Public Comment
2016 Bay-Delta Plan Amendment & SED
Deadline: 3/17/17 12:00 noon

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Jacob Johnson

Santa Cruz, Ca 95060

March 16, 2017

Ms. Jeanine Townsend
Clerk to the Board
State Water Resources Control Board P.O. Box 100
Sacramento, California 95814-0100

Comments on the Bay-Delta Water Quality Control Plan; Phase 1; SED

Dear Ms. Townsend,

I write this letter to the board with great concern over the future of our state, our water, and our natural resources. I am a simple man who until recently was not very well informed about the situation of what is going on in the delta region and rivers that feed into it. Now as a student at UCSC I have had an opportunity to learn what exactly is happening in my Legal studies class that is focused on California water law. I am not a radical and I understand the farmers need water to farm and the world needs the food they produce. However, we need to put in place responsible limits so we do not destroy our beautiful natural environment for profit.

As an American, a Californian, a father, and a human being, I ask that the board do its' duty to protect what nature man has not yet destroyed by his shortsightedness. Limits put in to save the Salmon and the Delta Smelt are not only good for the environment they are good for the future prosperity of our state. I fully support the mandate of leaving 60% UF of the water in the rivers so the fish have some chance of surviving and thriving. I also support possibly increasing that amount if in a few years that amount proves inadequate. I know that farmers planted in almonds, in particular, will suffer with less water and may have to grow less almonds or perhaps switch to less water intensive crops. The farmers historically have been able to survive growing other crops and it is only in the last ten or so years that they have become so reliant on almonds doubling their yield from 1 billion pounds to 2 billion pounds between 2004 and 2013 according to http://www.npr.org/sections/thesalt/2014/08/21/342167846/california-drought-has-wild-salmon-competing-with-almonds-for-water (last visited 3/16/17) ("NPR").

1. The Real Costs

The Delta is starving for fresh water. It is not something that is up for debate. It is proven. How we understand that not enough fresh water is coming into the Delta is by how much salinity is in the Delta region. The levels of this salt water intrusion we've seen in the last 50 years have only been seen 3 times in the previous 1600 years according to the fresh water report (attached) from the bay institute. There is some debate about salinity levels , however, it is beyond question that the Delta is naturally a freshwater environment. Only after the advent of large-scale diversions did salinity begin intruding into the Delta. [2nd related attachment contra costa water district salinity report]. This sort of environmental degradation not only affects the fish, it affects the entire ecosystem. It prevents the native plants from growing, and allows non-native/ invasive species into these wetlands. According to the NPR report on average less than 50% of the water is allowed flow out to the bay and during drought years it is less than 35%.

2. The Future

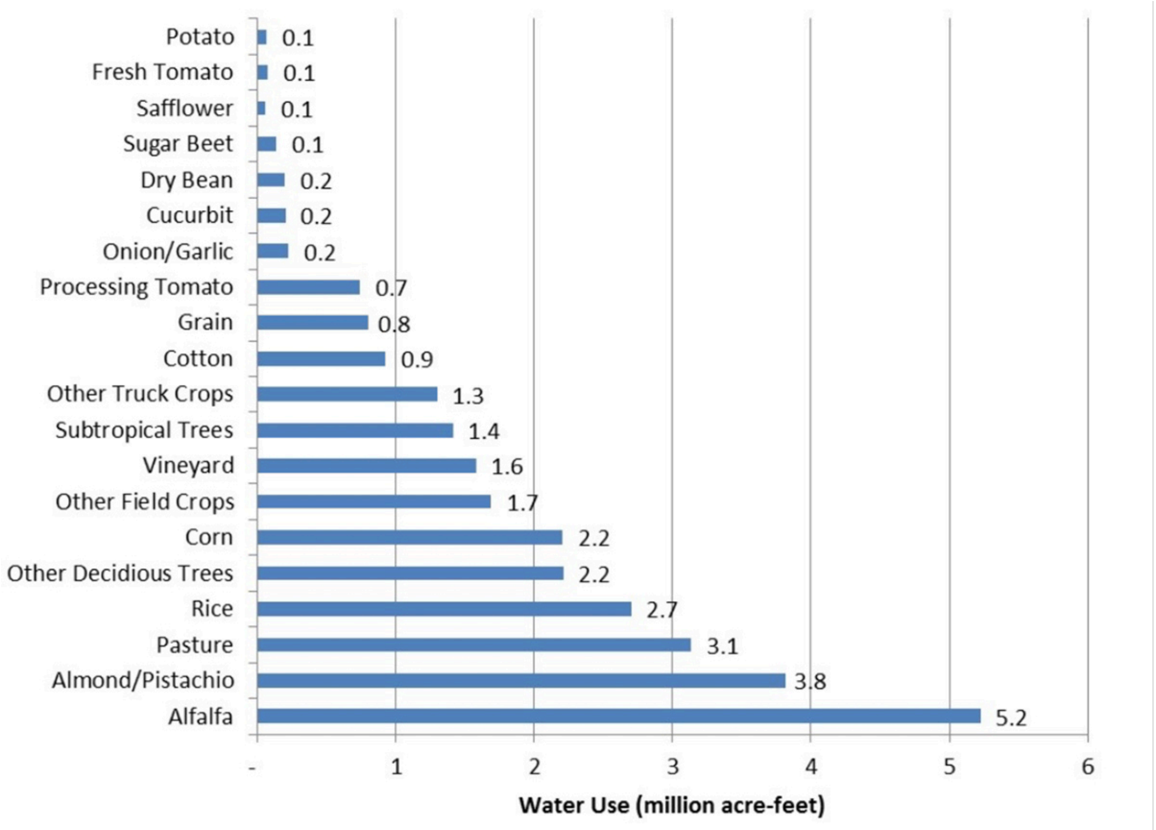
No one knows what the future will hold, but until we have a future where salmon can live on land we need to give them their water back. At least the 60% UF in the Merced, Stanislaus, Tuolumne, and lower San Joaquin Rivers so they have a fighting chance. When our children or grandchildren ask what was the biggest struggle of our generation do we want to say it was stopping the large business interests from destroying our ecosystems or would we rather say that we never struggled for anything but making sure China got enough California almonds.

3. Suggested Flow

There is a lot of science that strongly supports allowing as close to natural flow as possible. In a perfect world perhaps that would be possible, but in a world where human beings are ever growing in population and consumption we know we can't go completely back to nature. What we can do is impose smart limits that hopefully are enough to allow nature to rebound, and agriculture to co-exist. We only have one chance to get this right and our window time to correct our errors in overly-taxing our water supply in California is running short. Lack of action is a choice, and if we don't act soon we risk losing this habitat and these amazing fish forever.

Asking for 80-90% flows into the Delta is not reasonable for a number of reasons. It would completely devastate farming in the Central Valley and cost millions of dollars to our economy. I am all for sacrifice but not of the scale that will destroy lives and cripple our entire economy. If we allow 60% flow there would still be enough water for farmers to grow some almonds, perhaps not 2 billion tons a year. The farmers obviously will have options to grow other crops such as melons.

This next chart sourced from www.takepart.com (lat visited 3/16/17) shows how much water per acre foot various crops use. You see almonds take twenty-six times as much water as any of potato, tomato, sunflower, sugar beet, beans, onions, and garlic.]



4. Smart Choices

The water board has the authority to decide how much water is left in the river. Using your authority to keep 60% in the river meets the basic legal expectation established by the Water Control Plan. This is the most beneficial use of our water. Article X section 2 of the California Constitution suggests we do what is most beneficial. Continuing to allow Salmon in our rivers and fresh water is good for the environment and good for people who are in the fishing and tourism industry.

The EPA wants even more water according to a letter to the board from March 28th , 2013 “These scientists recommended the equivalent of no less than 90% UF to achieve a high level of ecological protection, and no less than 80% UF to achieve a moderate level of ecological protection.” The person writing the letter from the EPA is obviously an expert referring to the work of scientists that are looking at this issue from a global perspective. Honestly 60% might not be enough but it is a good jumping off point and when the plan is revisited in 3 years perhaps we will have to keep more water in the rivers.

5. Wealth and Influence

One thing is certain there will be those wielding wealth and influence to try and deter the Board from doing the job of reducing the water being taken out of the rivers. Almond farmers have become a force to reckon with as their crop becomes more and more valuable each year, and they can use their money to fund campaigns against fish, and against the environment. Their arguments can seem very plausible citing other threats against our salmon beyond lack of water. One thing big-Ag has trouble competing against is common-sense. According to NPR "California's almonds consume three times more water than the entire city of Los Angeles." That kind of usage is simply not sustainable.

The Almond.com website is ground zero for their own propaganda machine, and I will share a quote from them I absolutely agree with, "With population growth and increased regulatory demands, California's water resources are more stretched than ever." Something has got to give, and that is either we back off the extremely unsustainable use of water or we just let the environment and the fish die. The fishing industry and tourism generated by the fishing and the natural surrounding will not be able to come back because once it is gone it is gone for good. The farmers on the other hand can grow less almonds or grow other crops.

I hold the board in the utmost esteem and am certain the members can rise above politics, above outside influences, and make a decision that is in the best interests of all Californians. This is a choice that if made poorly could effect California negatively forever, along with marine life.

While whales, birds, and salmon can not be their own lobbyists they depend on people like me to become informed and advocate for them. According to the Fresh Water Report I cited earlier by Stephanie Wong, Page 23 "As the effects of climate change become more acute, the benefits of freshwater flow for coastal waters will become even more critical. Warming ocean conditions, weaker upwelling, and shifts in the Pacific Decadal and North Pacific Gyre Oscillation are reducing marine productivity along the California coast with cascading effects on the food web."

Table ES-2 on page ES-22 of the executive summary of changes to the WQCP now being considered shows that if the flow objectives were set at 60% of unimpaired flow, the loss to farmers would be 689,000 acre-feet of water annually. Table 11-2 on page 11-42 shows that 115,054 acres that would "lose" water are planted in almonds and pistachios. The choice is not one between saving the salmon and their ecosystem and depriving farm families of their livelihood. Rather, the choice is whether agribusiness and hedge funds will continue to reap exorbitant profits from almonds, or whether the affected acreage will be re-planted with crops reasonably grown in an arid climate.

6. No Good Alternatives

We've seen fish populations dwindle. Not doing anything to increase water is not helping. It is frightening how much damage we as humans can do to the world around us. The argument of doing things in the name of progress is false, having whole species die out so people all over the world can eat more nuts is, well, nuts. The only thing we can do in good conscience is take a stand.

For the sake of our state, our nation, and our planet we should make the hard choice and allow California to continue being the beacon of good environmental stewards. It is our values, and our commitment to one another and the environment that makes us unique and makes us special. We are the envy of the nation and the world. This is one of the most beautiful places in the world, shouldn't we keep it that way? There is no good alternative, except to do the right thing and allow at least 60% unimpaired flow.

7. Conclusion

For me writing this comment started as an alternative choice to writing a final paper. Writing this letter was an opportunity to allow my voice to be heard. It ended up becoming a passionate plea for mercy for our environment. Mercy for the fish and their habitat. I am asking the board to make a controversial decision that will have long lasting consequences that will possibly drastically alter some people's lives.

As a single father of 3, I am constantly explaining to my kids the difference between right and wrong. The basic stuff like don't steal, don't hurt people or animals. It occurs to me this is very similar. We have been stealing a large majority of the water and it is hurting the fish and the environment. One of the other lessons I teach my kids is to do things to make up for harm you've done. Say you are sorry and do things to make up for your actions. Lets make up for taking the water and give some back, it's the right thing to do.

Back in the sixties and seventies when air pollution was coming into its own we created more and more rigid pollution controls on vehicles because it made sense to protect the environment. Richard Nixon signed on for the creation of the EPA because rich or poor we all have to breathe, eat food, and drink water. In California we have some of the strictest environmental regulations in the country and in the world. There is a reason for our strict regulations, because we know we need them and we believe in science.

I read the letter from the EPA representative that I cited earlier, and I know she is much smarter and in the know than I am. I personally am not calling for as much water in the river as she is but in 3 years we may have to increase to her suggested levels. I think it is better to get the farmers used to less now than to wait and do something that drastic in one shot. There is one thing that is clear, the time is now, the power is yours, I ask please use your power wisely and for the best for all not the few.

Best Regards, Jacob Johnson

Historical Fresh Water and Salinity Conditions in the Western Sacramento-San Joaquin Delta and Suisun Bay

A summary of historical reviews, reports, analyses and measurements

Water Resources Department

Contra Costa Water District

Concord, California

February 2010

Technical Memorandum WR10-001

Antioch-216

Acknowledgements

CCWD would like to thank the City of Antioch for their contribution towards funding a technical review of CCWD's draft report "Trends in Hydrology and Salinity in Suisun Bay and the Western Delta" (June 2007); their review substantially improved the work and led to the final report "Historical Fresh Water and Salinity Conditions in the Western Sacramento-San Joaquin Delta and Suisun Bay". CCWD is grateful to the many reviewers including Richard Denton, Matthew Emrick, Gopi Goteti, Phil Harrington, E. John List, Susan Paulsen, David Pene, Mat Rogers, and Peter Vorster. We also thank the following for sharing their data and analyses: Roger Byrne, Chris Enright, Spreck Rosekrans, and Scott Starratt, and we thank Ann Spaulding for her contributions.

