005) WEAP baseline, all GCM / emission scenario combinations showed an earlier timing of streamflow. This shift in runoff timing appeared consistent for all reservoirs across models and emission scenarios. These results are consistent with the supposition that warmer temperatures lead to earlier loss of snowpack.

[2] Box covers middle 50% of data, from 25th to 75th percentile. Whiskers are the 1.5*interquartile range. Outliers are not shown. In some plots, whiskers are so close to the box as to appear missing.

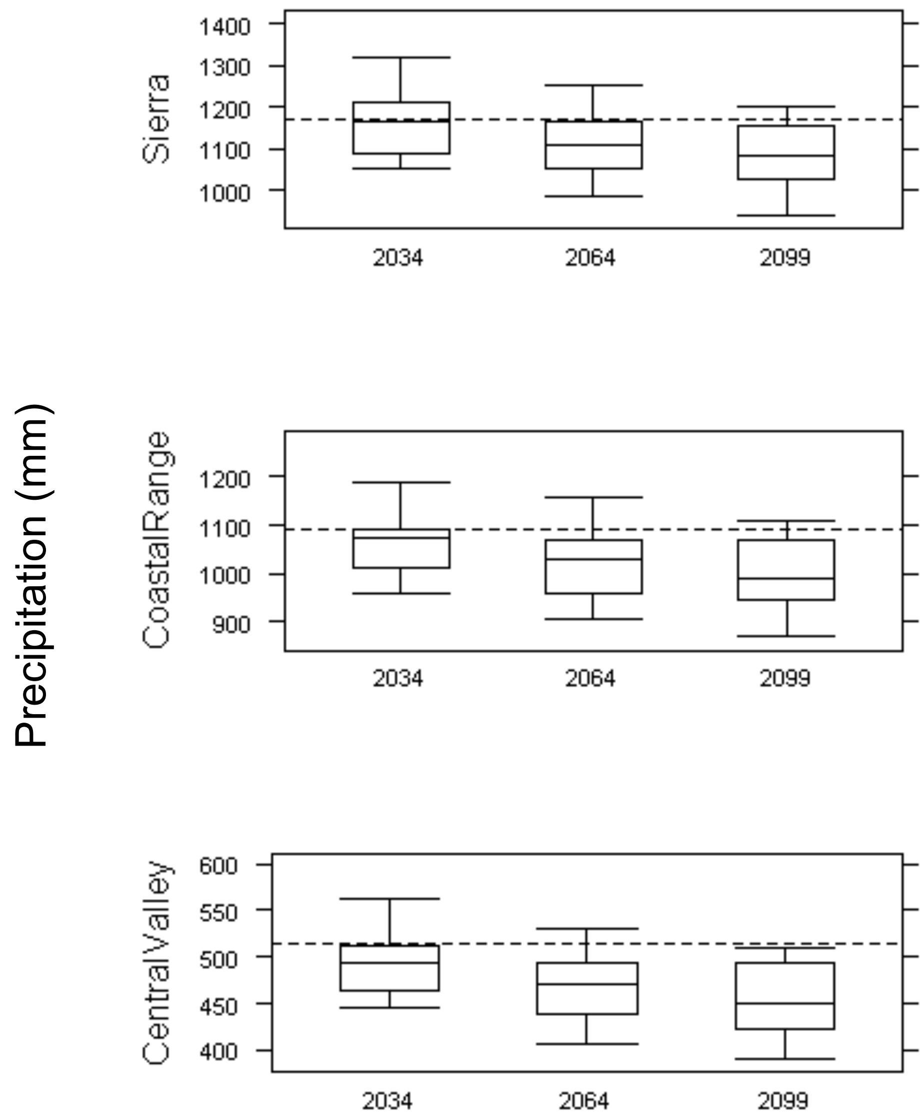


Figure 9. Boxplots[1] of precipitation across all projections for three periods (2006–2034, 2035–2064, and 2065–2099). The dotted horizontal line is historic (1961–1999) mean precipitation.

[1] Box covers middle 50% of data, from 25th to 75th percentile. Whiskers are the 1.5*interquartile range. Outliers are not shown.

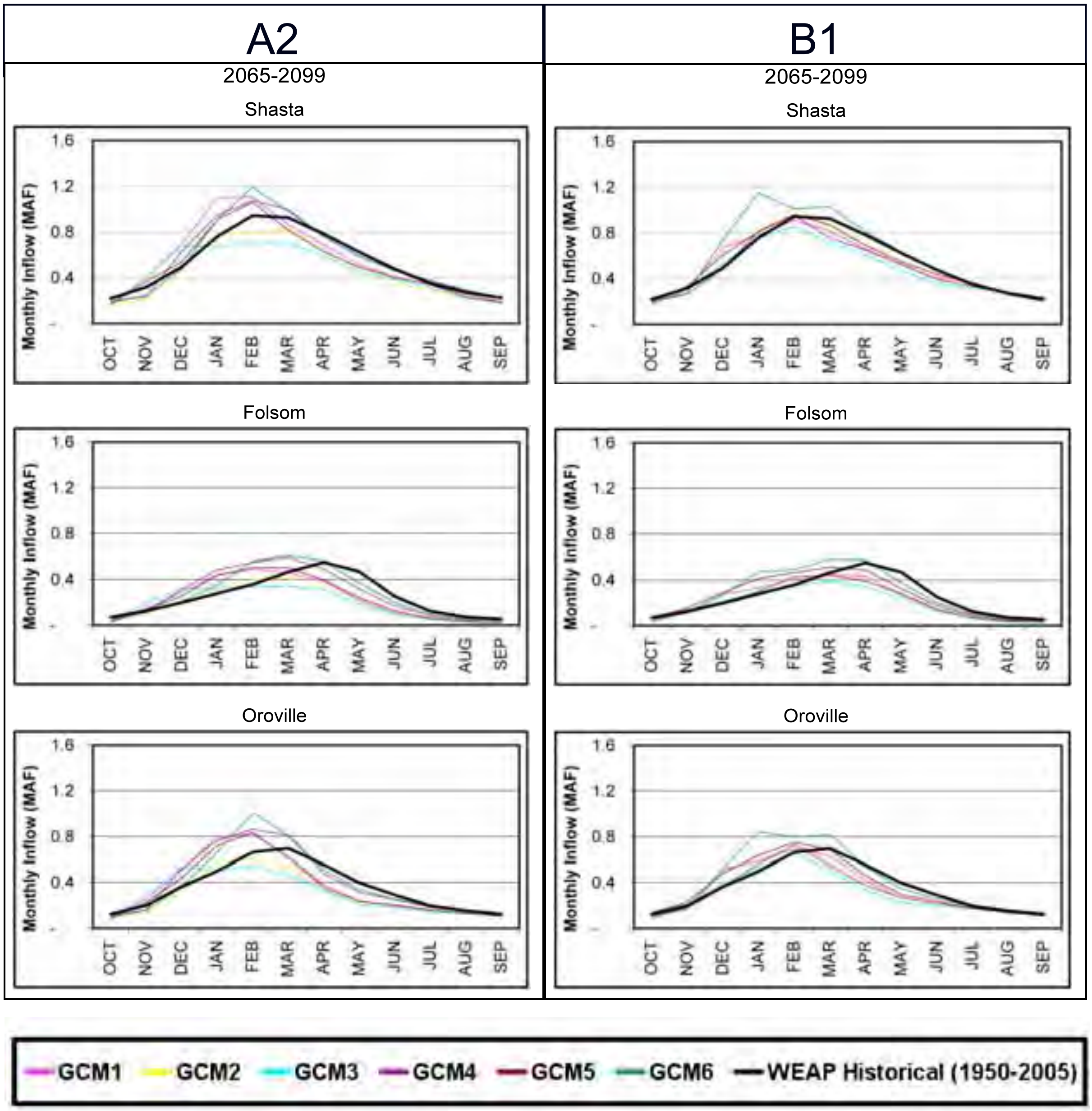


Figure 11. Average monthly inflow to Shasta, Folsom, and Oroville for A2 and B1 emission scenarios

3.2.2. Occurrence of Drought

Whereas some analysis approaches use historic sequences of wet and dry years for future analyses, a major advantage of the WEAP model is that it can examine evolving sequences of wet and dry years for GCM based future climate projections. Thus, WEAP can simulate conditions under different levels of drought persistence that might occur with climate change. This paper includes an estimate of possible changes in future hydrologic conditions in terms of drought persistence. Drought conditions in the Sacramento Basin were described using a construction of the Sacramento Valley 40-30-30 Water Year Hydrological Classification Index

(State Water Resources Control Board 1995).[3] This index is measured in million acre-feet and is composed of unimpaired runoff into Shasta, Oroville, and Folsom Reservoirs plus streamflow at the Yuba River. Based on the value of this index, a water year is classified as wet, above normal, below normal, dry, or critical. Droughts were assumed to occur during years designated as critically dry. The severity of the drought was indicated by a value called the accumulated deficit, which is calculated by subtracting the value of the 40-30-30 index for a given year for a given climate change scenario from the threshold value for the critical year designation (5.4 MAF). These deficits were accumulated in consecutive dry years and were reset to zero whenever the index exceeded the threshold for the critical year designation,.

Figure 12 shows the accumulated deficits for the historic period (the 1976–1977 and early 1990s droughts are apparent) and each of the twelve climate change conditions included in this analysis. The results show much variability in drought persistence between the various climate change projections—with some GCM / emission scenario combinations replicating historic drought conditions, some showing more moderate droughts than observed, and others suggesting more severe droughts. In general, the A2 emission scenario predicted more severe droughts than the B2 scenarios, which agrees with the lower precipitation seen with these scenarios.

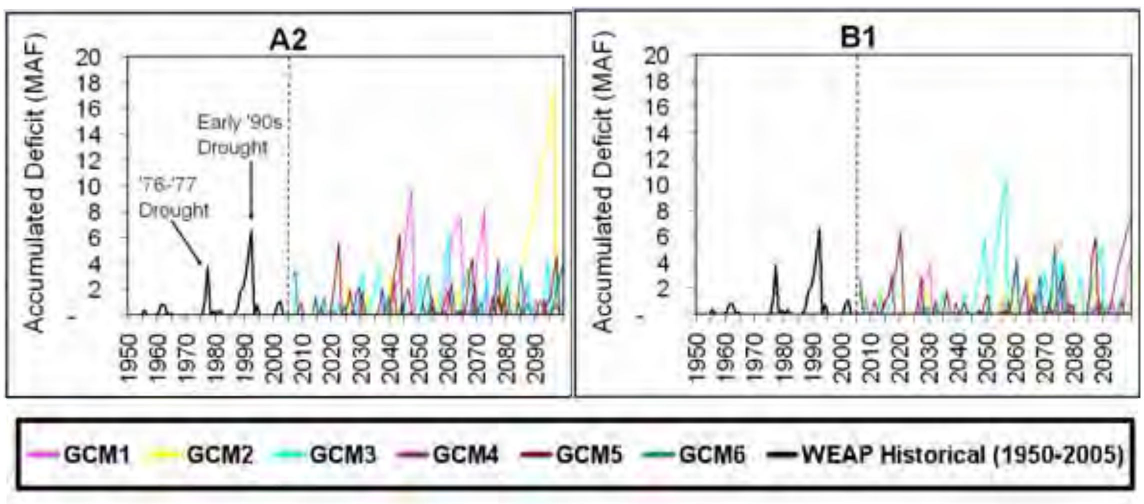


Figure 12. Changes in drought conditions. Vertical dotted line delineates the historical period from the future climate projection period.

3.3. Demand Analysis

Annual supply requirements for agricultural areas in the Sacramento and western San Joaquin valleys are summarized in Figure 13 and Figure 14, respectively. These are the sums of the crop water requirements for all irrigated areas calculated from the future climate time series using WEAP's internal Penman-Montieth routine, adjusted based on assumed losses in delivering water to meet these requirements. Following a trend consistent with the predicted changes in

[3] The Sacramento Valley 40-30-30 Water Year Hydrological Index is equal to 0.4 x current April to July unimpaired runoff + 0.3 x current October to March unimpaired runoff + 0.3 x previous year's index (if the previous year's index exceeds 10.0, then 10.0 is used).

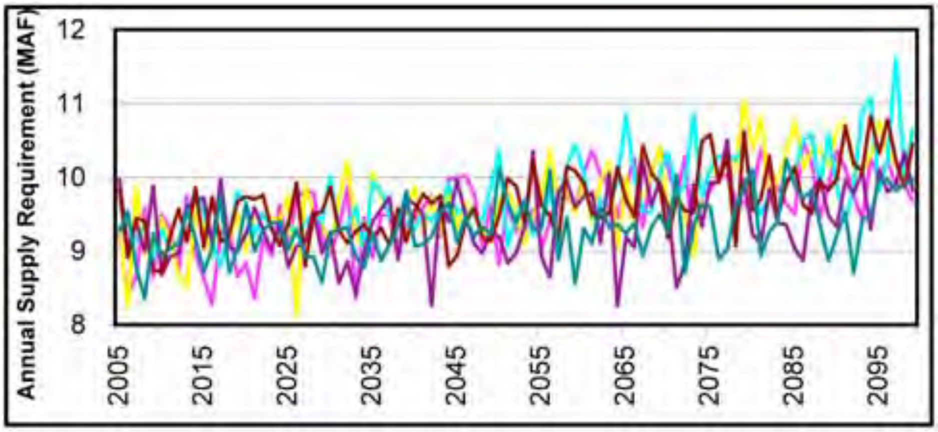
temperature (Figure 8), both emission scenarios showed an increasing trend in water requirements with time, with the A2 scenario exhibiting a more pronounced increase than the B1 scenario.