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Foreword - Establishing the Historical Baseline

The watershed of the Sacramento–San Joaquin Delta (Delta) provides drinking water to more than 23 million Californians as well as irrigation water for millions of acres of agriculture in the Central Valley. The Delta itself is a complex estuarine ecosystem, with populations of many native species now in serious decline. The Delta estuary as we know it began to form about 6,000 years ago, following the end of the last ice age. Because the estuary is connected to the Pacific Ocean through San Francisco Bay, seawater intrusion causes the salinity of Suisun Bay and the Delta to vary depending on hydrological conditions. This seawater intrusion into the Delta affects estuarine species as well as drinking water and irrigation water supplies.

Successful restoration of the Delta ecosystem requires an understanding of the conditions under which native species evolved. Contra Costa Water District's report on "Historical Fresh Water and Salinity Conditions in the Western Sacramento-San Joaquin Delta and Suisun Bay" presents a detailed review of more than 100 years of studies, monitoring data, scientific reports, and modeling analyses that establish an historical record of the salinity conditions in the Western Delta and Suisun Bay.

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Executive Summary

The historical record and published studies consistently show the Delta is now managed at a salinity level much higher than would have occurred under natural conditions. Human activities, including channelization of the Delta, elimination of tidal marsh, and water diversions, have resulted in increased salinity levels in the Delta during the past 150 years.

Eighty years ago, Thomas H. Means wrote ("*Salt Water Problem, San Francisco Bay and Delta of Sacramento and San Joaquin Rivers*," April 1928, pp 9-10):

> "Under natural conditions, Carquinez Straits marked, approximately, the boundary between salt and fresh water in the upper San Francisco Bay and delta region of the two tributary rivers—the Sacramento and San Joaquin. Ordinarily salt water was present below the straits and fresh water was present above. Native vegetation in the tide marshes was predominately of salt water types around San Pablo Bay and of fresh water types around Suisun Bay….
>
> The definite statement that salt water under natural conditions did not penetrate higher upstream than the mouth of the river, except in the driest years and then only for a few days at a time, is warranted.…
>
> At present [1928] salt water reaches Antioch every year, in two-thirds of the years running further [sic] upstream. It is to be expected that it will continue to do so in the future, even in the years of greatest runoff. In other words, the penetration of salt water has become a permanent phenomenon in the lower river region.
>
> The cause of this change in salt water condition is due almost entirely to the works of man."

In 1928, Thomas Means had limited data over a short historical period from which to draw these conclusions. Nonetheless, his conclusions remain accurate and have been confirmed by numerous subsequent studies, including paleosalinity records that reveal salinity conditions in the western Delta as far back as 2,500 years ago. The paleosalinity studies indicate that the last 100 years are among the most saline of periods in the past 2,500 years. Paleoclimatology and paleosalinity studies indicate that the prior 1,500 years (going back to about 4,000 years ago) were even wetter and less saline in San Francisco Bay and the Delta. The recent increase in salinity began after the Delta freshwater marshes had been drained, after the Delta was channelized and after large-scale upstream diversions of water, largely for agricultural purposes, had significantly reduced flows from the tributaries into the Delta. It has continued, even after the construction of reservoirs that have been used in part to manage salinity intrusion.

Increased Salinity Intrusion into the Delta

Studies and salinity measurements confirm that despite salinity management efforts, Delta salinity is now at or above the highest salinity levels found in the past 2,500 to 4,000 years. Under equivalent hydrological conditions, the boundary between salt and fresh water is now 3 to 15 miles farther into the Delta than it would have been without the increased diversions of fresh water that have taken place in the past 150 years.

Reservoir operations artificially manage salinity intrusion to conditions that are saltier than had been experienced prior to the early 1900's. While these managed conditions are certainly fresher than would occur in today's altered system if operated without any salinity management, they are still saltier than what the Delta experienced under similar hydrological conditions in the past. While the Delta is being managed to a somewhat acceptable saline condition to meet many beneficial uses, it is still managed at a more saline condition than would have occurred prior to the anthropogenic changes of the past 150 years.

For example, the 1928-1934 drought was one of the driest periods in the past 1,000 years (Meko *et al*., 2001a), and occurred after tidal marshes within the Delta had been reclaimed and water diversions began removing substantial amounts of fresh water from the Bay-Delta system. Nonetheless, the Delta freshened during the winter in those drought years. This winter freshening of the Delta has not occurred during recent droughts. While salinity intrusion into the Delta was previously only seen in the driest years, significant salinity intrusion now occurs in nearly every year – exceptions are only found in the wettest conditions.

Changed Variation in Salinity

The variability of fresh and saline conditions in the Delta has considerably changed because of upstream and in-Delta water diversions and water exports (Enright and Culberson, 2009). This change in variability results largely from the lack of fresh conditions in Suisun Bay and the western Delta, especially in the winter and spring. Restoring a variable salinity regime that more closely approximates conditions prior to the early 1900's would require much higher flows and much fresher conditions than current management practices provide, with larger outflows in the fall in most years and much larger outflows in the late winter and spring in all years.

Key Conclusions

The major conclusions of this study are:

1. Salinity intrusion during the last 100 years has been among the highest levels over the past 2,500 years. The Delta has been predominantly a freshwater tidal marsh for the last 2,500 years.
2. Human activities during the last 150 years, including channelization of the Delta, elimination of tidal marsh, construction of deep ship channels, and diversion of water, have resulted in the increased salinity levels in the Delta.

3. Conditions in the Delta during the early 1900's were much fresher than current conditions for hydrologically similar periods. Salinity typically intrudes 3 to 15 miles farther into the Delta today.
4. The historical record and published studies uniformly demonstrate and conclude the Delta is now managed at a salinity level that is much higher than would have occurred under pre-1900 conditions. Operation of new reservoirs and water diversion facilities for salinity management reduces salinity intrusion somewhat, but the levels still exceed pre-1900 salinities.
5. Seasonal and inter-annual variation in salinity has also been changed; however, this change is largely the result of reduced freshwater flows into the Delta. At any given location in the western Delta and Suisun Bay, the percentage of time during the year when fresh water is present has been greatly reduced or, in some cases, largely eliminated.

Background

Flows and water quality in the Sacramento-San Joaquin Delta (Delta) are strongly influenced by freshwater inflow from the rivers, by the tides in San Francisco Bay and by salinity from Bay waters. Prior to human influence, the historical distribution of salinity in the Delta was controlled primarily by the seasonal and inter-annual distribution of precipitation, the geomorphology of the Bay and Delta, daily tides, the spring-neap[1] tidal cycle, and the mean sea level at Golden Gate. Extended wet and dry periods are both evident in the historical record. Since about 1860, a number of morphological changes to the Delta landscape and operational changes of reservoirs and water diversions have affected flows and the distribution of salinity within the Delta.

Between 1860 and 1920, there was significant modification of the Delta by humans:
(i) marsh land was reclaimed,
(ii) hydraulic mining caused extensive deposition and then erosion of sediment, and,
(iii) Delta channels were widened, interconnected and deepened.

Large-scale reservoir construction began in about 1920 and continued through the 1970's, changing the timing and magnitude of flows to the Delta. Large volumes of water began to be diverted for agricultural use upstream of and within the Delta in the same time period. In more recent times, California's Delta water resources have been extensively managed to meet the water supply needs of the State's municipal, industrial, and agricultural water users, with attempts made to also provide flow and water quality conditions to meet fishery needs.

Proposals for significant additional alteration of the Delta and of flows within the Delta are currently being developed as part of the Bay-Delta Conservation Plan process[2]. To

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[1] During a spring tide, the gravitational forces from the sun and moon are largely the same direction and the high-low tidal range is greatest. During a neap tide, the gravitational forces sun and moon are largely not aligned and the tidal range is the lowest. The spring-neap tidal cycle, from strong spring tides through weak neap tides and back to spring tides, in San Francisco Bay has a period of about 14 days.

[2] www.baydeltaconservationplan.com

understand the effect of those proposals, it is important to accurately establish historical conditions. For example, for ecological restoration to be successful, it is necessary to establish and understand the conditions to which native species have previously adapted and survived in order to predict their response to future changes in climate or water management. This report uses available data and modeling to examine the consequences of structural changes in the Delta (channelization, channel dredging), increased diversions of water upstream of the Delta, reservoir operations, climate and sea level effects, and other factors on Delta salinity.

Objective

The objective of this report is to answer two major questions regarding the historical extent of fresh water and salinity in the western Delta and Suisun Bay:

I. What was the extent of fresh water and what were the salinity conditions prior to large-scale reservoir operations and water diversions (i.e., prior to early 1900's) and prior to structural changes in the Delta (i.e., prior to the 1860's)?

II. What are the effects of large-scale water management practices (reservoir operations and diversions) on salinity conditions in the western Delta and Suisun Bay?

Approach

Available data were used to characterize historical and present-day fresh water extent and salinity intrusion into the Delta. The data examined in this report include paleohistorical records (over geologic time scales) of river flow and salinity (Section 2), instrumental observations of hydrology and salinity (Section 3), and literature reports on the extent of fresh water in the Delta (Section 4). Additional details and supplemental information are presented in the Appendices to this report.

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Historical Fresh Water and Salinity Conditions in the Western Sacramento-San Joaquin Delta and Suisun Bay

Tables

Figures

Acronyms

C&H	California and Hawaiian Sugar Refining Corporation
CCWD	Contra Costa Water District
CDEC	California Data Exchange Center
Cl	Chloride concentration
CVP	Central Valley Project
DPW	Department of Public Works
DSM2	Delta Simulation Model 2
DWR	California Department of Water Resources
DWSC	Deep water ship channel
EC	Electrical conductivity
ENSO	El Niño/Southern Oscillation
ESA	Endangered Species Act
IEP	Interagency Ecological Program
M&I	Municipal and Indutrial
NDO	Net Delta Outflow
PDO	Pacific Decadal Oscillation
PPIC	Public Policy Institute of California
SWRCB	State Water Resource Control Board
SRI	Sacramento River Index
STORET	Storage and Retrieval
SWP	State Water Project
TBI	The Bay Institute
TDS	Total Dissolved Solids

Units

AF	Acre-feet
MAF	Million acre-feet
TAF	Thousand acre-ft
µS/cm	MicroSiemens per centimeter, a measure of EC
cfs	Cubic feet per second
mg/L	Milligrams per liter
ppm	Parts per million
ppt	Parts per thousand

1. Introduction

1.1. Background

The Sacramento-San Joaquin River Delta (Delta) is fed by fresh water from the Sacramento River and the San Joaquin River basins (Figure 1-1). The Delta is connected to the San Francisco Bay through Suisun and San Pablo Bays, and the movement of water back and forth between the Delta and the Bay results in mixing between saline water from the Pacific Ocean and fresh water from the rivers flowing into the Delta. The extent to which salty ocean water intrudes into the Delta is a function of natural processes such as ocean tides and precipitation and runoff from the upstream watersheds. It has also been greatly influenced by anthropogenic activities (e.g. construction of artificial river channels, removal of tidal marsh, removal of floodplain connections to channels, deepening of channels for navigation purposes, reservoir storage and release operations, and water diversions).

Proposals for significant additional alteration of Delta channels and marshland, of flows within the Delta, and of reoperation of upstream reservoirs are currently being developed as part of the Bay-Delta Conservation Plan, which builds upon earlier work by the Delta Vision Blue Ribbon Task Force[3], and others (e.g., see Lund *et al.,* 2007). To understand the context and effect of those proposals, it is important to accurately understand the historical conditions previously experienced by Delta species.

An analysis of the salinity trends and variability in northern San Francisco Bay since the 1920's and the factors controlling those salinity trends has recently been published (Enright and Culberson, 2009), with a focus on a comparison of pre-1968 salinity and flows with post-1968 conditions. This report includes analysis and review of reports, data and information from the period prior to Enright and Culberson's analysis, and includes the review of salinity trends using paleohistorical data.

Historically, reproduction of most species in the Bay-Delta (biotic production phase) occurred during the high-flow periods (winter and spring) and biotic reduction occurred in the low-flow periods (summer and fall) (Baxter *et al.,* 2008). Multi-year wet periods most likely resulted in population increases, whereas drought periods likely resulted in reduced reproduction and increased predation. The recent report on Pelagic Organism Decline (POD, Baxter *et al.,* 2008) indicated that reduced flow variability under the current water management conditions may have exacerbated the effects of predation on the population abundance of pelagic fish species in the Bay-Delta estuary. Native species of the Bay-Delta system adapted to the historical salinity conditions that occurred prior to large-scale water management practices and physical changes in the Delta. The historical salinity conditions in the Delta provide insight into the response of fish species to proposed ecosystem restoration actions, and the response of species to future changes in climate or water management.

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[3] Delta Vision Blue Ribbon Task Force was appointed by California Governor Arnold Schwarzenegger in February 2007 and adopted the Delta Vision Strategic Plan in October 2008.

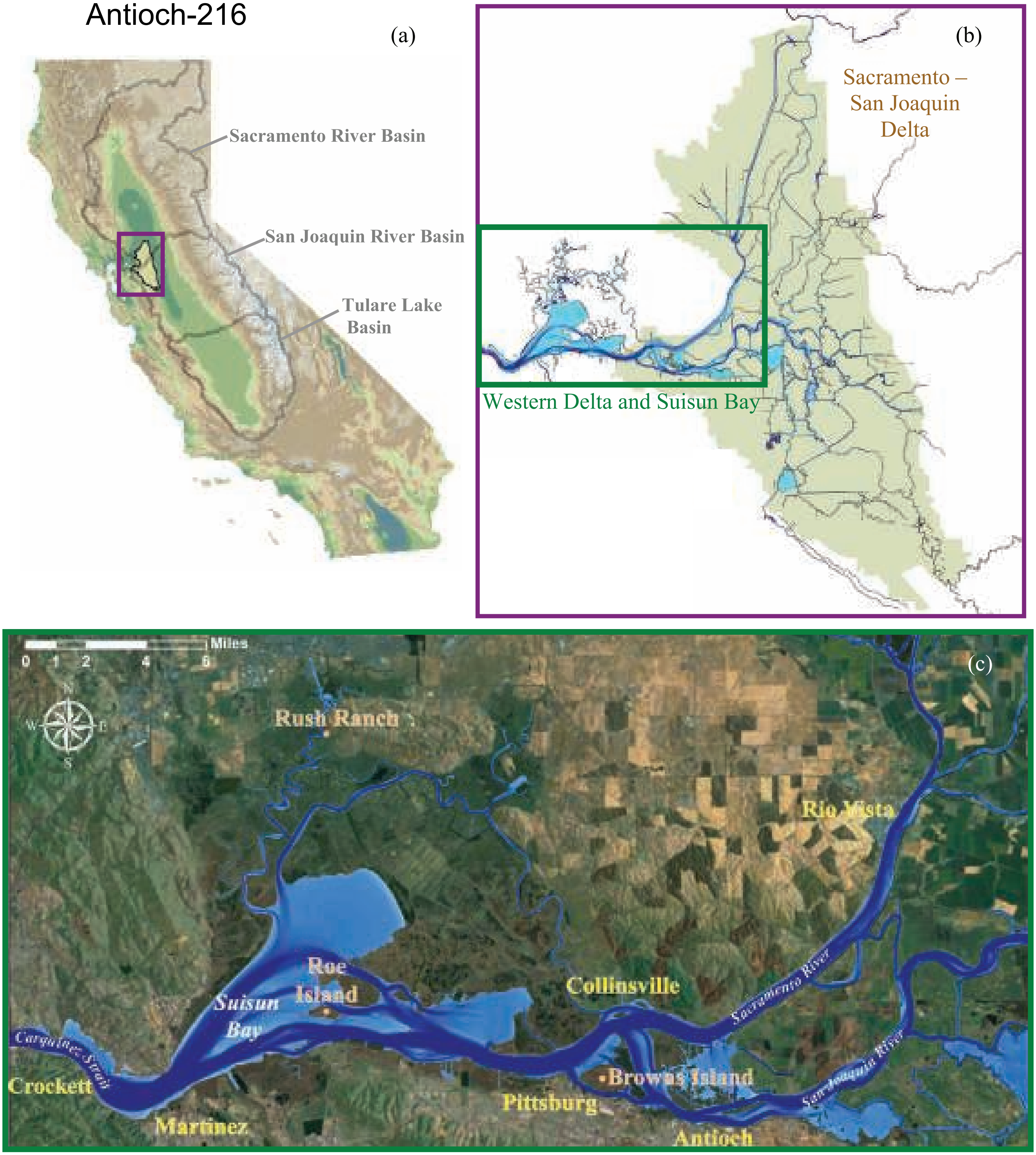

Figure 1-1 – Map

(a) Topographical map of California, with outlines of the Sacramento River, San Joaquin River, and Tulare Lake basins; purple rectangle indicates the extent of the inset in panel (b). (b) Sacramento – San Joaquin Delta and Suisun Bay region; green rectangle indicates the extent of the Western Delta and Suisun Bay enlarged in panel (c). (c) Extent of salinity evaluations considered within this study, including names of locations referenced throughout this report.

The salinity concentrations in San Francisco Bay and the Delta are the result of tides that move seawater into the system and are controlled in large part by the amount of fresh water passing through the system (Denton, 1993; Uncles and Peterson, 1996; Knowles *et al*., 1998). The salinity distribution is driven by the motion of the tides, which convey ocean water into the system on the flood tide and draw a mixture of ocean and river water back out again on the ebb tide. These tides act on natural diurnal (repeating twice per day) and spring-neap (repeating every 14 days) cycles driven by the gravitational forces of the sun and moon (Oltmann and Simpson, 1997; Burau *et al*., 1999).

Other factors affecting Bay-Delta salinity (discussed in Appendix A) may be smaller but are not insignificant. When comparing historical salinity conditions in the Bay-Delta watershed, it is often helpful to compare periods with similar hydrological conditions so that the changes due to other factors can be discerned. This will reveal if there is an anomalous change in salinity, even if the specific cause of that change in salinity is not known.

Major anthropogenic modifications to the Delta that affect salinity intrusion began with the European settlement of the region and can be classified into two categories: physical modifications of the landscape (e.g., removal of tidal marsh, separation of natural floodplains from valley rivers, construction of permanent artificial river channels, and land-use changes) and water management activities (e.g. diversion of water for direct agriculture, municipal, or industrial use, and reservoir storage and release operations).

As shown in Figure 1-2, tidal marsh acreage in the Delta decreased significantly from nearly 346,000 acres in the 1870’s to less than 25,000 acres in the 1920’s and has since continued to decrease. Even after hydraulic mining for gold was banned in California in 1884, large quantities of mining debris continued to be carried by runoff into the Delta, where it was deposited as sediment, filling channels in the Delta and Suisun Bay. Between 1887 and 1920, Suisun Bay became an erosional environment and continued to lose sediment through 1990. Enright and Culberson (2009) discuss the effects of the changes in Suisun Bay bathymetry on salinity intrusion. Major dredging projects on the main Delta channels to create the Stockton and Sacramento Deep Water Ship Channels (DWSC) have also changed how flows and, therefore, salinity are distributed throughout the Delta.

Each of these factors has changed the salinity regime: loss of tidal marsh lands has allowed increased tidal energy deeper into the Delta, increasing tidal flows and salinity dispersion (Enright and Culberson, 2009), net erosion and increasing depth within Suisun Bay likely increased dispersive transport of salt up the estuary (Enright and Culberson, 2009), and deeper channels allow increased salinity intrusion due to increased baroclinic circulation and increased tidal flow and dispersion..

However, these physical modifications generally have had less effect on salinity intrusion in the Delta than the major water management activities that have resulted in large-scale diversion of water for reservoir storage and agricultural, domestic, and industrial water use (Nichols *et al,* 1986; Knowles, 2002). As will be seen in data presented in this document, early diversions before large-scale storage projects resulted in greatly increased salinity intrusion, especially in the summer irrigation season, peaking in September. Later, reservoir operations reduced salinity intrusion in the summer and fall, but increased it in the winter and spring, up until the mid-1980's. Subsequent water operations have resulted in increased salinity intrusion year round.

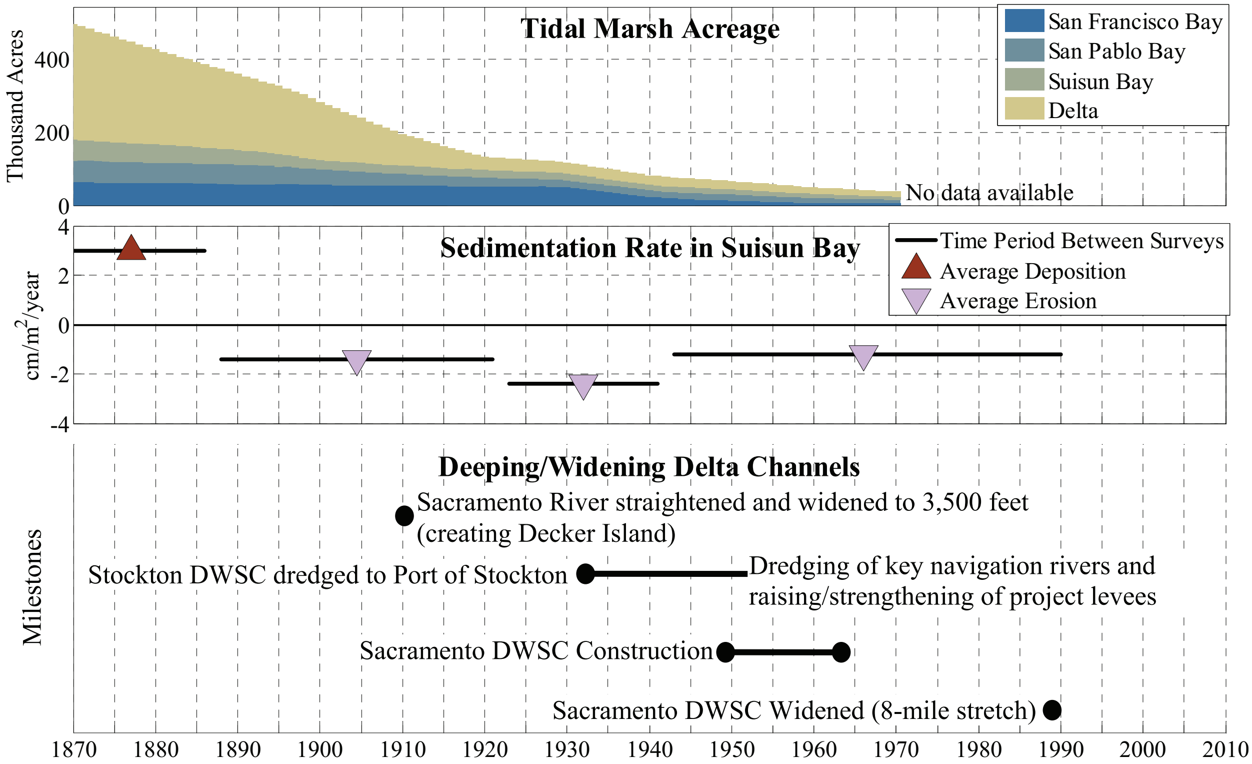

Figure 1-2 – Chronology of anthropogenic modifications to the Bay-Delta landscape

Bay-Delta landscape has undergone significant changes since the mid-1800's. Tidal marsh acreage (top panel) has been significantly reduced (data from Atwater, et al., 1979). Suisun Bay received a pulse of sediment from hydraulic mining in the late 1800's (middle panel), but lost sediment from 1887 to 1990 (data from Cappiella et al., 1999). Numerous efforts to widen and deepen the main channels within the Delta have occurred throughout the 20th Century (bottom panel).

The largest reservoir of the federal Central Valley Project (CVP), Lake Shasta, was completed in 1945, and the largest reservoir of the State Water Project (SWP), Lake Oroville, was completed in 1968. Total upstream reservoir storage capacity increased from 1 MAF in 1920 to more than 30 MAF by 1979. The CVP began exporting water from the southern Delta through Jones Pumping Plant (formerly known as the Tracy Pumping Plant) in 1951, and the SWP began exports through Banks Pumping Plant in 1968. By 1990, the combined export of water from the southern Delta through the Banks and Jones Pumping Plants was about 6 MAF per year.

Figure 1-3 shows that the greatest increase in upstream reservoir storage occurred from the 1920's through the 1960's. Prior to the construction of major water management reservoirs, irrigated acreage grew to about 4 MAF. The construction of the reservoirs allowed irrigated acreage to increase to about 9 MAF. Since 1951, when the first south Delta export facility was completed, annual diversions from the Delta have increased to a maximum of about 8 MAF; total annual diversions from the system are estimated at up to 15 MAF.