The model also suggested that crop water requirements would experience a greater increase in the Sacramento Valley (9% under A2, 6% under B1) than in the western San Joaquin Valley and Tulare Basin (6% under A2, 4% under B1) by the end of the century. This trend was driven by differences in the mix of crops in the two regions. In particular, there is almost a 100-fold difference in the amount of rice grown—with the Sacramento Valley having just over 600,000 acres in production and the western San Joaquin Valley and Tulare Basin having only 6,600 acres in production.

It should be noted again that these simulations reflect possible changes under future climate scenarios where the total cropped acreages remained fixed, irrigation technology and scheduling remain unchanged, and the development of crops is unaffected by changes in climate. It may be argued that agricultural water usage will adapt to changing climate through a combination of changes in management strategies and changes in crop physiology. These changes could maintain, or even reduce, the current level of annual crop water demand. Alternatively, annual crop water demands could increase if the length of time to crop maturation shortened to a point where additional crops could be planted within a single growing season. As such, the projections presented here should be interpreted as a first-order estimate of changes in crop water demand.

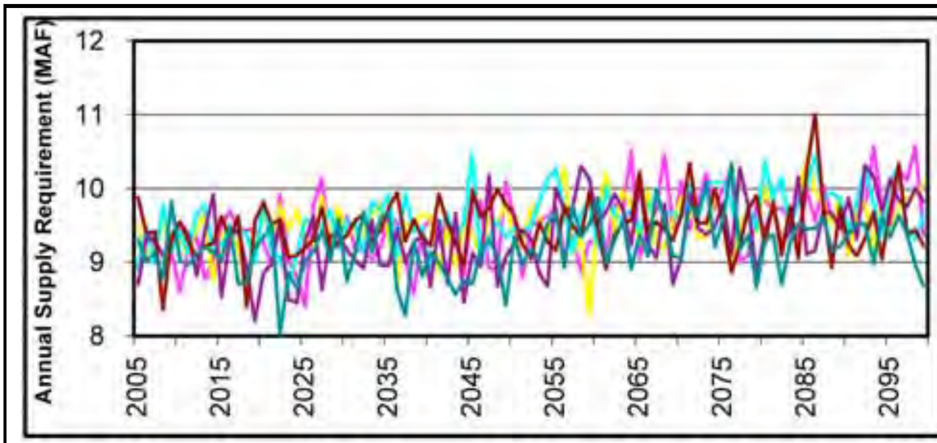
Sacramento Valley

A2



	1950 - 2005	2006 - 2034		2035 - 2064		2065 - 2099	
	average (maf)	average (maf)	difference (%)	average (maf)	difference (%)	average (maf)	difference (%)
GCM1	8.98	9.10	1%	9.55	6%	9.90	10%
GCM2	9.09	9.27	2%	9.61	6%	10.13	11%
GCM3	9.08	9.34	3%	9.65	6%	10.16	12%
GCM4	9.10	9.17	1%	9.37	3%	9.61	6%
GCM5	9.09	9.36	3%	9.53	5%	9.99	10%
GCM6	9.10	9.10	0%	9.34	3%	9.48	4%

B1



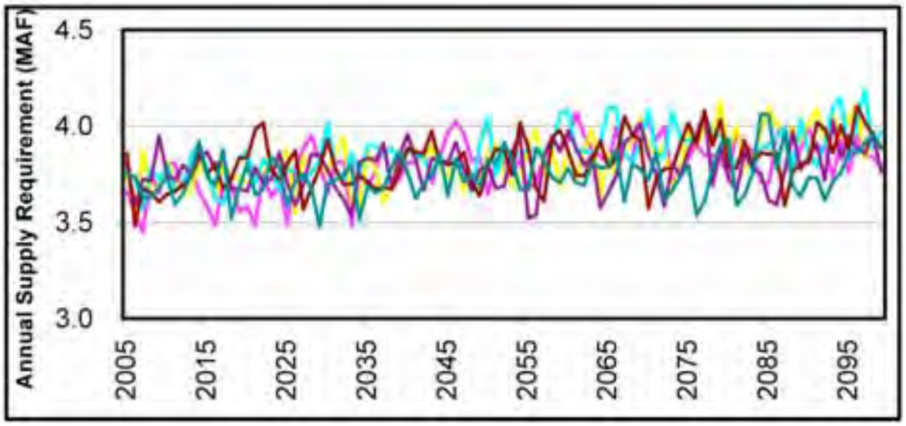
	1950 - 2005	2006 - 2034		2035 - 2064		2065 - 2099	
	average (maf)	average (maf)	difference (%)	average (maf)	difference (%)	average (maf)	difference (%)
GCM1	9.08	9.27	2%	9.41	4%	9.75	7%
GCM2	9.09	9.38	3%	9.46	4%	9.63	6%
GCM3	9.08	9.38	3%	9.58	5%	9.81	8%
GCM4	9.07	9.13	1%	9.35	3%	9.60	6%
GCM5	9.06	9.33	3%	9.50	5%	9.58	6%
GCM6	9.07	9.11	0%	9.12	1%	9.37	3%

GCM1 GCM2 GCM3 GCM4 GCM5 GCM6

Figure 13. Projected water supply requirements for the Sacramento Valley

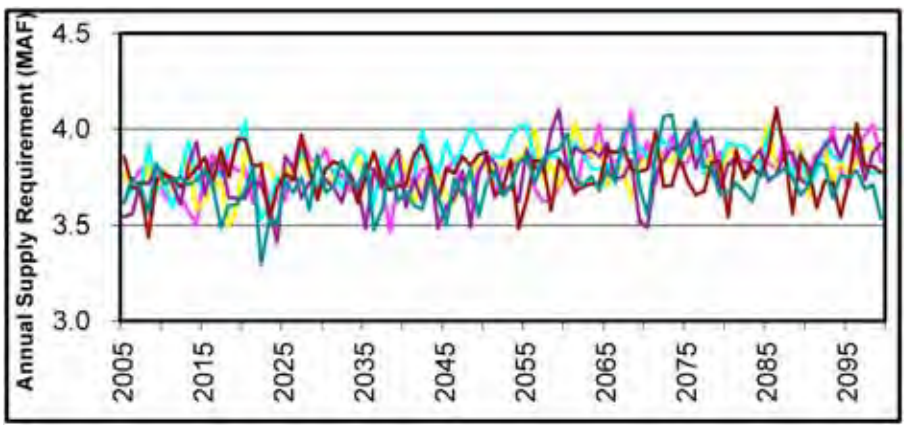
Western San Joaquin and Tulare Lake

A2



	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	3.67	3.68	0%	3.83	4%	3.86	5%
GCM2	3.68	3.74	2%	3.80	3%	3.93	7%
GCM3	3.68	3.76	2%	3.86	5%	3.94	7%
GCM4	3.68	3.74	2%	3.79	3%	3.82	4%
GCM5	3.67	3.75	2%	3.81	4%	3.88	6%
GCM6	3.67	3.70	1%	3.75	2%	3.78	3%

B1



	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	3.68	3.73	2%	3.75	2%	3.86	5%
GCM2	3.68	3.74	2%	3.79	3%	3.83	4%
GCM3	3.67	3.76	2%	3.85	5%	3.86	5%
GCM4	3.67	3.71	1%	3.76	3%	3.82	4%
GCM5	3.66	3.75	3%	3.75	2%	3.79	3%
GCM6	3.67	3.68	0%	3.71	1%	3.78	3%

GCM1 — GCM2 — GCM3 — GCM4 — GCM5 — GCM6

Figure 14. Projected supply requirements for the western San Joaquin Valley/Tulare Basin

3.4. Operations Analysis without Adaptation

The WEAP system attempts to satisfy crop water requirements by delivering water through canals and by pumping groundwater. The extent to which it is able to meet the full crop requirements depends upon surface water supplies and capacity constraints on canals and groundwater pumping. As a surrogate for contract allocations, WEAP imposes limits on the amount of water that can be released from reservoirs by restricting releases to a fraction of remaining active storage. This limits the amount of surface water available that can be diverted from rivers and, ultimately, pumped from the Delta.

Each of the twelve climate change scenarios was run continuously over a historical period (1950–2005) and a future period (2006–2099) using downscaled GCM climate data and current operational rules. The results of these scenarios are summarized in the following graphs, where climate change scenarios are compared against a historic baseline, which was generated by running the WEAP model over the period 1950–2005 using historical gridded climate data (Maurer et al. 2002).

Figure 15 and Figure 16 present the volume of surface water pumped annually from the rivers and streams of the Sacramento Valley and from the Sacramento-San Joaquin Delta for the A2 and B1 scenarios. The graph suggests that under both emission scenarios higher crop water requirements (Figure 13) resulted in increasing diversions from rivers in the Sacramento Valley as the simulation progressed into a warmer era at the end of the century. This resulted in less water flowing into the Delta and, thus, less water available to be exported to San Joaquin Valley and Tulare Basin irrigators.

This pattern of higher water deliveries within the Sacramento Valley at the expense of Delta exports underlines an important distinction in the way in which WEAP allocates water among different users. As previously mentioned, demands are given priorities, such that WEAP delivers water according to a hierarchical ordering of water users. In this scheme, lower priority water users receive surface water deliveries only after the higher priority users have received their full request for water (subject to constraints on delivery capacities). In the Sacramento-San Joaquin application, agricultural water users share the highest priority for water with environmental (i.e., in-stream flows) and indoor urban demands.

Under this configuration, Delta exports are only permissible after the environmental requirements for Delta outflow (see Section 2.2.2) are satisfied. Because the outflow requirements are given equal priority to Sacramento Valley agricultural deliveries, it also means that the model prioritizes irrigation in the Sacramento Valley over Delta exports. This was not intended to suggest a preference for irrigators in the Sacramento Valley, but reflects a priority structure that mimics the observed historical system operations. Under the historical reference case, much of the water delivered to irrigators on the Westside of the San Joaquin Valley comes from San Luis Reservoir, which pumps water from the Delta at a time of year when its demands are not in direct competition with those of irrigators in the Sacramento Valley.

Sacramento Valley

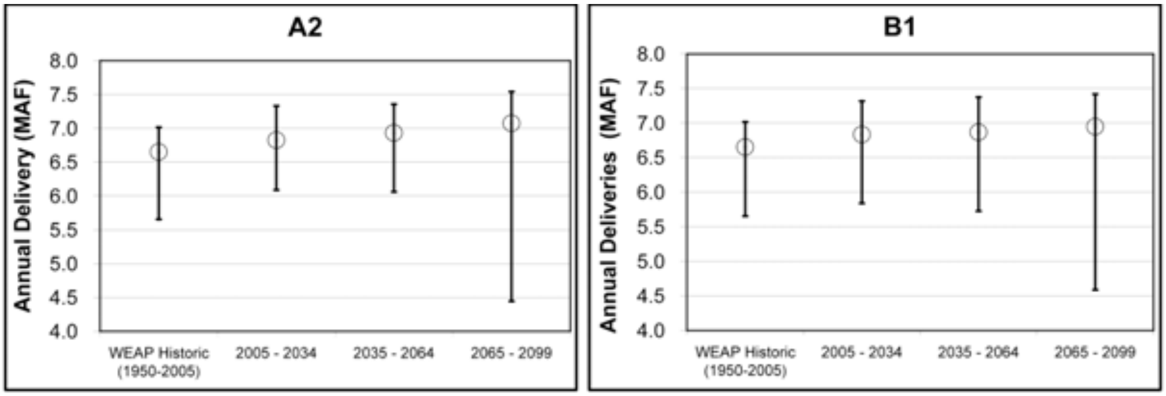


Figure 15. Sacramento Valley agricultural surface water deliveries for both emission scenarios without adaptation. Circles indicate period median and hash marks indicate minimum and maximum values.

Western San Joaquin and Tulare Lake

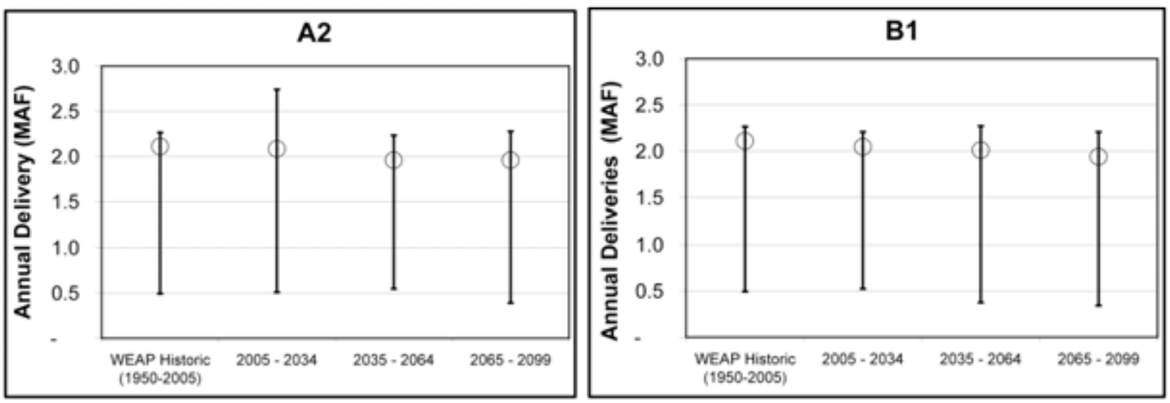


Figure 16. Western San Joaquin and Tulare Lake agricultural surface water deliveries for both emission scenarios without adaptation. Circles indicate period median, and hash marks indicate minimum and maximum values.