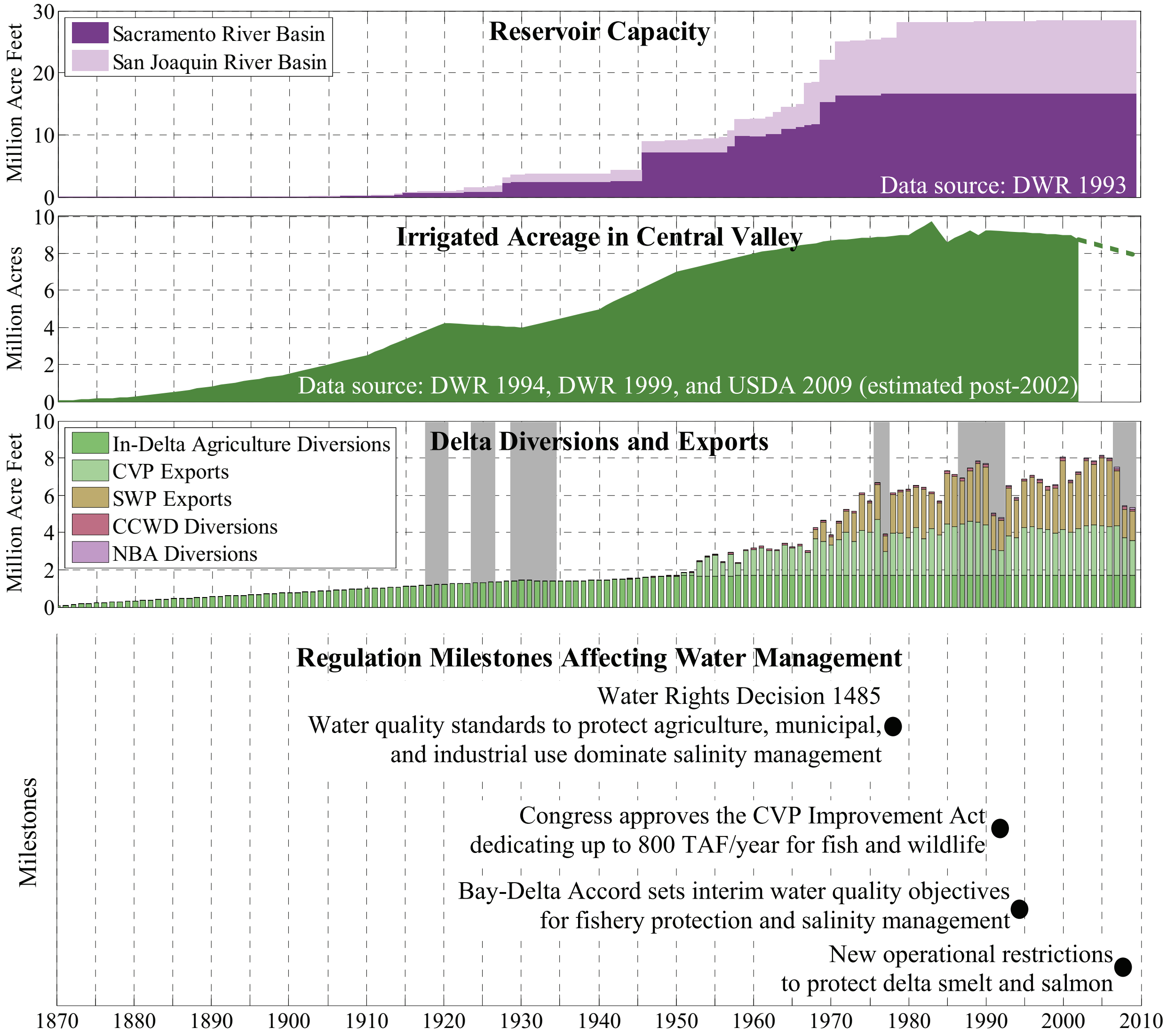

Figure 1-3 – Chronology of anthropogenic activities that affect water management

Reservoirs (top panel) and irrigated crops in the Central Valley (second panel) alter the timing and magnitude of water flow to reach the Delta. Diversions and exports within the Delta (third panel) further reduce the amount of water to flow through the Delta to Suisun Bay. Regulations (bottom panel) require modifications to water management activities to meet specific flow and water quality objectives.

Figure 1-3 also presents the timeline for recent regulatory milestones that have affected Delta water quality. Salinity management was dominated by water quality standards to protect Delta agriculture and municipal and industrial (M&I) uses in the 1978 Water Quality Control Plan and State Water Resources Control Board (SWRCB) Decision 1485. The Bay-Delta Accord of 1994 and subsequent SWRCB Water Rights Decision 1641 made fishery protection the dominant factor for salinity management with new estuarine habitat or “X2 Standards”[4] from February through June, with minimum outflows for the remainder of the

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[4] X2 is the distance, in kilometers from the Golden Gate, to the location of the 2 part per thousand salinity line. A larger X2 means salinity has intruded farther into the Delta.

year. The relationship between X2 and estuarine habitat is discussed in detail in Jassby *et al.* (1995).

These regulations apply throughout the year and have modified how the large-scale water management reservoirs and export facilities are operated. For instance, delta smelt was listed as a threatened species under the federal Endangered Species Act in 1993, and Sacramento River winter-run salmon was listed as endangered in 1994. The subsequent biological opinions, 1994 Bay-Delta Accord, and the adoption of a new water quality control plan by the State Water Resources Control Board in 1995, required increased reservoir releases in some months for temperature control in the Sacramento River below Shasta and for salinity control in Suisun Bay. They also applied additional limits on pumping at the export facilities in the south Delta.

Changes in water diversions and reservoir operations have altered the magnitude and timing of river flows to the Delta, and anthropogenic modifications to the Delta landscape have altered the interaction of fresh water from the rivers with salt water from the ocean, thus changing patterns of salinity intrusion into the Delta.

1.2. Comparing Historical Conditions

Flow and salinity conditions prior to human interference varied according to seasonal and annual hydrological conditions, short-term and long-term drought cycles and other natural changes, so “natural” conditions include variability that must be considered in any analysis. Hydroclimatic variability is described by “unimpaired” runoff, which represents the natural water production of a river basin, unaltered by water diversions, reservoir storage and operation, and export of water to or import of water from other basins.

As discussed above, large-scale water management operations during the last 100 years superimposed on the anthropogenic modifications to the Delta landscape have significantly changed Delta conditions. It is possible to remove the effect that water management operations have had on flows and generate a corresponding set of unimpaired flows. However, it is not possible, without complex assumptions and modeling, to also remove the additional effect of the land use, channel and tidal marsh modifications to the Delta.

The historical conditions presented in this report have been determined from records in paleoclimatic fossils and measured directly with various scientific instruments. The paleoclimatic data start well before human influence, but continue through the 20th Century when anthropogenic modifications became significant.

Because of the natural hydroclimatic variability, no past historical period may fully represent “natural” conditions. Therefore, this report summarizes the available historical salinity information with reference to the time period of the observations, and then compares each period to the salinity regime during present day periods with similar upstream unimpaired hydrology. Where there are significant changes in salinity, despite similar upstream unimpaired hydrology, other factors such as landscape modifications and water management operations must be contributing factors.

1.3. Objective

The objective of this report is to answer two major questions regarding the historical extent of fresh water and salinity in the western Delta and Suisun Bay:

I. What was the extent of fresh water and what were the salinity conditions prior to large-scale reservoir operations and water diversions (i.e., prior to early 1900's) and prior to structural changes in the Delta (i.e., prior to the 1860's)?

II. What are the effects of large-scale water management practices (reservoir operations and diversions) on salinity conditions in the western Delta and Suisun Bay?

1.4. Report Structure

The remainder of this report is organized as follows:

Section 2: Paleoclimatic Evidence of the Last 10,000 Years

Estimated river flow data and salinity records for the past several thousand years have been obtained from paleoclimatic records, such as tree rings and sediment cores. These records capture the hydroclimatic variations over decadal and centennial time scales and are useful tools in understanding the freshwater flow and salinity regimes before modern instrumentation.

Section 3: Instrumental Observations of the Last 140 Years

Long-term precipitation and river runoff records from the 1870's to the present provide context for the salinity observations. Climatic variability of precipitation and runoff in the upper watershed has a significant influence on salinity intrusion, with greater salinity during dry periods and lower salinity during wet periods. If, for example, the salinity is greater or less than what would be expected based on the natural climatic variability, as measured by unimpaired runoff, other factors must be influencing salinity intrusion.

Reservoir operations, diversions and consumptive use (collectively termed "water management") alter the amount of runoff from the upper watershed that actually flows out of the Delta. Observations and common computer models are used to assess the effects of this water management on Net Delta Outflow (the net quantity of water flowing from the Delta to the Suisun Bay) and on salinity in the western Delta and Suisun Bay. Observations include measurements of salinity indicators by the California & Hawaiian Sugar Refining Corporation (C&H) from the early 1900's and long-term monitoring data from the Interagency Ecological Program (IEP). Modeling tools include the DAYFLOW program from IEP, the DSM2 model from the California Department of Water Resources, the X2[5]

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[5] X2 is defined as the distance from the Golden Gate to the 2 part-per-thousand isohaline (equivalent to a salinity of 2 grams of salt per kilogram of water), measured along the axis of the San Francisco Estuary. X2 is often used as an indicator of freshwater availability and fish habitat conditions in the Delta (Jassby *et al.*, 1995; Monismith, 1998).

equation (Kimmerer and Monismith, 1992) and Contra Costa Water District's salinity outflow model (also referred to as the G-model) (Denton, 1993; Denton and Sullivan, 1993).

Section 4: Qualitative Observations of Historical Freshwater Flow and Salinity Conditions

Qualitative observations on salinity conditions in the western Delta and Suisun Bay from an early water rights lawsuit and from various literature reports are discussed to provide a perspective of the salinity conditions prevailing in the late 1800's and early 1900's. The 1920 lawsuit filed by the Town of Antioch against upstream irrigation districts alleged that the upstream water diversions were causing increased salinity intrusion at Antioch (Town of Antioch v. Williams Irrigation District, 1922). Briefings and testimony from the legal proceedings are indicative of the salinity conditions prevailing in the early 1900's, as are literature reports of conditions in the western Delta and Suisun Bay. These reports contain both qualitative observations and anecdotal information regarding historical salinity conditions. Because the proceedings were adversarial in nature, this report focuses on the testimony of the upstream interests, who were trying to demonstrate the extent of salinity intrusion in the Delta prior to their diverting water. Note that the Supreme Court did not base its final decision on the evidence of whether or not Antioch had continuous access to fresh water. The Court's decision was based on the State policy to irrigate as much land as possible for agriculture; the Court did not pass judgment on the accuracy of the testimony of either side.

Section 5: Conclusions

This section synthesizes the findings from Sections 2 through 4 and presents the overall conclusions regarding trends in the historical Delta salinity.

2. Paleoclimatic Evidence of the Last 10,000 Years

Paleoclimatic evidence from the watershed of San Francisco Bay (Bay) and Sacramento-San Joaquin Delta (Delta), obtained from proxy information such as tree rings and sediment deposits, provides a history of conditions before modern direct instrumental observations. Evidence of major regional climatic events that represent long-term wet period and drought cycles will be discussed, followed by discussions of Delta watershed runoff and Delta salinity, as measured by flow and electrical conductivity instrumentation.

2.1. Major Regional Climatic Events

The modern Bay-Delta is relatively young in terms of geologic timescales. The estuary started forming around 8,000 to 10,000 years ago (Atwater *et al.* 1979), when rapid sea level rise allowed the ocean to enter the Golden Gate. At this time, there was no Bay or Delta, but simply river valleys. Rapid sea level rise continued, such that approximately 6,000 years ago, the outline of San Francisco Bay, including San Pablo Bay and Suisun Bay, resembled the modern extent. At about the same time, sea level rise slowed to a more moderate pace, allowing tidal marshes to begin to form.

Malamud-Roam *et al.* (2007) review paleoclimate studies in the Bay-Delta watershed, summarizing evidence of climate variability through the development of the present day Bay-Delta system (Table 2-1).

Table 2-1 – Climate during the evolution of the Bay-Delta estuary

Overview of precipitation, temperature, and sea level conditions during the last 10,000 years based on data from Malamud-Roam et al. (2007) and Meko et al. (2001). Time periods are given in terms of number of years ago (represented as age, a; or ka for 1,000 year ago) and the Common Era (BCE/CE) calendar system. The shading indicates relatively dry periods.

Approximate Time Period	*Prevailing Climate and Geomorphology*
10 ka to 8 ka 8000 BCE to 6000 BCE	▪ Rapid sea level rise ▪ Ocean enters Golden Gate ▪ San Francisco Bay is just a river valley ▪ Cooler than 20th Century, but becoming warmer and drier
6 ka to 5 ka 4000 BCE to 3000 BCE	▪ Sea level rise slows to more moderate pace ▪ Outline of San Francisco Bay resembles modern extent ▪ Tidal marsh begins to form in the Delta ▪ Temperature reaches a maximum of the last 10,000 years ▪ Relatively dry conditions ▪ Central Valley floodplain system began to develop

Approximate Time Period	*Prevailing Climate and Geomorphology*
4 ka to 2 ka 2000 BCE to 1 CE	▪ Cooling trend with increased precipitation ▪ Large flood occurred ~ 3,600 years ago (1600 BCE)

2 ka to 0.6 ka
1 CE to 1400 CE
	▪ Trend to more arid, dry conditions
	▪ Severe droughts:
	  ▪ 1,100 to 850 years ago (900 CE to 1150 CE)
	  ▪ 800 to 650 years ago (1200 CE to 1350 CE)

0.6 ka to 0.2 ka 1400 CE to 1800 CE	▪ Relatively cool and wet conditions ▪ Numerous episodes of extreme flooding ▪ Includes "Little Ice Age" (1400 CE to 1700 CE)

90 a to 50 a
1910 CE to 1950 CE
	▪ Dry period in the Sacramento River Basin.
	  ▪ Longest dry period in the last 420 years (34 years centered on the 1930's)
	  ▪ Driest 20-year period in the last 370 years (1917 CE to 1936 CE)

A number of scientific studies have used paleo-reconstruction techniques to obtain long-term (decadal, centennial and millennial time scale) records of river flow (e.g., Earle, 1993; Meko *et al.*, 2001) and salinity of the Bay and Delta (e.g., Ingram and DePaolo, 1993; Wells and Goman, 1995; Ingram *et al.*, 1996; May, 1999; Byrne *et al.*, 2001; Goman and Wells, 2000; Starratt, 2001; Malamud-Roam and Ingram, 2004; Malamud-Roam *et al.*, 2006; Malamud-Roam *et al.*, 2007; and Goman *et al.*, 2008). The reconstructions described in the following sections focus on the 2,000 years before present. As indicated in Table 2-1, this period was relatively dry with two extreme regional droughts, followed by relatively cool and wet conditions during the "Little Ice Age," then by a return of dry conditions at the early part of the 20th Century.