Thus, the decline in Delta exports under future scenarios suggests that the environmental requirements within the Delta may represent the biggest constraint on Delta exports. This situation is compounded by irrigators in the Sacramento Valley using more water at the expense of inflows to the Delta. Figure 15 and Figure 16 suggest that there may be opportunities for a reallocation and/or transfer of water rights among irrigators in the Sacramento and San Joaquin Valleys.

In addition to changing patterns in surface water deliveries, increasing crop water requirements led to a greater usage of groundwater resources in both the Sacramento and San Joaquin Valleys (Figure 17 and Figure 18). The pattern of increasing groundwater pumping corresponded with the drought periods observed in Figure 12 and resulted in greater groundwater drawdown during these periods (Figure 19). The higher groundwater pumping, however, was not maintained across all years, resulting in only a marginal increase in total groundwater pumping.

Sacramento Valley

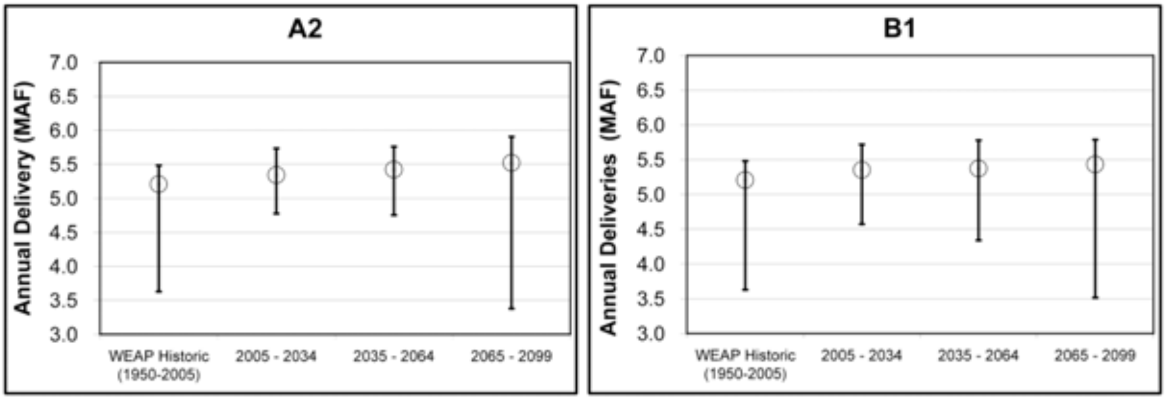


Figure 17. Sacramento Valley annual groundwater pumping for both emission scenarios without adaptation. Circles indicate period median and hash marks indicate minimum and maximum values.

Western San Joaquin and Tulare Lake

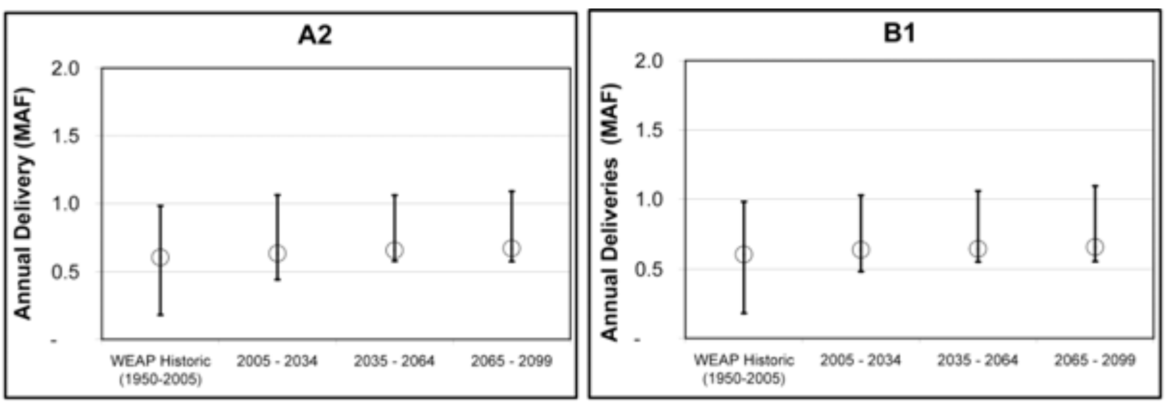


Figure 18. Western San Joaquin and Tulare Lake annual groundwater pumping for both emission scenarios without adaptation. Circles indicate period median, and hash marks indicate minimum and maximum values.

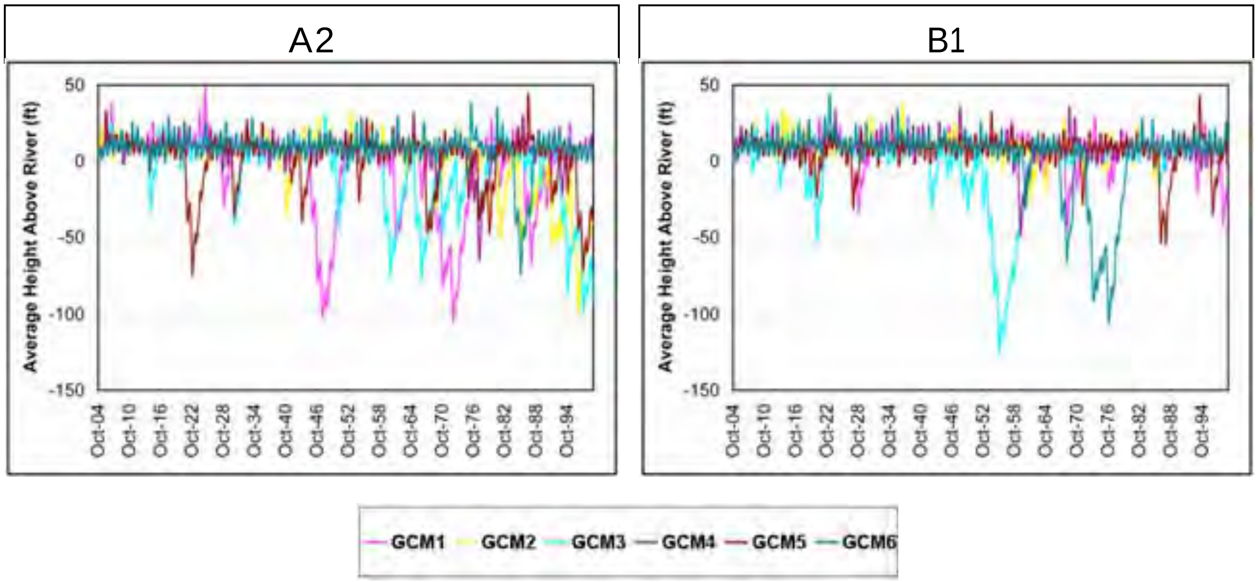


Figure 19. Average groundwater depths in the western San Joaquin Valley for A2 and B1 emission scenarios

Whereas regional deliveries and groundwater pumping trends are indicative of differences in priorities assigned to various water users, end-of-year (or carryover) storage is reflective of total annual deliveries to all water users represented in the model. Figure 20 shows exceedance probability plots for carryover storages at the end of century, 2065–2099, for both the A2 and B1 scenarios. Future scenarios consistently suggest that carryover storages will be much lower by the end of the century. Since there was no corresponding decrease in reservoir inflows for this same period (Figure 11), this change is primarily due to increases in surface water deliveries. Thus, in addition to modifying the allocation of surface water supplies among irrigators, reservoir operations should also be updated to preserve the inter-annual water supply objectives (i.e., drought protection) of these reservoirs.

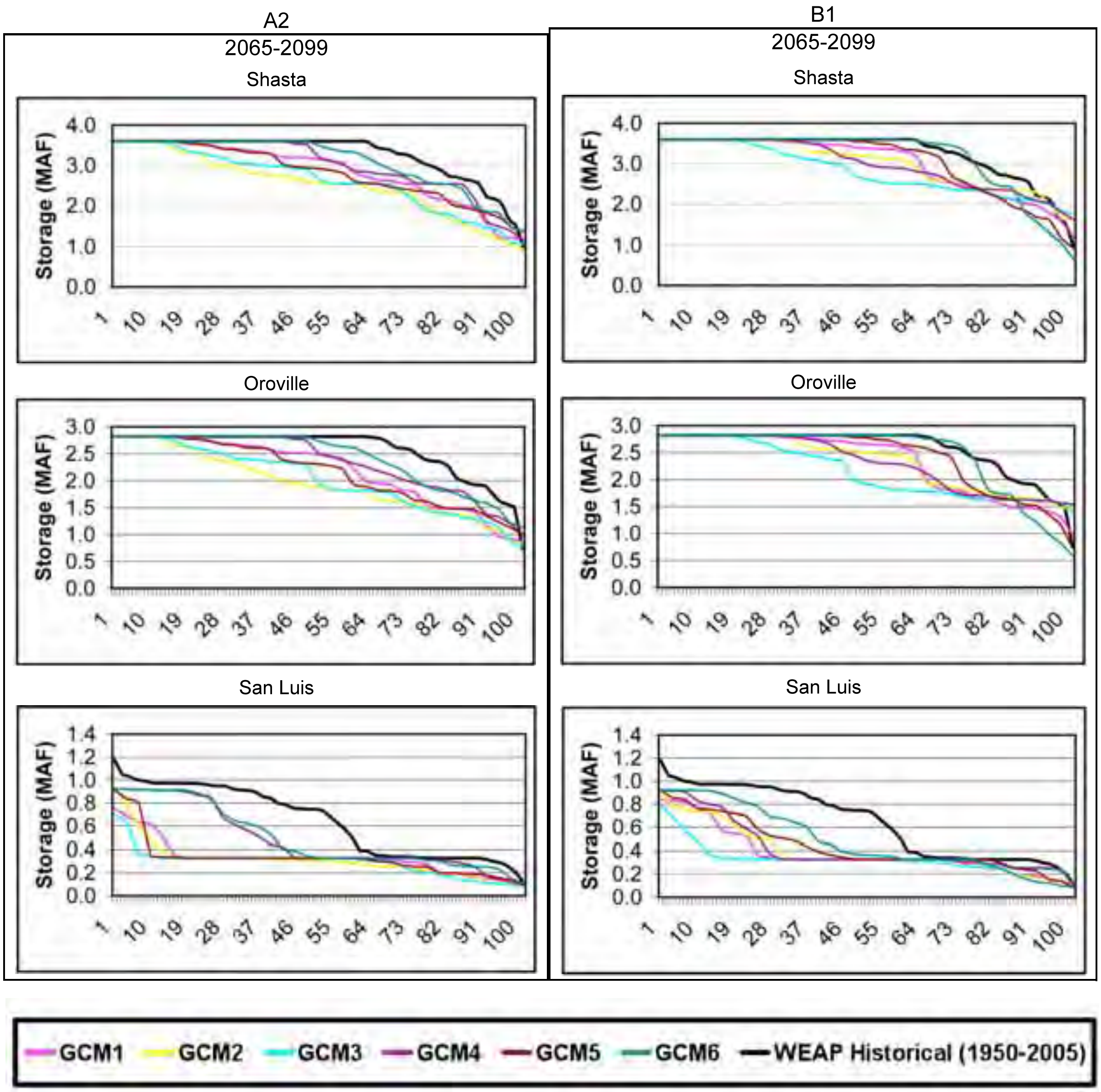


Figure 20. Carryover storage for A2 and B1 scenarios without adaptation

3.5. Operations Analysis with Adaptation

The previous section presented results suggesting that increasing crop water demands in the future will alter the water management regime such that certain water users will divert more water at the expense of others. It should be noted now that these changes may be overstated, because simulations assumed fixed cropped acreages for all commodities—implying that the modeled changes in demand were entirely driven by changes in climate. It can be reasonably assumed that, as crop water demands rise, farmers will adopt new strategies of growing crops using fixed water resources. This may involve planting fewer acres of higher valued crops, switching to crops with lower water needs, and / or improving irrigation technology such that the same crops can be grown with less applied water. The implications of two adaptation strategies—irrigation technology and shifting cropping patterns—are discussed below.

3.5.1. Water Supply Requirements with Adaptation

Improved Irrigation Efficiency

For the purposes of this study, it was assumed that external regulatory pressures motivated irrigators to improve irrigation efficiency without regard to future climatic conditions. These improvements in irrigation efficiency were phased in gradually throughout the first half of the twenty-first century and reached a maximum in 2050, after which efficiencies remained constant.

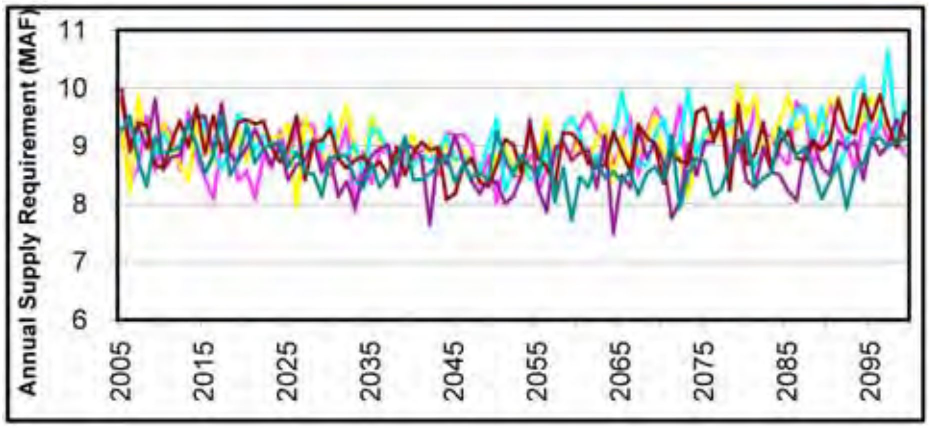
Changes in irrigation efficiency differed among crops based upon assumptions made in the amount of land converted to low-volume (e.g., drip) irrigation systems. It was assumed that orchards, vineyards, and row crops (including tomatoes and truck crops) would be entirely irrigated with low-volume irrigation systems, while field crops (including cotton, sugar beet, alfalfa, grain, and pasture) would convert only half of the irrigated land. Rice acreage, on the other hand, will be irrigated by gravity-fed irrigation in 2050, as it is today.

The implications of improvements in irrigation efficiency on water supply requirements in the Sacramento and San Joaquin Valleys are shown in Figure 21 and Figure 22. These results suggest that improvements in irrigation efficiency could largely offset the increases in water demand anticipated with increasing temperatures (see Figure 13 and Figure 14). In fact, in some cases, water demands actually decrease by the end of the century.

In general, the offset in crop water demand was greatest for the B2 emission scenarios and more pronounced in the San Joaquin Valley. The difference in forecasted temperatures between emissions scenarios accounted for the greater capacity of improvements in irrigation efficiency to offset water demands in the B2 scenario. That is, changes in irrigation technology were more effective when the counteracting changes in temperature were lower. The larger impact in the San Joaquin Valley was due to the predominance of orchard, row crops, and field crops, which all have a high potential for improvements in irrigation technology. Water demands in the Sacramento Valley, on the other hand, were largely driven by rice acreage, which has little potential for improved irrigation technology because it relies on flooded fields.

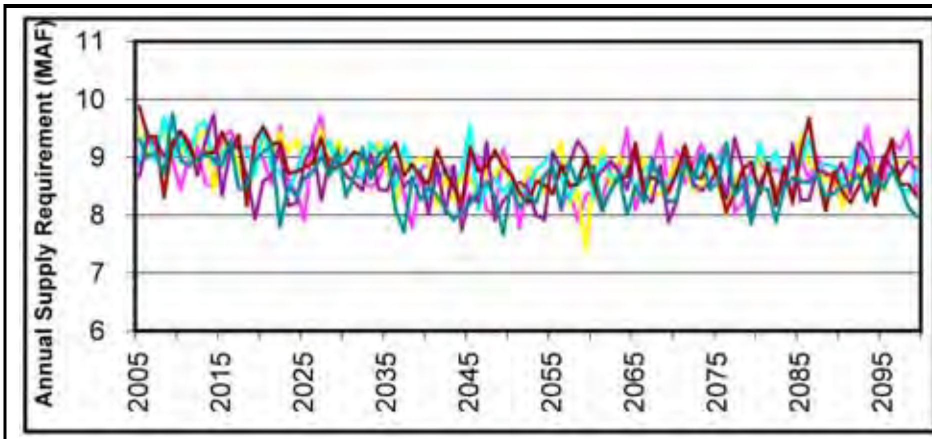
Sacramento Valley

A2



	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	8.98	8.83	-2%	8.81	-2%	9.14	2%
GCM2	9.09	9.02	-1%	8.88	-2%	9.27	2%
GCM3	9.08	9.07	0%	8.87	-2%	9.28	2%
GCM4	9.10	8.90	-2%	8.61	-5%	8.76	-4%
GCM5	9.09	9.07	0%	8.75	-4%	9.12	0%
GCM6	9.10	8.83	-3%	8.58	-6%	8.66	-5%

B1



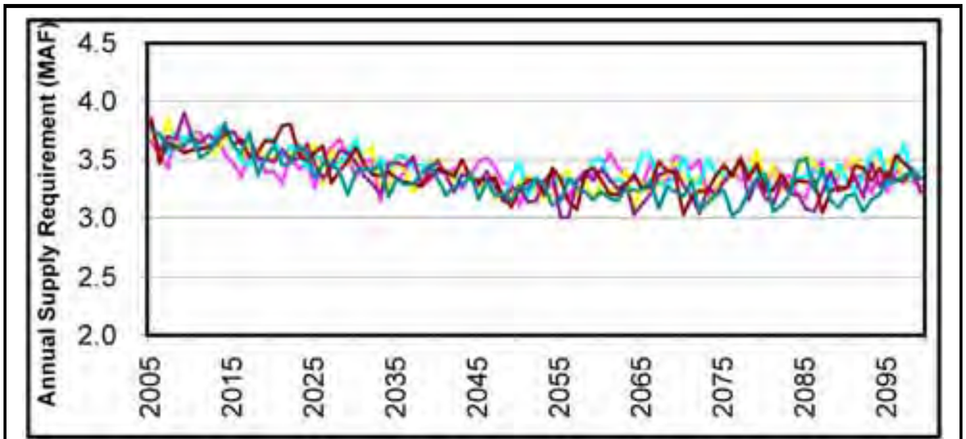
	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	9.08	8.94	-2%	8.56	-6%	8.79	-3%
GCM2	9.09	9.08	0%	8.63	-5%	8.68	-4%
GCM3	9.08	9.08	0%	8.69	-4%	8.80	-3%
GCM4	9.07	8.85	-2%	8.55	-6%	8.66	-5%
GCM5	9.06	9.04	0%	8.68	-4%	8.65	-4%
GCM6	9.07	8.84	-3%	8.37	-8%	8.49	-6%

GCM1 GCM2 GCM3 GCM4 GCM5 GCM6

Figure 21. Changes in water supply requirement in Sacramento Valley associated with improvements in irrigation technology for A2 and B1 scenarios

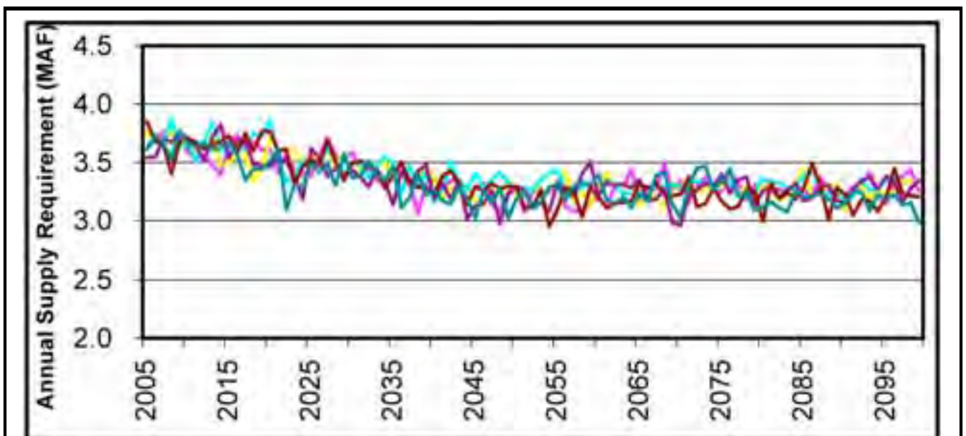
Western San Joaquin and Tulare Lake

A2



	1950 - 2005	2006 - 2034		2035 - 2064		2065 - 2099	
	average (maf)	average (maf)	difference (%)	average (maf)	difference (%)	average (maf)	difference (%)
GCM1	3.67	3.50	-5%	3.35	-9%	3.34	-9%
GCM2	3.68	3.56	-3%	3.30	-10%	3.38	-8%
GCM3	3.68	3.58	-3%	3.36	-9%	3.39	-8%
GCM4	3.68	3.56	-3%	3.30	-10%	3.27	-11%
GCM5	3.67	3.56	-3%	3.30	-10%	3.33	-9%
GCM6	3.67	3.52	-4%	3.25	-11%	3.23	-12%

B1



	1950 - 2005	2006 - 2034		2035 - 2064		2065 - 2099	
	average (maf)	average (maf)	difference (%)	average (maf)	difference (%)	average (maf)	difference (%)
GCM1	3.68	3.55	-3%	3.24	-12%	3.28	-11%
GCM2	3.68	3.56	-3%	3.28	-11%	3.26	-11%
GCM3	3.67	3.58	-2%	3.32	-10%	3.29	-11%
GCM4	3.67	3.53	-4%	3.25	-11%	3.25	-11%
GCM5	3.66	3.57	-2%	3.24	-12%	3.22	-12%
GCM6	3.67	3.50	-5%	3.22	-12%	3.21	-12%

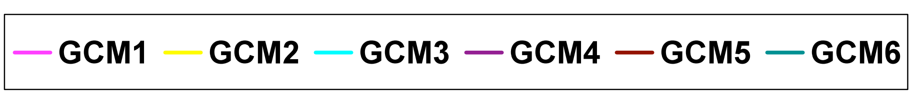


Figure 22. Changes in water supply requirement in western San Joaquin/Tulare Basin associated with improvements in irrigation technology for A2 and B1 scenarios

Shifting Cropping Patterns

In addition to improvements in irrigation technology, another potential adaptation to climate change involves adjusting cropping patterns as a function of the evolving status of available water supplies. At the beginning of the growing season, farmers decide which crops to plant based on anticipated surface water supplies and groundwater levels. How farmers respond to these changing conditions is a function of a number of factors, which change depending on the reliability of various available water sources. For example, farmers who rely solely on groundwater for irrigation base cropping decisions on the depth to groundwater, which relates directly to their operating costs. Central Valley Project settlement contractors in the Sacramento Valley, on the other hand, have guaranteed contracts for surface water deliveries that are only reduced when inflows to Lake Shasta reach a critical level (i.e., less than 3.4 million acre-feet). Their cropping choices are then more responsive to changes in surface water supplies. In the Sacramento and San Joaquin Valley there are many CVP and SWP agricultural contractors whose allocations for surface water deliveries vary from year to year based upon current storage and predicted inflows to the main project reservoirs.

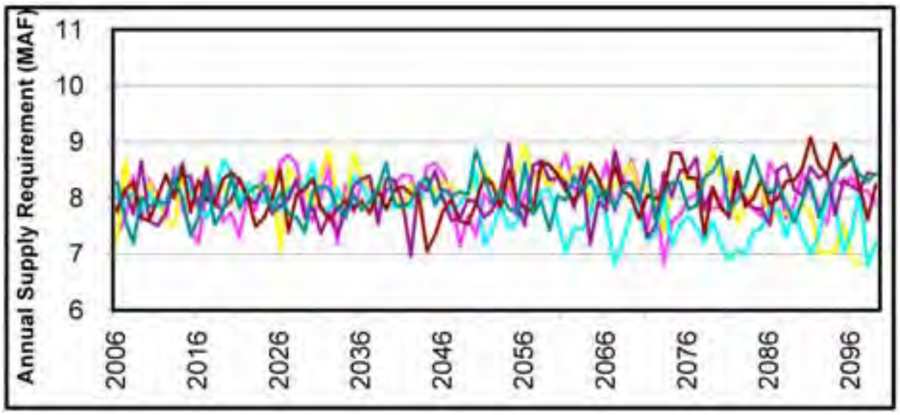
The implication is that indexes of available supply must be calculated for each year in order to permit the various types of water user to make appropriate cropping decisions. Based on the value of these supply indexes, a multinomial logit model of cropping shares, estimated from historical data, is employed to determine the distribution of crops and fallow land in that year for the given user. These logit equations were programmed into WEAP so that at the start of every cropping season over the course of the twenty-first century, an adaptive simulated cropping pattern was defined.

The impacts of these cropping shifts on water supply requirements are shown in Figure 23 and Figure 24. Here there are a couple of important things to note. The first thing to observe is that the average crop water demands in both regions are substantially less than those estimated in previous simulations. This change is due to the introduction of a fallow land class, which allows land to be put into or taken out of production. Since all scenarios (with and without adaptation) assumed the same amount of irrigable land, this meant that any land fallowed (i.e., idled or retired) as an adaptive response to climate change resulted in less land in production relative to the other simulations. In fact, it was observed that the minimum amount of land fallowed in any year for all adaptation scenarios was between 10% and 15%. It is important to note this difference in demands from the baseline scenarios, especially when considering the impacts on water supply and delivery. For our purposes here, we focus on how cropping patterns change and what impact these changes have on crop water demands relative to a modified baseline, where the model was run with changing cropping patterns over a historical time period, 1950–2005.