2.2. Reconstructed Unimpaired Sacramento River Flow

Meko *et al.* (2001a,b) used tree-ring chronologies in statistical regression models to reconstruct time series of annual unimpaired Sacramento River flow[6] for approximately the past 1,100 years (for the period 869 CE – 1977 CE). As discussed in Section 1.2, unimpaired flow is an estimate of the flow that would occur in the basin without the effects of water management activities.

The 1,100-year record shows strong variability between individual water years (Figure 2-1), with annual flow ranging from approximately 8% of average to 265% of average, where average is defined here for practical purposes as the average observed unimpaired flow from

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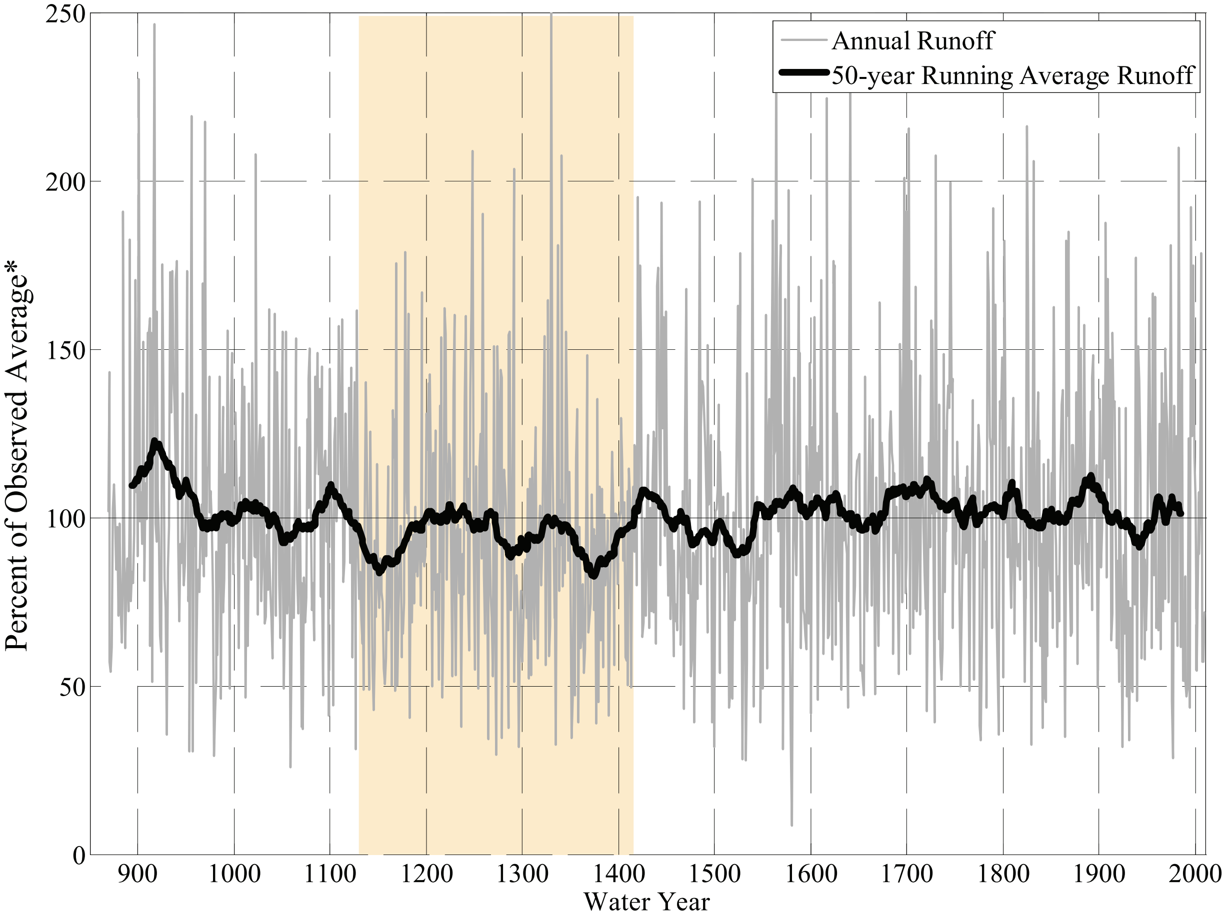
[6] Meko *et al.* (2001a) used the annual unimpaired flow record for the Sacramento River provided by the Department of Water Resources, which is the sum of the following: flow of the Sacramento River at Bend Bridge, inflow of the Feather River to Lake Oroville, flow of the Yuba River at Smartville, and the flow of the American River to Folsom Lake. This definition is consistent with the definition typically used in hydro-climatic studies of this region (e.g., http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST)

1906 to 2009 of 18 million acre-feet per year (MAF/yr). The reconstructed record shows alternating periods of wet and dry conditions and is consistent with historical droughts (such as the drought in the Mono Lake region of California in the medieval period, around 1150 CE) reported by other paleoclimate studies (Malamud-Roam *et al.*, 2006).

As indicated by the shading in Figure 2-1, the driest long-term drought in the Sacramento River basin in the last 1,100 years occurred from approximately 1130 CE to 1415 CE when the 50-year average flow was seldom above normal for nearly 300 years. Following this drought, conditions were relatively wet (from approximately 1550 CE to 1900 CE). The timing of these droughts and wet periods will be compared to paleosalinity records in the following section.



* Average of 1906-2009 Observed Runoff is 18 MAF/yr.

Figure 2-1 – Reconstructed annual unimpaired Sacramento River flow 869 CE to 2009 CE

Annual reconstructed unimpaired Sacramento River flow (grey line) as a percentage of the average annual observed runoff from 1906 to 2009 shows strong variability between years. The 50-year running average (thick black line) illustrates there were extended periods of above-normal and below-normal runoff conditions. The orange shading highlights an extended dry period in the reconstructed unimpaired Sacramento River data when the 50-year average flow is seldom above normal for nearly 300 years. Data for 869 CE to 1905 CE were reconstructed by Meko et al. (2001b); data for 1906 CE to 2009 CE are observed records from the California DWR (2009).

Meko *et al.* (2001a) indicated that for their 1,100-year reconstructed period, the 1630-1977 data are more reliable than the earlier time period, because of better availability of tree-ring information and superior regression model statistics. Figure 2-2 shows the reconstructed time series of annual unimpaired Sacramento River flow from 1630 to 1977 from Meko *et al.* (2001b). The inset in Figure 2-2 shows there is a good match between the reconstructed flows (grey line) and the observed annual flows (red line) during the period of overlap between the reconstructed and observed records (from 1906 to 1977).

Multi-decadal periods of alternating wet and dry conditions are pervasive throughout the reconstructed record. The wet conditions of the late 1800's and early 1900's, which were followed by severe dry conditions in the 1920's and 1930's, are consistent both with observed precipitation and estimated Sacramento River runoff for these time periods (see Section 3) and with literature reports of historical conditions (see Section 4).

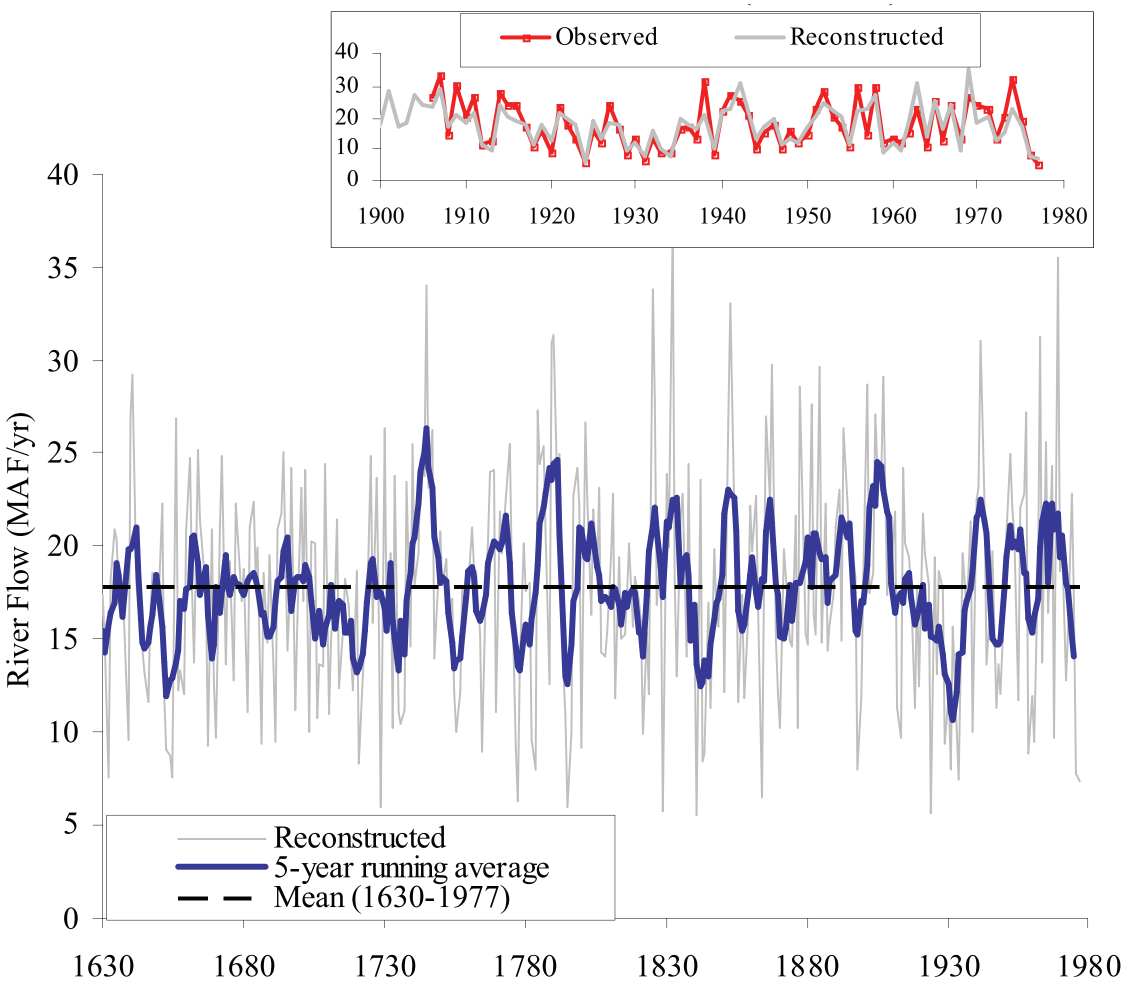


Figure 2-2 – Reconstructed annual unimpaired Sacramento River flow from 1630-1977.
Annual reconstructed unimpaired Sacramento River flow (grey line in main panel and inset) for the 1630 to 1977 time period was identified by Meko et al. (2001a) as the most accurate period of reconstruction. Inset panel illustrates the comparison between observed (red) and reconstructed (grey) unimpaired flows during the overlap period. The mean of the reconstructed unimpaired flow for 1630-1977 is 17.7 MAF/yr (dashed horizontal line in main panel). The 5-year centered running average (thick solid blue line in main panel) illustrates the decadal trends.

Meko *et al.* (2001a) identified the severe drought periods in the reconstructed Sacramento River flow record (1630-1977) by computing the lowest *n*-year moving average. For instance, to determine the most severe 6-year drought, Meko *et al.* calculated the moving average using a 6-year window for the entire data set and then identified the lowest 6-year average. Meko *et al.* found that the period from the early 1920's to late 1930's experienced the lowest 6-year, 10-year, 20-year, and 50-year averages (or droughts), both in the reconstructed and observed records. The observed droughts in Table 2-2 have been updated through present (1906-2009) using the same analysis; this update did not change the drought time periods identified by Meko *et al*. The reconstructed record of unimpaired Sacramento River flow shows the period from early 1920's to late 1930's experienced some of the worst drought conditions since 1630. Additional data are presented in Appendix B.