Second, unlike the previous simulations that contained either no adaptation or pre-defined changes in water usage (i.e., improvements in irrigation efficiency), these simulations exhibited similar impacts on water supply requirement for both the A2 and B1 emission scenarios. This would suggest that feedback between water supply and agricultural demands allows the model to compensate (or adapt) such that the system achieves similar water demands under different climate forcings.

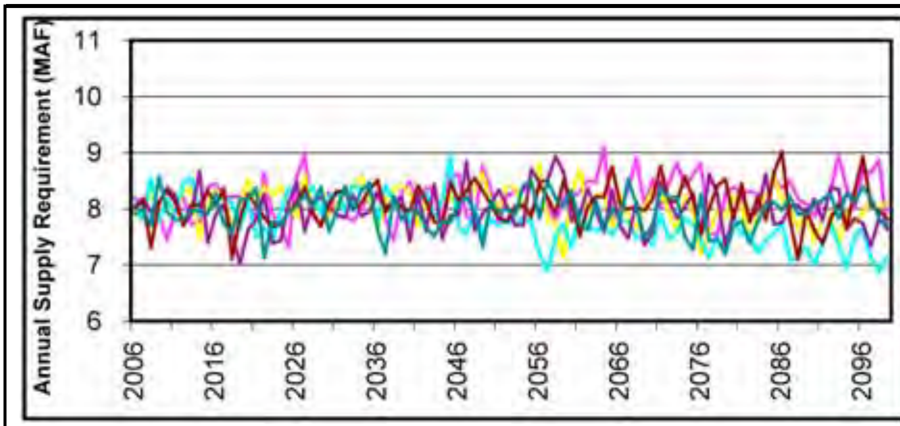
Sacramento Valley

A2



	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	7.87	7.95	1%	8.10	3%	8.02	2%
GCM2	7.91	8.07	2%	8.29	5%	7.86	-1%
GCM3	7.90	8.07	2%	7.83	-1%	7.45	-6%
GCM4	7.94	7.94	0%	8.06	2%	8.14	3%
GCM5	7.92	8.01	1%	8.00	1%	8.23	4%
GCM6	7.91	7.90	0%	8.08	2%	8.17	3%

B1



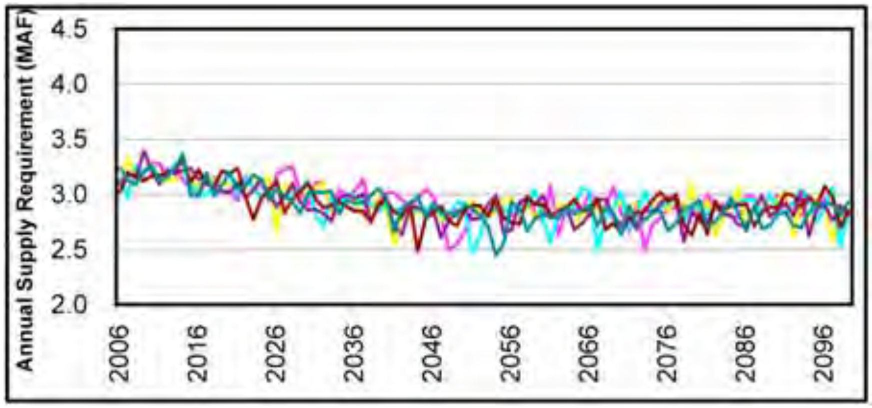
	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	7.89	8.06	2%	8.22	4%	8.30	5%
GCM2	7.89	8.16	3%	8.15	3%	7.92	0%
GCM3	7.89	8.08	2%	7.83	-1%	7.44	-6%
GCM4	7.91	7.93	0%	8.09	2%	7.94	0%
GCM5	7.89	8.00	1%	8.12	3%	8.10	3%
GCM6	7.88	7.98	1%	7.95	1%	7.92	0%

GCM1 GCM2 GCM3 GCM4 GCM5 GCM6

Figure 23. Changes in water supply requirement in Sacramento Valley associated with changes in cropping patterns for A2 and B1 scenarios

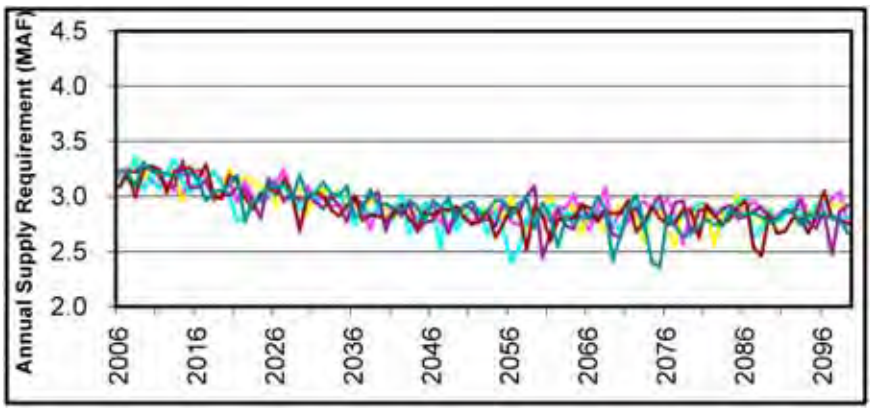
Western San Joaquin Valley and Tulare Lake

A2



	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	3.12	3.10	-1%	2.87	-8%	2.87	-8%
GCM2	3.10	3.09	-1%	2.85	-8%	2.86	-8%
GCM3	3.12	3.06	-2%	2.85	-9%	2.88	-8%
GCM4	3.13	3.06	-2%	2.84	-9%	2.83	-10%
GCM5	3.12	3.07	-1%	2.84	-9%	2.86	-8%
GCM6	3.10	3.08	-1%	2.83	-9%	2.81	-9%

B1



	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	3.12	3.08	-1%	2.85	-8%	2.87	-8%
GCM2	3.11	3.10	0%	2.87	-8%	2.83	-9%
GCM3	3.13	3.06	-2%	2.80	-11%	2.84	-9%
GCM4	3.12	3.06	-2%	2.83	-9%	2.83	-9%
GCM5	3.11	3.08	-1%	2.81	-10%	2.80	-10%
GCM6	3.10	3.10	0%	2.88	-7%	2.77	-11%

GCM1 — GCM2 — GCM3 — GCM4 — GCM5 — GCM6

Figure 24. Changes in water supply requirement in western San Joaquin/Tulare Basin associated with changes in cropping patterns for A2 and B1 scenarios

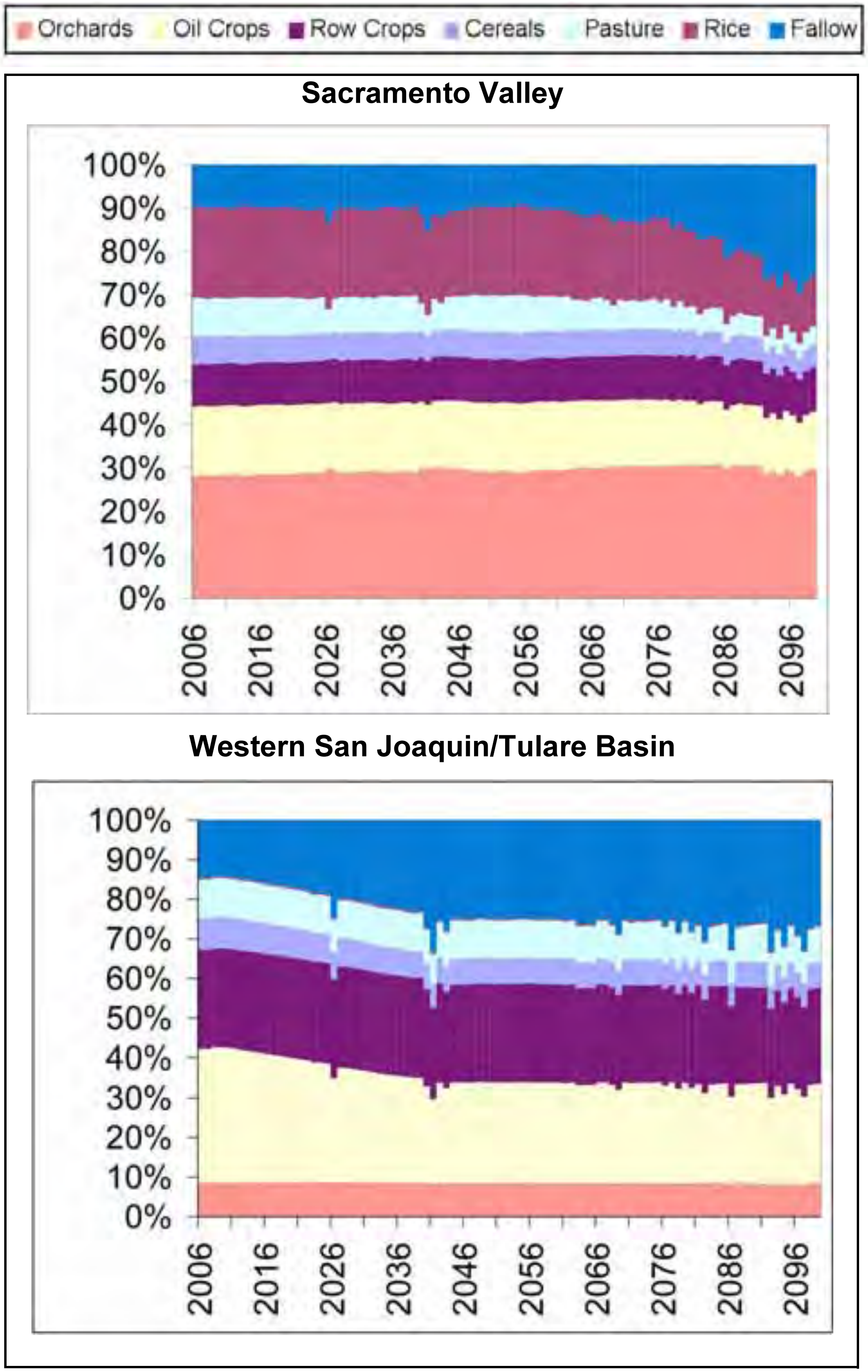


Figure 25. Simulated changes in cropping patterns in the Sacramento[4] and San Joaquin Valleys for A2/GFDL-CM21 scenario

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[4] Row crops include truck crops as well as process and market tomatoes. Oil crops include cotton, sugar beet, and field crops. Pasture includes alfalfa. Orchards include subtropical and vineyard. Cereals include grain.

The last thing to note is that there is a very clear decrease in water supply requirements for the western San Joaquin and Tulare Basins under both emission scenarios. Further, the trend in the Sacramento Valley shows more variability and, as such, is ambiguous. These general trends are again indicative of the mix of crops in the two regions. Figure 25 shows an example of how the cropping pattern changed in both regions under one climate change scenario, A2 / GFDL-CM21 (or A2 / GCM2). This shows that, for both regions, the decrease in water supply requirement was due to an increase in the amount of retired (or fallowed) land. In the Sacramento Valley, rice accounted for the greatest decrease in cropped acreage, while in the western San Joaquin / Tulare Basin, the crop most affected was cotton.

It is interesting to observe that in this particular scenario there appear to be two different water supply conditions that lead to the large increases in fallowed lands in the two regions. In the Sacramento Valley, a prolonged drought at the end of the century led to low water supplies in several consecutive years. This prompted irrigators in this region to increase the amount of fallow land from a base of about 10% to as much as 30% in the driest years. Curiously, irrigators in the western San Joaquin Valley did not show the same type of response to the drought at the end of the century. While there was some variability from year to year, the models suggested that farmers' cropping decisions appeared to be relatively insensitive to changes in water supply. San Joaquin Valley irrigators, however, did increase the idled irrigated area by about 10% over the first half of the century, by retiring land that is currently being used to grow cotton. This trend was related to increasing pumping costs as groundwater heads declined—a trend that was as least partly due to underestimating the availability of supplemental surface water supplies from the San Joaquin and Kings Rivers.

3.5.2. Water Supply and Delivery

Improved Irrigation Efficiency

This section focuses on the cumulative effect of updating irrigation technology in the Central Valley. The analysis here presents WEAP simulations wherein changes in irrigation technology were applied across all agricultural areas of the model.

Figure 26 and Figure 27show annual surface water deliveries from the rivers and streams in the Sacramento Basin and from the Sacramento-San Joaquin Delta for the A2 and B1 scenarios. These graphs are companions to Figure 15 and Figure 16, which presented the same metric for scenarios run without adaptation. By comparing these graphs, we observe that improving irrigation efficiencies reduced the annual surface water deliveries from the rivers of the Sacramento Basin such that they are comparable to those simulated in the historic baseline. These reductions, however, had little effect on the ability to deliver water to irrigators in the western San Joaquin / Tulare Basin during dry years. This was likely due to a combination of decreasing crop water demands in the export zone and because environmental constraints in the Delta prevented the export of any additional water. Thus, the benefit of reduced water demands in the export zone materialized primarily in the form of reduced unmet demands.

Sacramento Valley

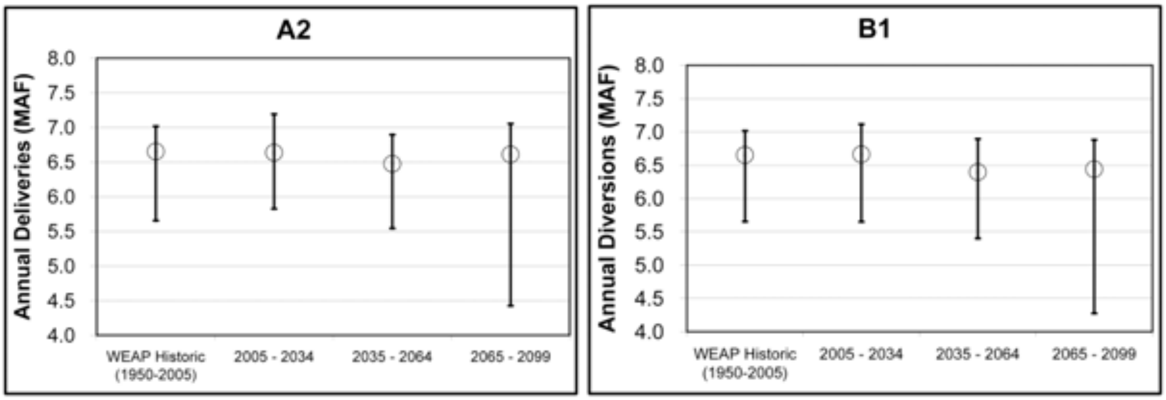

Figure 26. Sacramento Valley agricultural water deliveries for both emission scenarios with improved irrigation technology. Circles indicate period median, and hash marks indicate minimum and maximum values.

Western San Joaquin and Tulare Lake

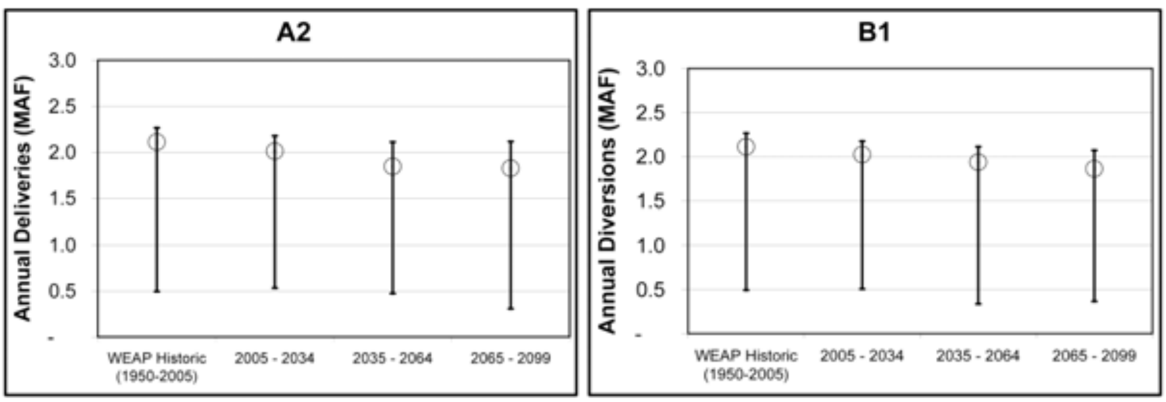

Figure 27. Western San Joaquin and Tulare Lake agricultural water deliveries for both emission scenarios with improved irrigation technology. Circles indicate period median and hash marks indicate minimum and maximum values.

Increasing irrigation efficiency through improvements in technology also led to an overall stabilization of annual groundwater pumping as compared to the historical period (Figure 28 and Figure 29). In fact, reductions in crop ET appeared to result in a reduction in groundwater pumping over the first half of the century, but this effect was lost as temperatures drove crop water demands higher toward the end of the century.

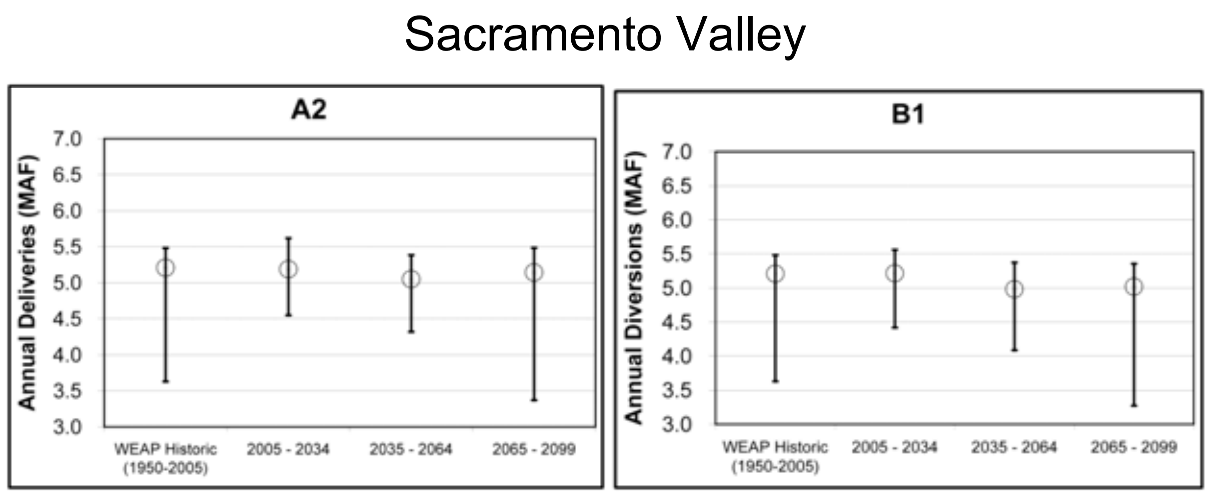

Figure 28. Sacramento Valley annual groundwater pumping for both emission scenarios with improved irrigation technology. Circles indicate period median, and hash marks indicate minimum and maximum values.

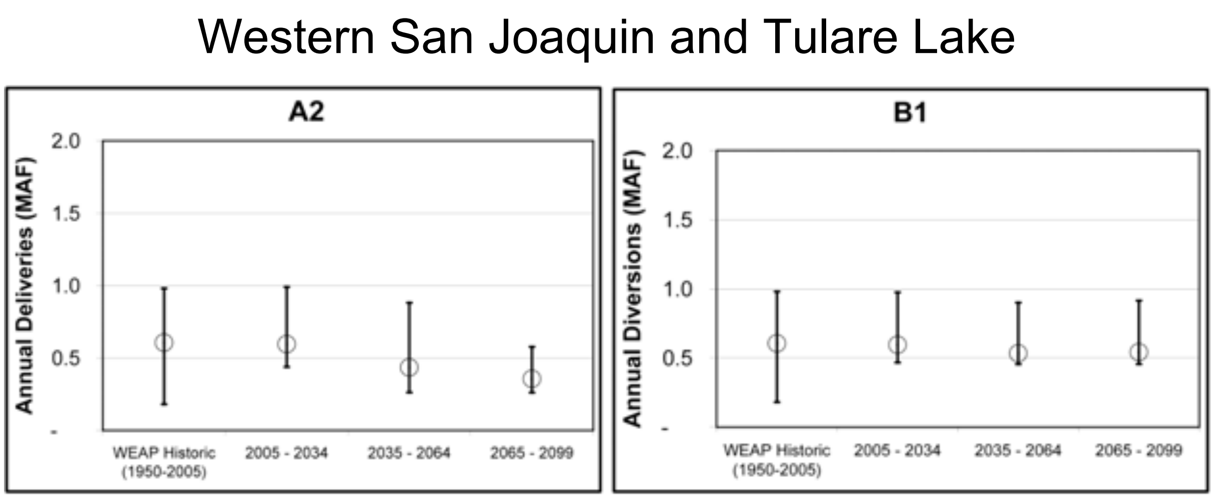

Figure 29. Western San Joaquin and Tulare Lake annual groundwater pumping for both emission scenarios with improved irrigation technology. Circles indicate period median, and hash marks indicate minimum and maximum values.

Figure 30 shows carryover storages at the end of century, 2065–2099, for both the A2 and B1 scenarios run with improved irrigation technology. Again, this graph is a companion to Figure 20, which shows the same metric for scenarios run without adaptation. These plots suggest that reduced surface water deliveries from the Sacramento and Feather rivers had little impact on carryover storage. The implication of this was that there was more water released from storage to meet the environmental requirements within the Delta.

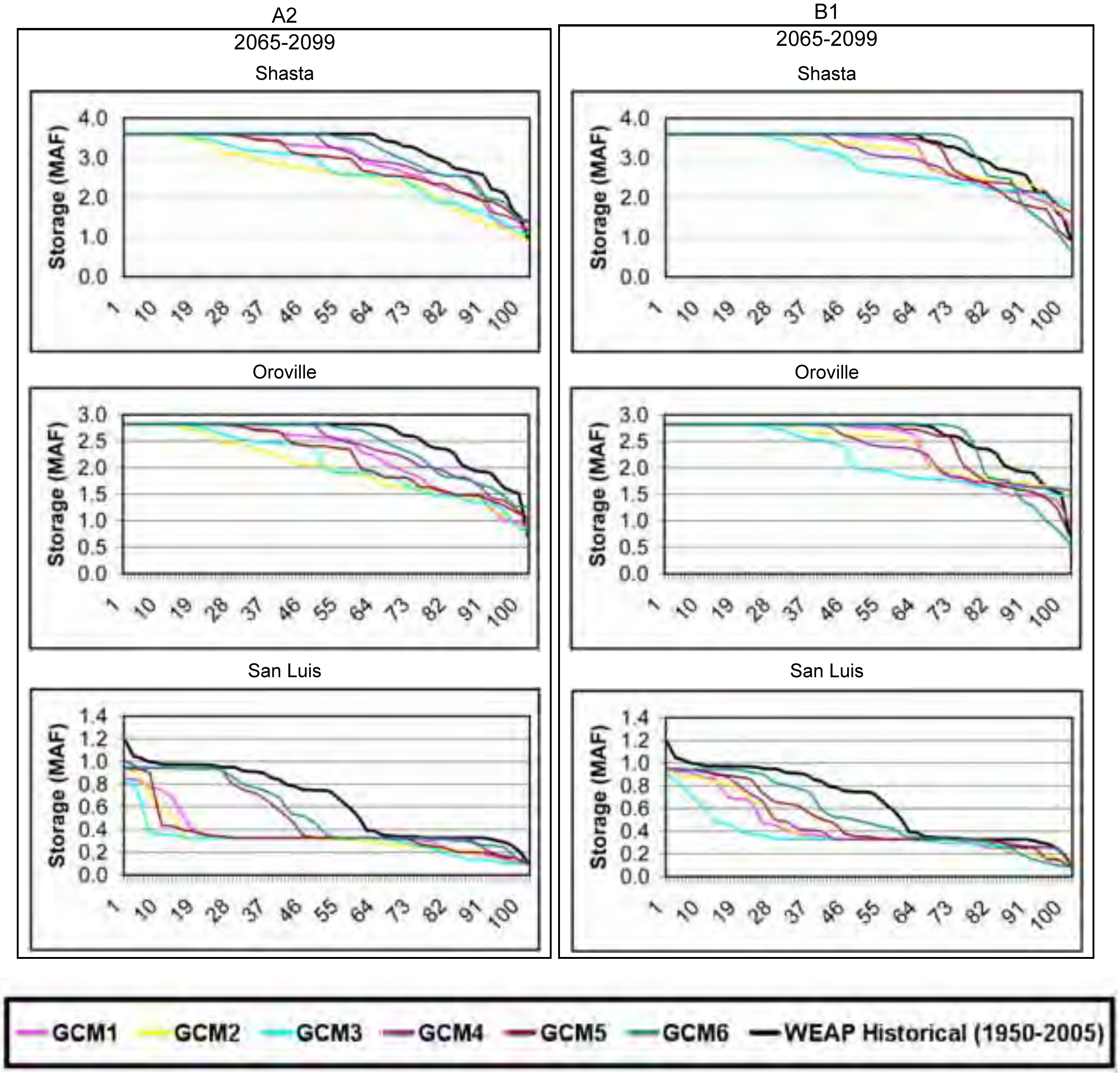

Figure 30. Carryover storage for A2 and B1 scenario with improved irrigation technology

Shifting Cropping Patterns

As previously mentioned, an analysis of water deliveries under the changing cropping patterns is not directly comparable to the model outputs for scenarios run with no adaptation and those run with increased irrigation efficiency, because the difference in the amount of land in production between the model runs alters the baseline water demands such that the impact on the water supply system is distorted. That is, the logit model presumed an ambient presence of fallowed land that was not considered in the other scenarios. This fallow land class accounted for a minimum of 10% of irrigated land in the Sacramento Valley and 15% of irrigated land in the San Joaquin Valley. Regardless of this incongruity in model runs, it is still illuminating to consider the modeled impacts on water supply.