Table 2-2 – Periods of drought from the reconstructed and observed records of unimpaired Sacramento River flow
Severe drought periods in the reconstructed Sacramento River flow record (1630-1977) were determined by Meko et al. (2001a) by computing the lowest n-year moving average of the reconstructed annual unimpaired Sacramento River flow. The same method was used to determine the most severe droughts of the observed record (1906-2009).

	Period of lowest *n*-Year moving average Sacramento River flow					
	1-Year	3-Year	6-Year	10-Year	20-Year	50-Year
Reconstruction (1630-1977)	1924	1775 to 1778	1929 to 1934	1924 to 1933	1917 to 1936	1912 to 1961
Observations (1906-2009)	1977	1990 to 1992	1929 to 1934	1924 to 1933	1918 to 1937	1917 to 1966

Conclusions

Reconstruction of unimpaired Sacramento River flow indicates:

- Annual precipitation is highly variable. Even during long dry periods, individual years can be very wet.
- The Sacramento River basin experienced a multi-century dry period from about 1100 C.E. to 1400 C.E.
- The drought period in the 1920's and 1930's represents some of the worst drought conditions in the last 400 years.

2.3. Reconstructed Salinity in the Bay-Delta Estuary

Tree Ring Data

The interaction between saline ocean water from the Pacific Ocean and fresh water from the rivers flowing into the Delta determines the ambient salinity conditions in the Delta and the Bay. Estimates of historical precipitation derived from tree ring data can therefore be used to estimate the corresponding salinity conditions in the Delta.

Stahle *et al.* (2001) used tree ring chronologies from blue oak trees located in the drainage basin to San Francisco Bay to reconstruct salinity at the mouth of San Francisco Bay. Recognizing that a number of factors influence salinity other than precipitation (estimated from tree rings), the authors chose a time period prior to substantial water development when the salinity data were fairly constant in mean and variance. During the calibration period (1922-1952), annual tree ring growth correlates well with average salinity near the Golden Gate Bridge (r^2=0.81). Using this transfer function, Stahle *et al.* (2001) reconstructed annual average January to July salinity for all years 1604 to 1997.

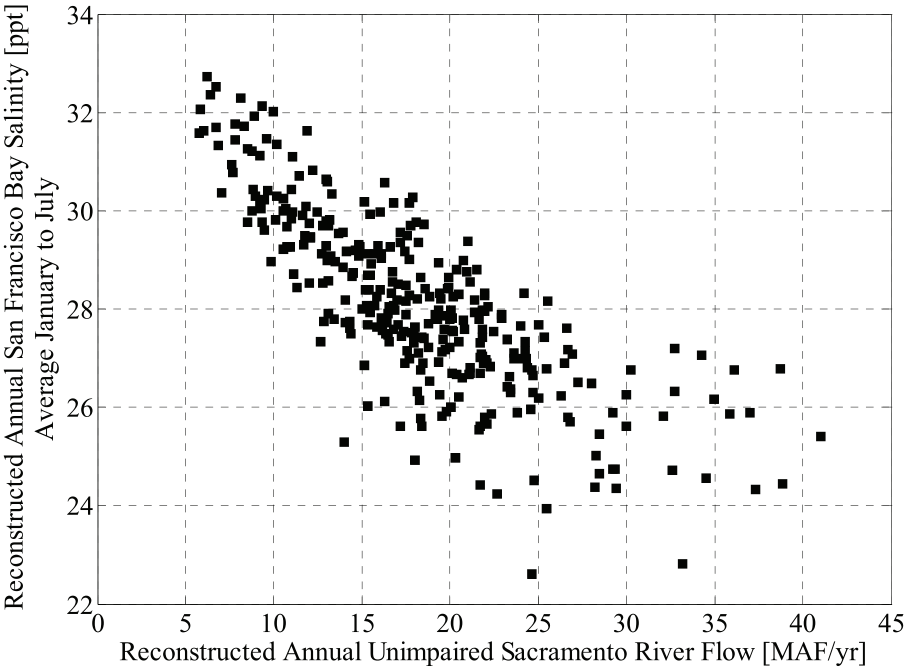


Figure 2-3 – Reconstructed salinity near the mouth of San Francisco Bay compares well with reconstructed unimpaired Sacramento River flow in the upper watershed

For each year from 1630 to 1952, the annual unimpaired Sacramento River flow (from Meko et al., 2001b) is plotted against the annual average salinity at Fort Point (from Stahle et al., 2001).

As shown in Figure 2-3, the salinity reconstruction by Stahle *et al.* (2001) compares well with the unimpaired flow reconstruction by Meko *et al.* (2001b). The data follow the expected inverse exponential relationship between flow and salinity. Over the period from

1630 to 1952, reconstructed salinity increases as reconstructed unimpaired Sacramento River flow decreases. The agreement is strongest in dry years. The increased scatter in wet years may reflect the limitations in the tree ring methods.

Stahle *et al.* (2001) identified an increasing divergence of observed salinity relative to predicted (reconstructed) salinity after 1952 (Figure 2-4) and suggested that the majority of differences are due to increased water diversions. During the calibration period (1922-1952), the observed salinity is typically within +/- 5% of the reconstructed salinity. However, from 1953-1994, the data show an increasing trend for observed salinity to be greater than predicted, exceeding reconstructed salinity by over 15% in 1978, 1979, 1991, and 1993. Since 1969, observed salinity has exceeded reconstructed salinity in all years except the extremely wet years of 1982 and 1983.

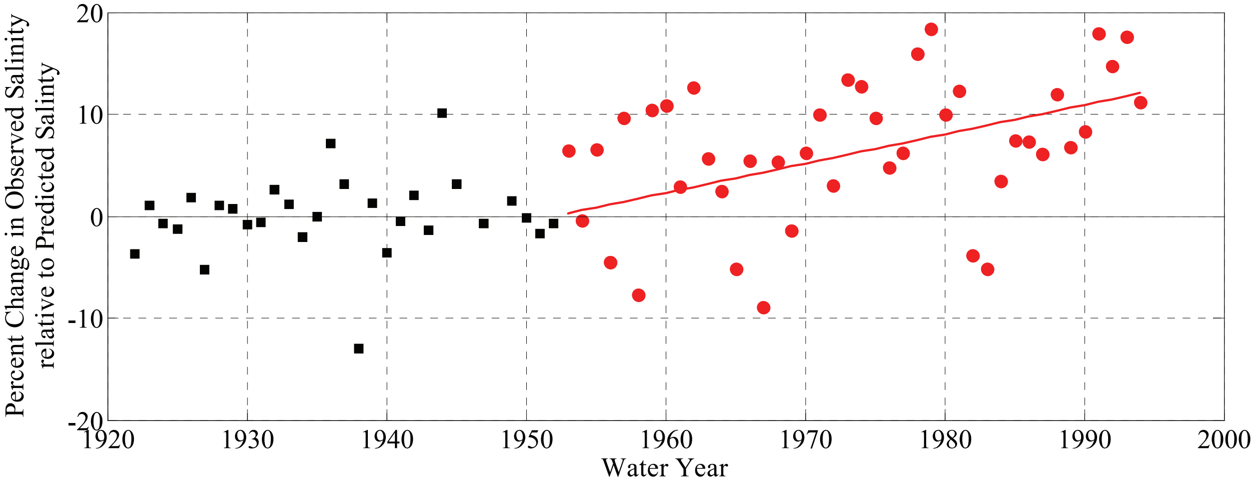


Figure 2-4 – Percent change in observed salinity relative to predicted (reconstructed) salinity for the period 1922 to 1994

The reconstructed salinity record by Stahle et al. (2001) overlaps with the observed salinity record from 1922 to 1994. During this period, the percent change of observed salinity relative to predicted salinity is determined as (observed salinity – reconstructed salinity) divided by reconstructed salinity, with positive values indicating when observed salinity exceeded the reconstructed salinity prediction. The calibration period is indicated with black squares, with the period outside the calibration window indicated by red circles. The straight red line is the linear trend in the post-calibration period, indicating observed salinity is increasingly diverging from predicted (reconstructed) salinity.

These data suggest that since the 1950's, water management operations have increased salinity, with an escalating effect over the period of record. In addition, it is worth noting that significant anthropogenic modifications to the landscape and water usage had already occurred prior to the 1922-1953 calibration period (see Figure 1-2 and Figure 1-3). Although this study is unable to evaluate the effect of anthropogenic modifications prior to 1953, the following section examines salinity prior to human interference at multiple sites in the Bay-Delta.

Tree ring reconstructions such as Meko *et al.* (2001a) and Stahle *et al.* (2001) have the advantage of providing high temporal resolution (i.e. annual) over approximately the last 1,000 years. However, a possible disadvantage of this method is the age of trees, limiting high accuracy estimates to approximately the last 400 years. A second possible disadvantage of using tree ring reconstructions for paleosalinity is the remote location of the trees relative to the estuary. Paleosalinity estimates from tree rings in the upper basin necessarily assume that the precipitation patterns archived in the tree rings are representative of the quantity of water that reaches the estuary. However, as observed by Stahle *et al.*, anthropogenic water management affects the amount of water that flows through the estuary.

Sediment Core and Fossil Data

Because of uncertainties in estimates of precipitation and salinity derived from tree ring data, other paleosalinity methods that rely on local fossils to determine local salinity have also been explored. Organic deposits accumulated in the sediments contain signatures of the ambient conditions that can be used to infer the variations in salinity over geologic time scales. Although reconstructions from sediment cores have a coarser temporal resolution than tree rings, the variations in climate and landscape responses to change are better defined geographically because the evidence of localized climate change is preserved as a time series *in situ*, at the site of interest.

The San Francisco Bay-Delta has been the focus of several paleoclimatic reconstructions from sediment cores. Changes in wetland plant and algae communities are the dominant response in the Bay and Delta to climate change and associated fluctuations in temperature and precipitation. Proxies of plant and algae response to environmental conditions are preserved in the sediment cores and determined by:

- quantification and taxonomic identification of
  - (i) diatom frustules (Byrne *et al.*, 2001; Starratt, 2001; Starratt, 2004),
  - (ii) plant seeds and roots (Goman *et al.*, 2008),
  - (iii) plant pollen (May, 1999; Byrne *et al.*, 2001; Malamud-Roam and Ingram, 2004), and,
- measurement of peat carbon isotope ratios (Byrne *et al.*, 2001; Malamud-Roam and Ingram, 2004).

Results from plant pollen identification for three sites in the western Delta and Suisun Bay and Marsh are summarized below in Figure 2-5. The data indicate that Browns Island tidal marsh, near the confluence of the Sacramento and San Joaquin Rivers in the western Delta (Figure 2-5) was predominately a freshwater system for 2,500 years, even during century-long droughts. This condition prevailed until the early 1900's. The shading in Figure 2-5 corresponds to the nearly 300-year dry period identified in the reconstructions of annual unimpaired Sacramento River flow (Figure 2-1). Although salinity intrusion occurred during this period in Suisun Bay at Roe Island, and during earlier long drought periods, salinity did not affect the western Delta to the same degree. This suggests a change in spatial salinity gradient characteristics, and is possibly due to the effect on salinity intrusion of the vast tidal marshes that existed in the Delta until the early 20th Century.

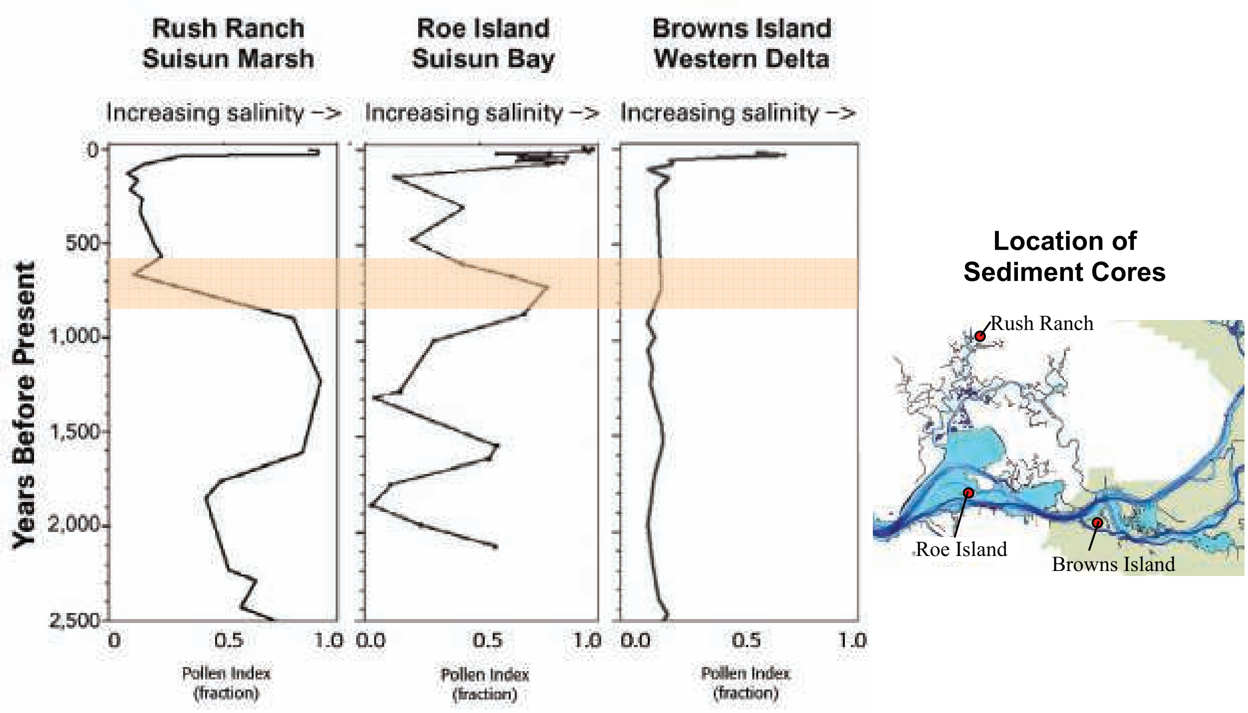


Figure 2-5 – Paleosalinity evidence derived from pollen data

Salinity variability over the last 2,500 years at Rush Ranch in Suisun Marsh (left panel), Roe Island in Suisun Bay (center panel), and Browns Island in the Western Delta (right panel). Data are reproduced from Malamud-Roam and Ingram (2004). Orange shading across each panel corresponds to the nearly 300-year dry period identified in the annual unimpaired Sacramento River flow reconstruction (see Section 2.2) Locations of each of the sediment cores are illustrated in the map on the right.