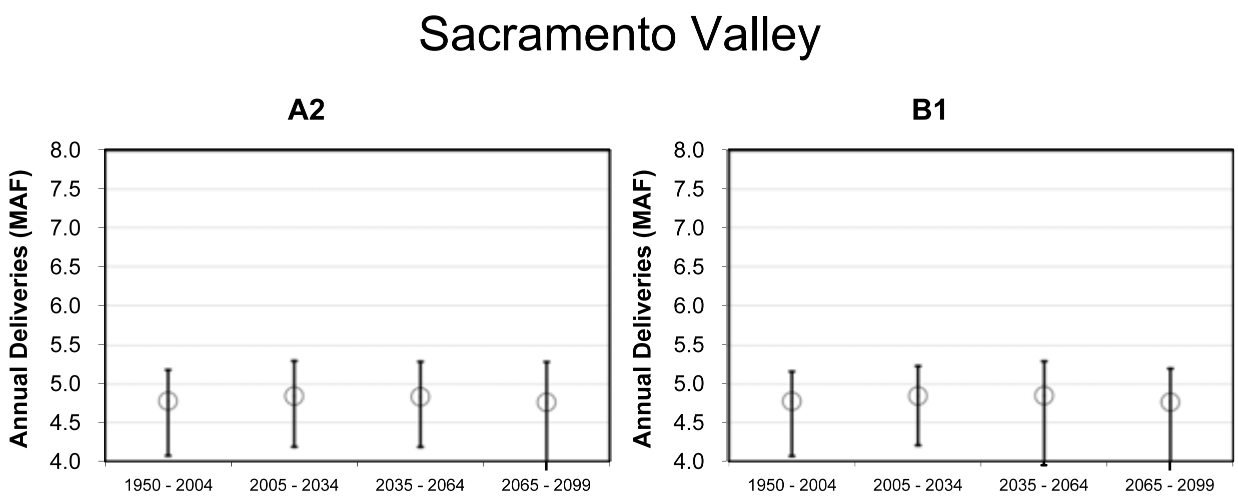

Figure 31. Sacramento Valley agricultural water deliveries for both emission scenarios with shifting cropping patterns. Circles indicate period median, and hash marks indicate minimum and maximum values.

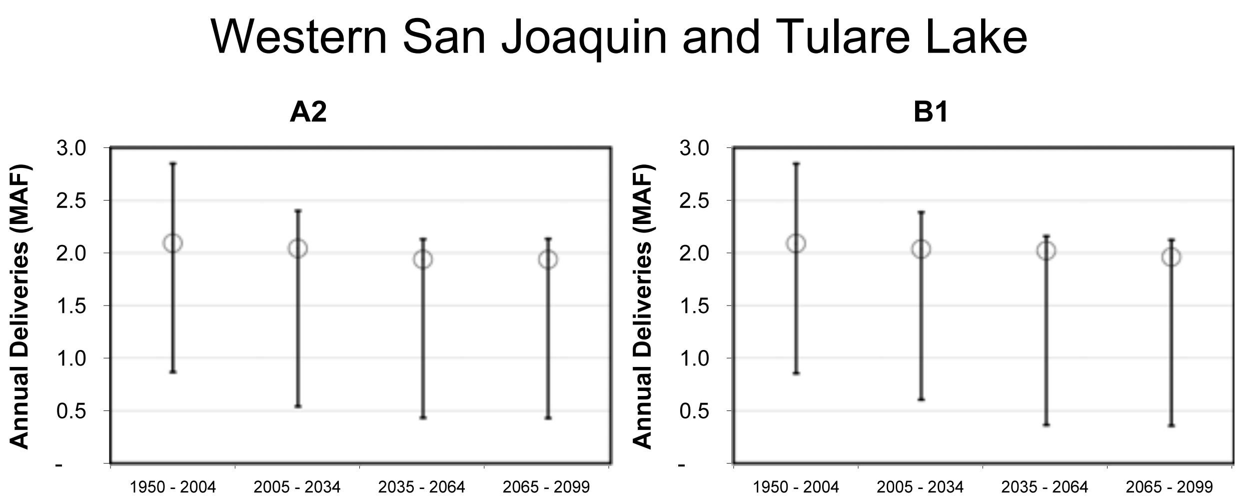

Figure 32. Western San Joaquin and Tulare Lake agricultural water deliveries for both emission scenarios with shifting cropping patterns. Circles indicate period median, and hash marks indicate minimum and maximum values.

Figure 33 and Figure 34 show annual surface water deliveries from the rivers and streams in the Sacramento Basin and from the Sacramento-San Joaquin Delta for the A2 and B1 scenarios. There are a couple of features to note about these results. First, as expected, the Sacramento Valley water deliveries were much lower than those reported for the scenarios run without adaptation and with the adaptation strategy of improved irrigation efficiency. This reflects the decrease in irrigated areas introduced with the fallow land class. Water deliveries to the western San Joaquin and Tulare Lake Basins, however, were only marginally different from the other scenarios. This suggests that the deliveries to the export zone in all of the scenarios were being constrained by Delta export operations and environmental considerations within the Delta.

The other trend to note is that the annual surface water deliveries for each region and emission scenario follow the same trends observed for the agricultural supply requirement (Figure 23 and Figure 24). In the Sacramento Valley, surface water deliveries are relatively stable throughout the simulation. In the western San Joaquin and Tulare Lake Basins, surface water deliveries decline toward the middle and end of century.

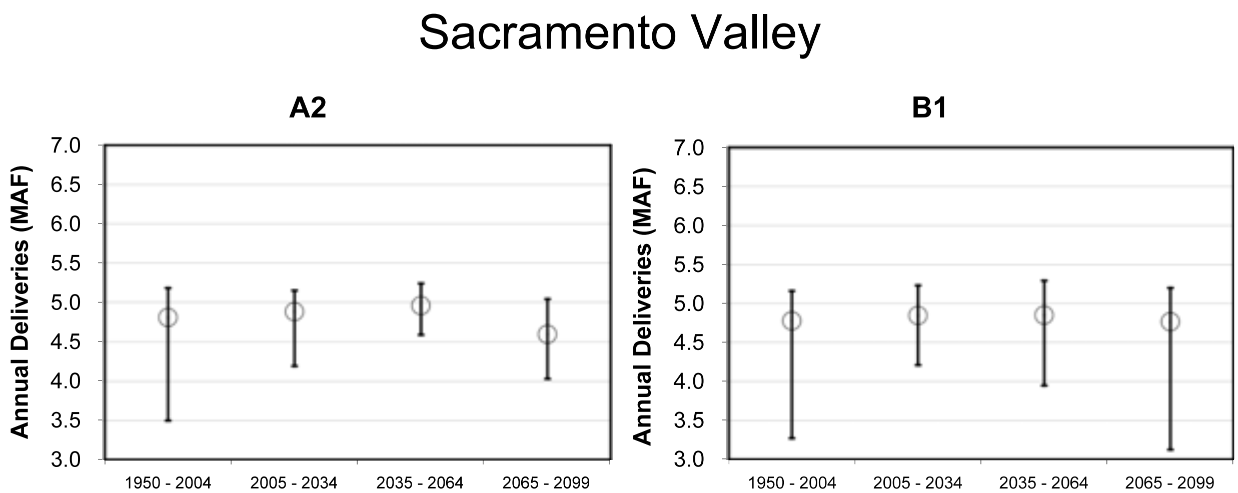

Figure 33. Sacramento Valley annual groundwater pumping for both emission scenarios with shifting cropping patterns. Circles indicate period median, and hash marks indicate minimum and maximum values.

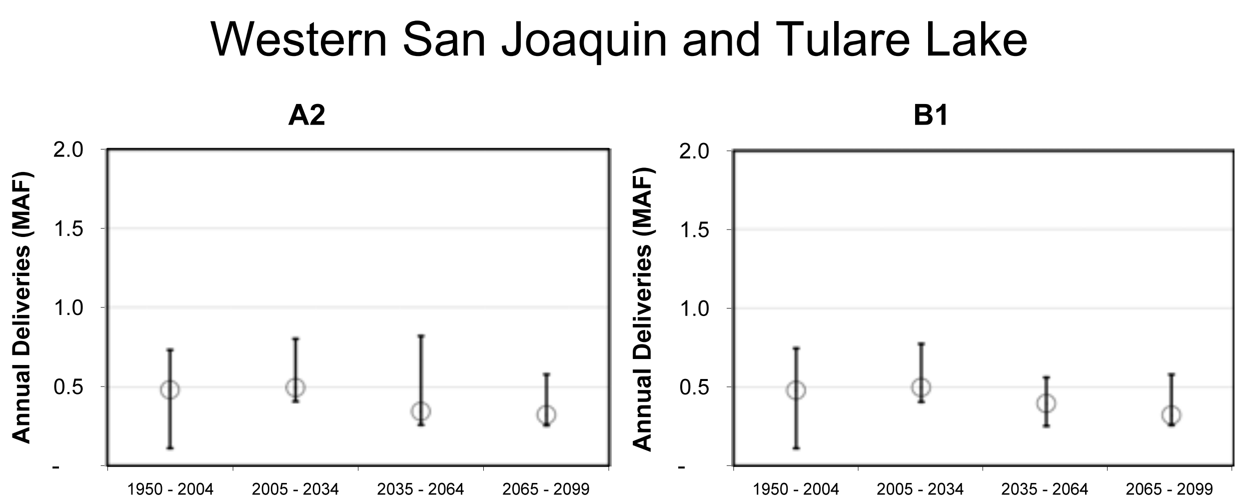

Figure 34. Western San Joaquin and Tulare Lake annual groundwater pumping for both emission scenarios shifting cropping patterns. Circles indicate period median and hash marks indicate minimum and maximum values.

Shifts in cropping patterns appeared to influence annual groundwater pumping within the two regions in a similar manner (Figure 33 and Figure 34). While the annual volumes were below those seen in other scenarios for reasons already discussed, the average volume of groundwater pumping in the two regions tended to follow the same pattern as changes in agricultural supply requirement (Figure 23 and Figure 24).

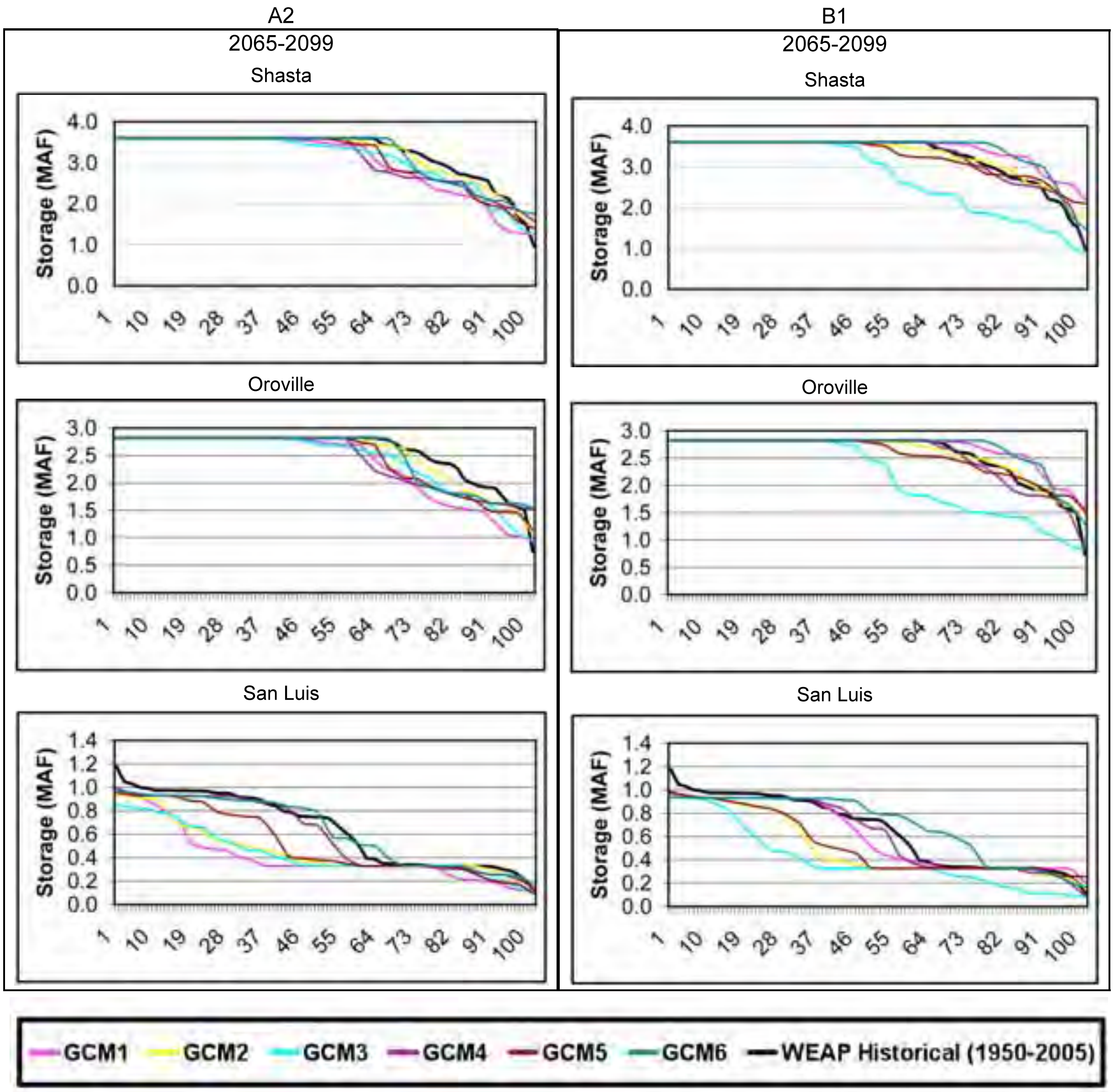

Figure 35. Carryover storage for A2 and B1 scenario with shifting cropping patterns

Figure 35 shows carryover storages at the end of century, 2065–2099, for both the A2 and B1 scenarios run with shifting cropping patterns. As expected, the lower overall demands and the subsequent lower agricultural water deliveries in these scenarios resulted in greater carryover storage than was simulated in scenarios run without adaptation and run with improved irrigation technology. Interestingly, the carryover storages in dry years for the main reservoirs in the Sacramento Valley (Shasta and Oroville) were somewhat higher than the 1950–2005 baseline for the B1 emission scenario and somewhat lower than the baseline in the A2 emission scenario. Carryover storage in San Luis reservoir exhibited greater variability and was generally lower than the baseline for both emission scenarios. This again suggests that Delta operations were limiting exports at the main pumping plants.