Malamud-Roam *et al.* (2006) attributed the differences between sites to a combination of methodological issues (such as sampling frequency and core chronology) and site-specific ecological differences (such as site elevation, location relative to channel and sedimentation rates over time). However, all of the paleosalinity reconstructions based on pollen, diatoms and carbon isotopes are in general agreement and suggest that salinity increased abruptly about 100 years ago, reaching or exceeding salinity levels at any other time in the 2,500 years of reconstructed records.

This increase in salinity may correspond to the reduction in unimpaired Sacramento River flow evidenced in the tree ring reconstructions by Meko *et al.* (2001a), which determined that the 1920's and 1930's experienced the worst droughts in the last 400 years. However, the droughts in the 1920's and 1930's do not appear to be as severe as the droughts between 1100 CE to 1400 CE (600 to 900 years ago), as categorized by unimpaired Sacramento River flow. Yet salinity in Suisun Bay and the western Delta appears to meet or exceed the level of the medieval droughts, indicating factors besides natural precipitation and runoff patterns have affected salinity in the last 100 years.

Conclusions

Reconstructions of salinity in the Bay and Delta indicate:

- Precipitation in the drainage basin for San Francisco Bay (as recorded in tree rings) is a good indicator of salinity near the mouth of the Bay for the period 1922-1953; however, since 1953, increased water diversions have increased observed salinity above the level predicted from precipitation estimates.

- The Delta was a predominately freshwater system for 2,500 years, until the early 1900's, even during century-long droughts.

- The multi-century dry period identified in unimpaired Sacramento River flow reconstruction is evident in Suisun Bay sediments but not in Delta sediments, indicating that salinity did not intrude as far into the Delta during past droughts as it has during the last 100 years.

- The evidence from most sites suggests that current salinity levels are as saline as, or more saline than, previous historical conditions.

3. Instrumental Observations of the Last 140 Years

Field measurements of rain and snow have far greater accuracy and resolution than the paleoclimate records of precipitation; similarly, field measurements of salinity have far greater accuracy and resolution than the paleosalinity records from sediment cores. These instrumental observations will be used to analyze in more detail the salinity increase identified in the paleoclimate records approximately 100 years ago and determine if the increase in salinity has persisted.

The first sub-section presents observations of precipitation and unimpaired runoff in the upper basin, indicating the natural climatic variability and amount of fresh water available within the Bay-Delta watershed. The second sub-section examines Net Delta Outflow (NDO), which is the amount of water flowing through the Delta into Suisun Bay, directly affecting the level of salinity intrusion into the Delta. NDO is analyzed under both unimpaired (without water diversions and reservoir storage and releases) and historical (actual) conditions; comparison between unimpaired and actual conditions reveals the effect of water management practices. The third sub-section presents field measurements and model-based estimates of salinity at various locations within the Delta and Suisun Bay.

3.1. Precipitation and Unimpaired Flow in the Upper Basin

Precipitation in the Bay-Delta watershed indicates the amount of water available within the system, which could ultimately reach the Bay and affect salinity conditions. However, since precipitation falls as both rain and snow, the timing of runoff to the river channels is often lagged a few months due to snow melt conditions. For this reason, estimates of unimpaired flow (runoff) are generally used to characterize hydrological variability. Unimpaired runoff represents the natural water production of a river basin, unaltered by water diversions, reservoir storage and operation, and export of water to or import of water from other basins.

Figure 3-1 illustrates the total annual precipitation at Quincy[7] in the northeastern Sierra, the total annual unimpaired Sacramento River flow[8] and total unimpaired San Joaquin River flow[9]. Figure 3-2 shows the locations of the eight precipitation stations in northern California used to compute the Sacramento eight-station precipitation index (left panel) and the measurement locations of eight flow gages used to calculate the Sacramento and San Joaquin unimpaired flow data (right panel). Additional information on the annual unimpaired flows is provided in Appendix C.

As discussed in Section 2.2, the total annual unimpaired Sacramento River flow exhibits strong variability between years, both in the reconstructed and observed data. Figure 3-1

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[7] Precipitation data are from Menne *et al.* (2009)

[8] "Unimpaired Sacramento River flow" is defined as the sum of the "full natural flows" from the Sacramento River at Bend Bridge, Feather River inflow to Lake Oroville, Yuba River at Smartville, and the American River inflow to Folsom Lake. (http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST)

[9] "Unimpaired San Joaquin River flow" is defined as the sum of the full natural flows from the Stanislaus River inflow to New Melones Lake, Tuolumne River inflow to New Don Pedro Reservoir, Merced River inflow to Lake McClure, and San Joaquin River inflow to Millerton Lake (http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST)

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indicates that the trends revealed in the total annual unimpaired Sacramento River flow (middle panel) are also evident in the total annual precipitation at Quincy (top panel) and the total annual unimpaired San Joaquin River flow (bottom panel). Alternating periods of wet and dry conditions are evident in both river basins. These data indicate there were wetter than normal conditions in the late 1800's and early 1900's, followed by severe dry conditions in the 1920's and 1930's. These were then followed by generally wetter conditions until the mid-1970's.

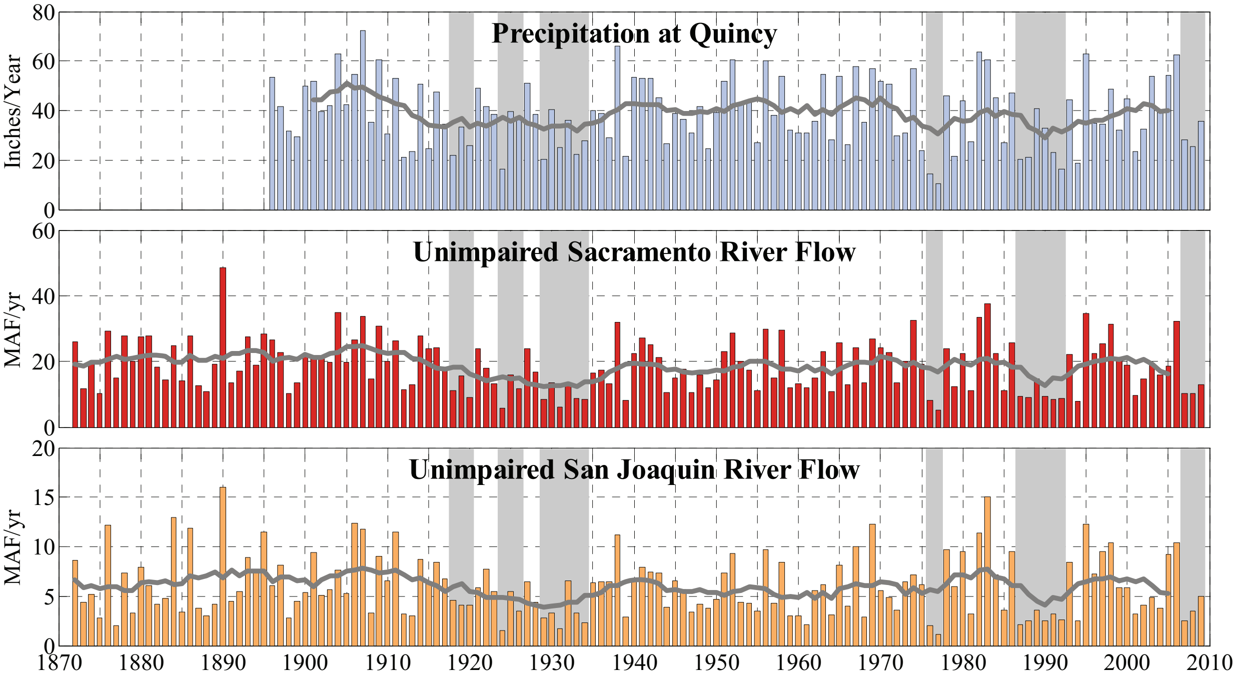

Figure 3-1 – Total annual precipitation and unimpaired flow in the upper Sacramento and San Joaquin River basins (1872-2009)

Total annual precipitation at Quincy in the northeastern Sierra (top panel), total annual unimpaired Sacramento River flow (middle panel), and total annual unimpaired San Joaquin River flow (bottom panel). Bar color on each panel indicates the regional location of the measurements, reflected in the remaining figures of this section (Figure 3-2, Figure 3-3 , and Figure 3-4). Grey line within each panel is the 10-year moving average for each parameter.

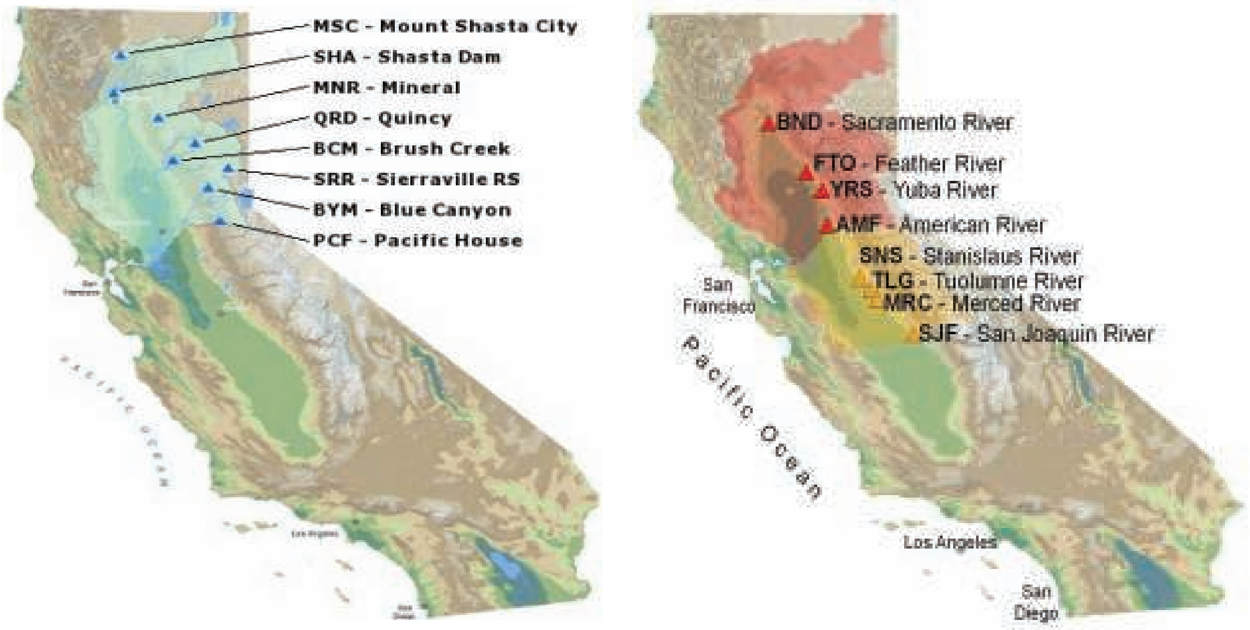

Figure 3-2 – Locations of Precipitation and Runoff Measurements

Location of stations used in the determination of the 8-station precipitation index for northern California (left map), including the location of Quincy (QRD), and the unimpaired Sacramento River flow (red stations, right map) and unimpaired San Joaquin River flow (orange stations, right map).

Knowles (2000) illustrated that the seasonal timing of runoff can significantly alter salinity intrusion without any change to the total annual runoff. For this reason, it is critical to examine the monthly variability in precipitation and unimpaired runoff. Monthly precipitation and unimpaired flow values are available for a shorter time period (generally 1921 to present) than the total annual values (generally 1870's to present).

The monthly distribution of the Sacramento eight-station precipitation index[10] indicates that most of the precipitation in northern California occurs during November through March (Figure 3-3). The variability between years, represented by the vertical bars and '+' marks, shows the distribution is positively skewed, i.e., excessively high precipitation occurs in relatively few years.