4.0 Conclusions

This study demonstrates how WEAP's integrated approach to modeling both the natural and managed components of the water resources system offers significant advantages for investigating climate change impacts in the water sector. Unlike standard water resources analysis models, the WEAP framework is able to directly evaluate future climate scenarios without relying on a perturbation of the historic patterns of hydrology that were observed in the past. In addition, potential increases in water demand associated with higher temperatures are included in the analysis in a more robust manner than with the other tools. This allows for the full evaluation of climate change impacts on both water supply and demand and their associated impacts on water management.

This study evaluated the potential implications on water management of twelve climate change scenarios. The consideration of these scenarios revealed a common theme that suggested increasing agricultural demands in the Sacramento and San Joaquin valleys may lead to increased stress on the management of surface water resources and, potentially, to over-exploitation of groundwater aquifers. Further, the model results suggest that water shortages may be felt more acutely in the western San Joaquin Valley and Tulare Basin as Delta exports become more constrained. As these simulations were run using the current set of operational rules for the system, these results suggest that there may be potential to reconfigure these rules such that a more equitable allocation among water users is achieved. Nevertheless, an overall decrease in system reliability is expected in the absence of any modification of operational rules and/or changes in agricultural practices.

Two examples of how agricultural practices may change in response to changing water supply conditions brought about by climate change include improvements in irrigation efficiency through the adoption of new technology and shifts in cropping patterns to crops with higher market value and/or lower water requirements. These two examples were considered in this study and both were found to offset the increasing demands caused by rising temperatures. However, the model suggested that changing climate patterns may limit water deliveries to agriculture in the western San Joaquin Valley and Tulare Basin despite the reduced demands, because Delta exports constrained by environmental requirements within the Delta.

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6.0 Glossary

CCSR	Center for Climate System Research
CCWD	Contra Costa Water District
CNRM	Center for National Weather Research
COA	Coordinated Operations Agreement
CVP	Central Valley Project
CVPIA	Central Valley Project Improvement Act
CVPM	Central Valley Production Model
DMC	Delta Mendota Canal
ET	Evapotranspiration
EWA	environmental water account
GCMs	general circulation models
GFDL	Geophysical Fluid Dynamics Laboratory model
IPCC	Intergovernmental Panel on Climate Change
MAF	million acre feet
MPI	Max Planck Institute
MWDSC	Metropolitan Water District of Southern California
NCAR	National Center for Atmospheric Research
PCM	Parallel Climate Model
SBCWD	San Benito County Water District
SC	sub-catchment
SCVWD	Santa Clara Valley Water District
SWP	State Water Project
WEAP	Water Evaluation and Planning

Appendix A

Model Calibration

Appendix A: Model Calibration

Expanding the Sacramento WEAP model to include the western San Joaquin Valley and Tulare Basin required the characterization of agricultural regions and the disaggregation of urban demands within the export zone (i.e., those areas serviced by the Delta Mendota Canal and the California Aqueduct). These demand areas were all previously represented as a single fixed time series of demands taken from the observed historical record. In the previous version of the model, the simplified representation of demands within the export zone facilitated the model calibration, because it obviated the need to consider many regulatory and operational changes that occurred during the period of the model calibration, 1968–1999 (Yates et al. 2008). Many of these changes concerned the Sacramento-San Joaquin Delta and impacted the operations of the main facilities that pump water from the Delta.

In updating the model to include a representation of Delta export operations, it was necessary to recalibrate the model such that it reproduced the observed operations over a timeframe that reflects the current management regime. To this end, we selected the water years 1993–2001 as the calibration period, because the most significant recent changes in management occurred just prior to this period with the passage of the Central Valley Project Improvement Act and the Bay-Delta Accord (later SWRCB Decision 1641). The goal of the recalibration was to capture the general behavior of the system components that were added to the model (i.e., monthly pumping at Banks and Jones Pumping Plants, San Luis Storage) while preserving the overall system operations characterized in the previous model. As such, we focus here on a comparison of the operations of the new model features with observed records. For a presentation of a wider system calibration see Yates et al. (2008) and Joyce et al. (2006).

Total annual and average monthly delta exports are shown for the two main pumping plants, Jones and Banks, in Figure A.1 and Figure A.2.

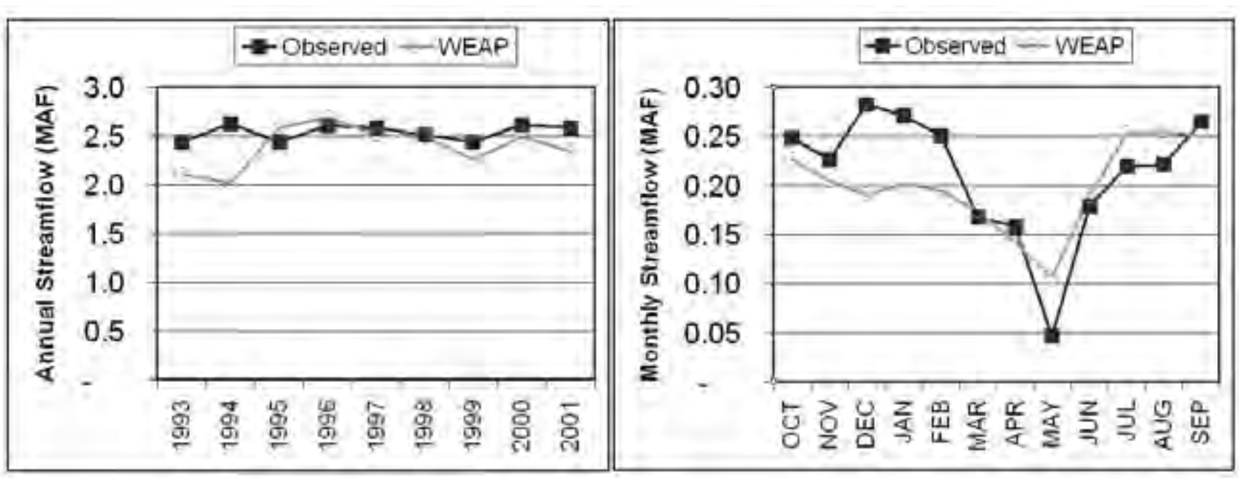

Figure A.1. Total annual and average monthly CVP pumping at Jones Pumping Plant (1993–2001)

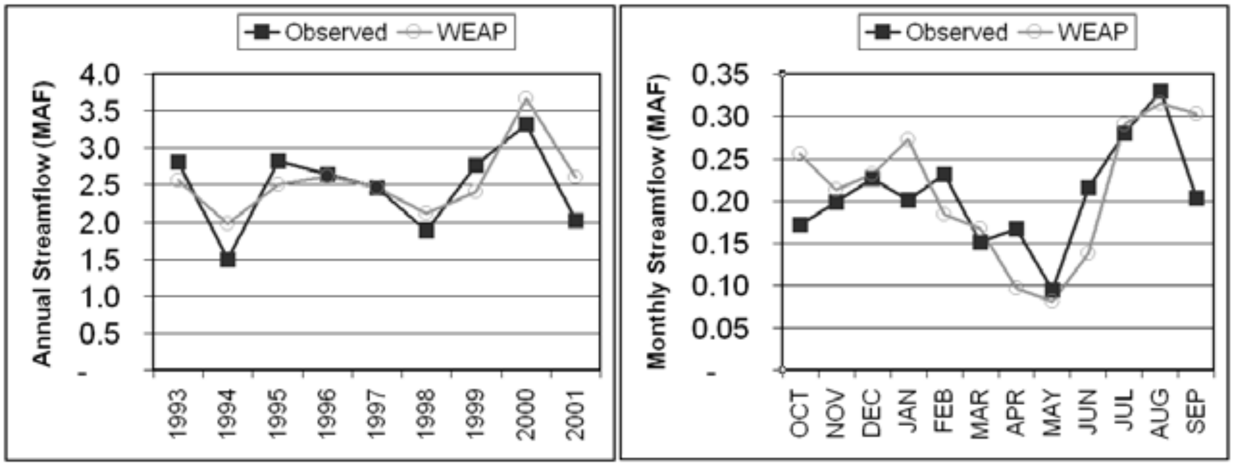

Figure A.2. Total annual and average monthly SWP pumping at Banks Pumping Plant (1993–2001)

For both pumping plants, the WEAP model approximates both the annual total exports and the monthly pattern of withdrawals. The agreement with monthly observed values, however, is less accurate than annual values, due largely to the fact that the model cannot duplicate with a uniform set of operating rules the many discretionary actions undertaken to limit delta pumping over this time frame.

The WEAP model represents San Luis operations using a fairly simple set of operating rules. By assigning the reservoir the lowest priority for storage, it acts to capture excess water (i.e., reservoir spills and unimpaired inflows) from the Delta in the Fall and Winter (Oct–Mar) and release it preferentially in the Spring and Summer to meet south of Delta water demands. Inflows to the reservoir are limited by pumping capacities at Banks and Jones Pumping Plants, which are subject to environmental constraints within the delta. Releases are limited in summer months to one-sixth of the storage available at the beginning of April. These simple rules suffice to operate San Luis reservoir storages in a manner consistent with observed records (Figure A.3).

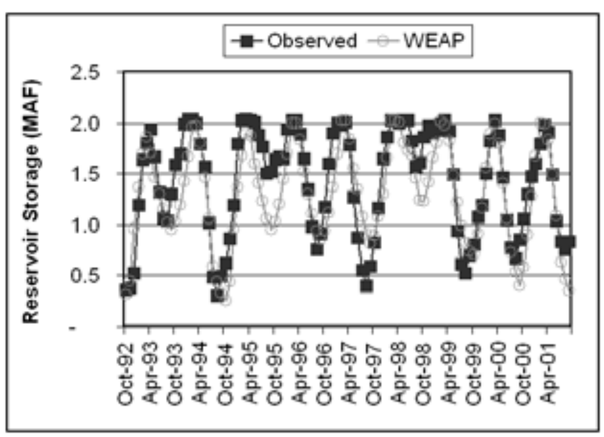

Figure A.3. San Luis storage (1993–2001)

The disaggregation of water demands in the export zone necessitated a reevaluation of the key indicator of Sacramento Valley operations—Sacramento River streamflows at Freeport—to judge whether the modifications influenced the behavior of water management in the Sacramento Basin. As the flows at Freeport are downstream of most of the diversions and return flows in the Sacramento Basin, they are presumed to reflect whether the model is capturing the overall management of water within the basin. Figure A.4 shows that with the modifications the model continues to recreate the overall system behavior in the Sacramento Valley for the calibration period.

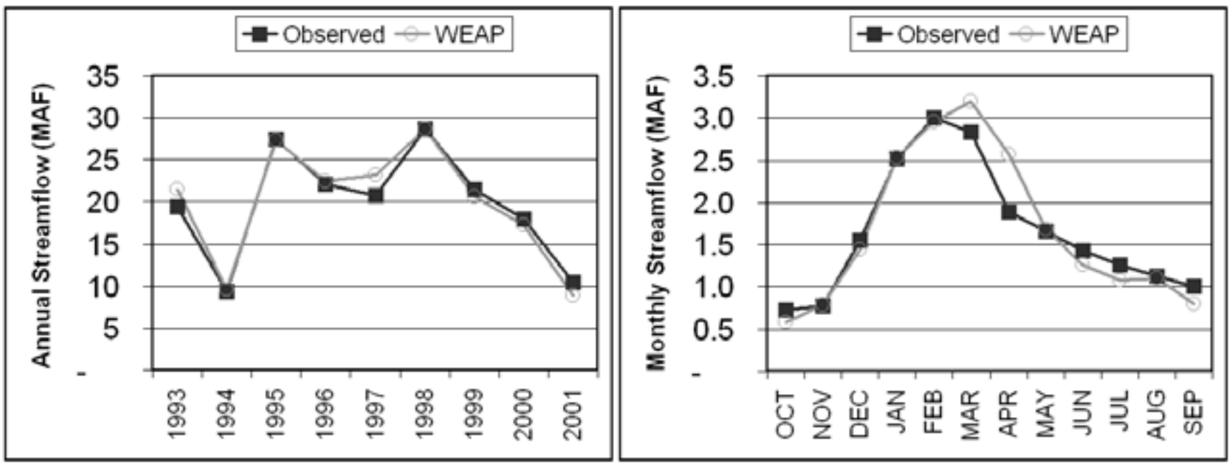

Figure A.4. Total annual and average monthly Sacramento River flows at Freeport (1993–2001)

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