Figure 3-4 presents the monthly distribution of unimpaired flow for both the Sacramento and San Joaquin River basins. River flow lags precipitation by about two months because of storage of some precipitation in the form of snow and subsequent snowmelt in the spring. Most of the unimpaired inflow to the Delta originates from the Sacramento Basin, although the contributions from the two basins are approximately the same during the months of late-spring and early-summer snow melt, when unimpaired runoff from the San Joaquin Basin peaks.

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[10] Data from 1921 through 2008, downloaded from http://cdec.water.ca.gov/cgi-progs/precip1/8STATIONHIST

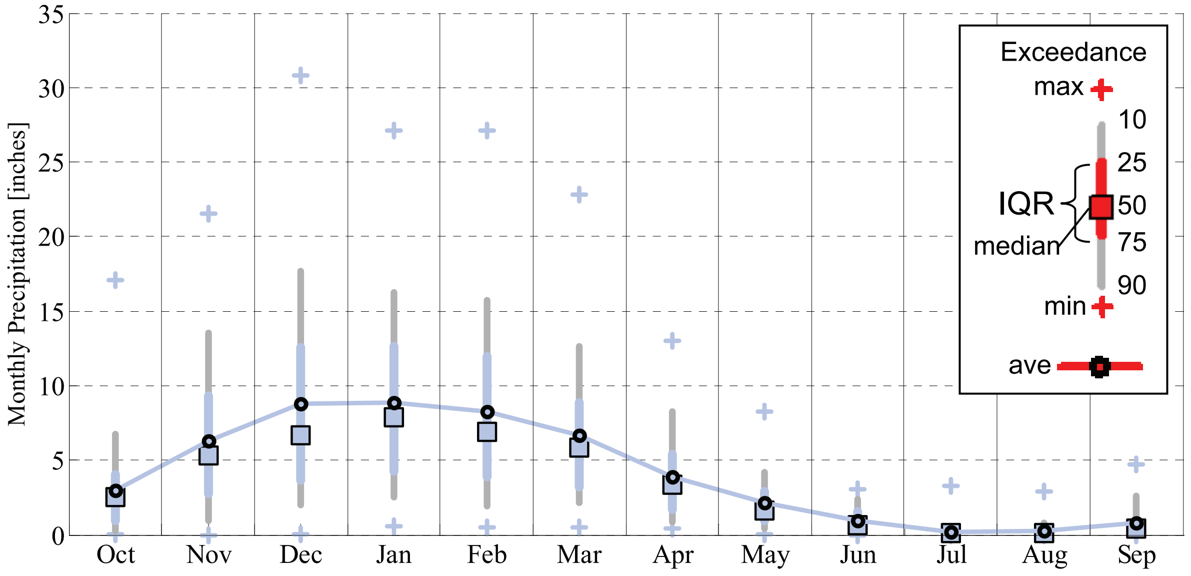

Figure 3-3 – Monthly Distribution of Precipitation in the Sacramento River Basin

Distribution of monthly precipitation for water years 1921 through 2008. Monthly averages are indicated by the blue line with black circles. Monthly median is given by the blue squares, while the interquartile range is indicated by the vertical blue line for each month and the vertical grey line extends to the 10th and 90th percentiles. Maximum and minimum values are indicated by '+' marks.

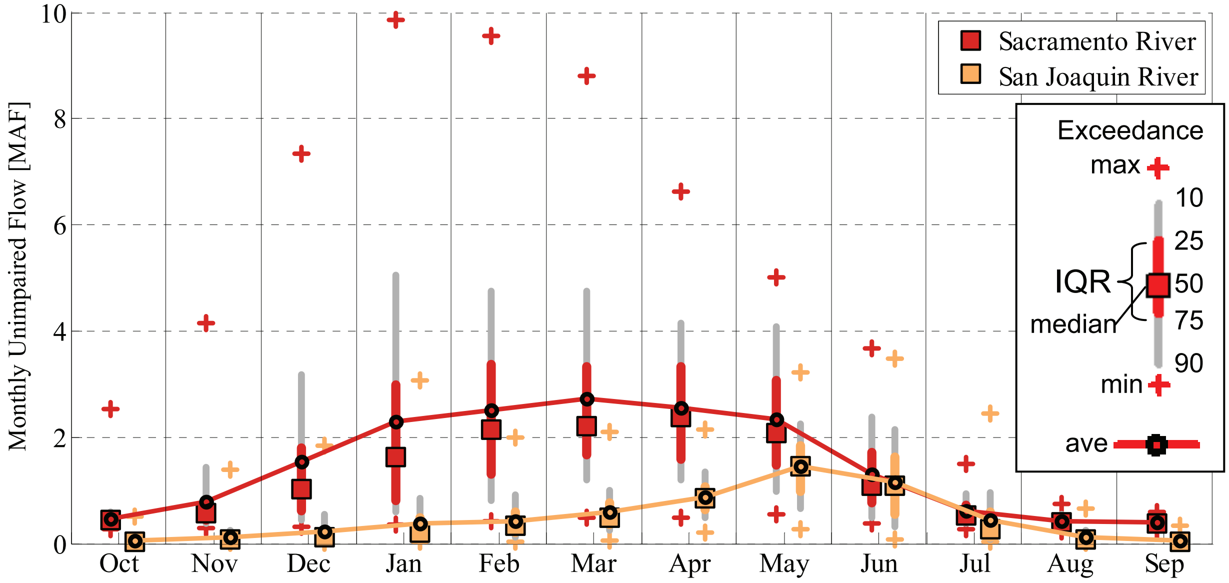

Figure 3-4 – Monthly distribution of unimpaired flow in the Sacramento and San Joaquin River basins

Distribution of monthly unimpaired flows for water years 1921 through 2008. Monthly averages are indicated by the lines with black circles. Monthly median is given by the squares, while the interquartile range is indicated by the vertical line for each month and the vertical grey line extends to the 10th and 90th percentiles. Maximum and minimum values are indicated by '+' marks.

Conclusions

The long-term observations of precipitation and unimpaired flow indicate:

- Relatively wet conditions occurred in the late 1880's to about 1917 in both the Sacramento and San Joaquin River watersheds prior to large-scale water management operations.
- Unusually dry conditions occurred from about 1918 through the late 1930's; these persistent dry conditions are not representative of the average conditions over the last 130 years.
- Precipitation in Sacramento River watershed peaks between December and March; the unimpaired river flow lags by about 1 to 2 months because of snow melt.

3.2. Net Delta Outflow

The quantity of water flowing from the Delta into Suisun Bay, defined as Net Delta Outflow (NDO), is the primary factor in determining salinity intrusion in Suisun Bay and the western Delta. Unimpaired NDO is calculated using unimpaired flow in the Sacramento and San Joaquin Rivers (Section 3.1) as well as contributions from other minor tributaries.[11] Unimpaired NDO is the hypothetical Delta outflow that would occur in the absence of any upstream diversion or storage, but with the existing Delta channel and upstream channel configuration.

Because the outflow from the Delta at the wide and deep entrance to Suisun Bay cannot be measured accurately, the parameter of historical (actual) NDO is estimated from a daily mass balance of the measured river inflows to the Delta, measurements of water diversions at major pumping plants in the Delta, and estimates of net within-Delta consumptive use (including Delta precipitation and evaporation).

The effect of anthropogenic water management on NDO is illustrated below by comparing monthly estimates of unimpaired NDO[12] and historical (actual) NDO[13] (Figure 3-5). Since unimpaired flow estimates also assume the existing Central Valley and Delta landscape (reclaimed islands, no natural upstream flood storage, current channel configuration, etc.), this comparison reveals the net effect of water management only. This analysis does not address the change due to physical modification to the landscape or sea level rise.

For the period of joint record, when both unimpaired and historical NDO values are available (water year 1930 through 2003), historical NDO decreased even though unimpaired NDO increased slightly. The long-term (74-year) linear trend in monthly unimpaired NDO (the black dashed line in top panel of Figure 3-5) increased on average 0.49 MAF/month; thus, by 2003, the average annual unimpaired NDO had increased 5.9 MAF/year since 1930. In contrast, the long-term linear trend in monthly historical NDO (the black dashed line in middle panel of Figure 3-5) decreased on average -0.29 MAF/month, totaling a decrease in historical (actual) NDO of -3.5 MAF/year. This corresponds to a net increase in diversion of 9.4 MAF/year of water from the Delta upstream watershed relative to the 1930 level[14].

Increased diversion and export of water have decreased historical NDO (middle panel of Figure 3-5), but this has been partially offset by a natural increase in unimpaired NDO (top panel). The difference between historical and unimpaired NDO (bottom panel) is due to the cumulative effects of upstream diversions, reservoir operations, in-Delta diversions, and

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[11] Unimpaired NDO does not include water imported from the Trinity River system, which is outside the Delta watershed.

[12] Unimpaired NDO data was obtained from Ejeta (2009), which is an updated version of DWR (1987).

[13] Historical NDO data was obtained from the IEP's DAYFLOW program (http://www.iep.ca.gov/dayflow/index.html).

[14] This is consistent with current estimates of approximately 15 MAF/year total diversion from the system, which includes the 4-5 MAF/year diversions established prior to 1930 and approximately 1 MAF/year additional water supply imported from the Trinity River system.

south-of-Delta exports. During most months, water management practices have historically resulted in historical (actual) NDO that is less than unimpaired conditions, indicated by a negative value for the quantity (historical NDO – unimpaired NDO).

Because the difference between monthly historical and unimpaired NDO has become more negative over time, the periods of excess conditions (when historical NDO exceeds unimpaired NDO) have become very infrequent. The only occurrences are now following the wettest years, primarily due to releases from reservoirs in the fall to make room for winter flood control storage.

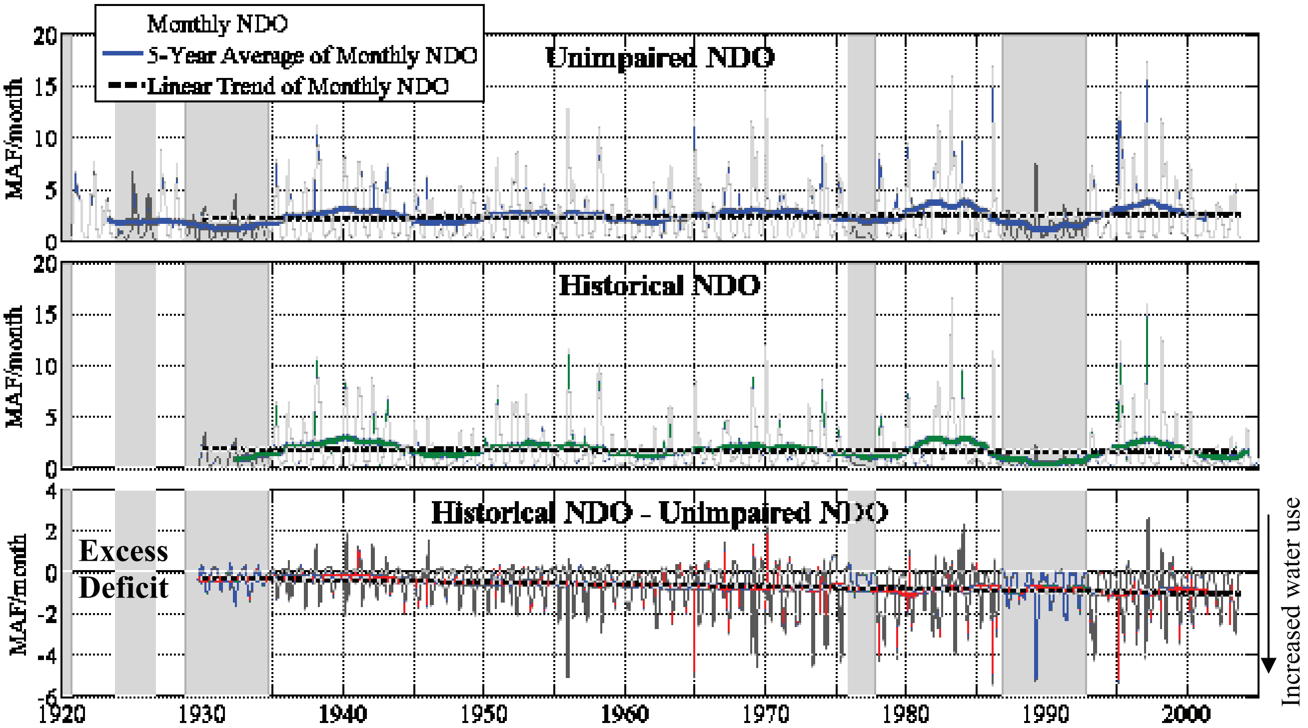

Figure 3-5 – Time series of Monthly Net Delta Outflow under unimpaired conditions and historical (actual) conditions

The thin color line on each panel indicates the monthly NDO, the thick color line indicates a running 5-year average of the monthly NDO, and the dashed black line indicates the linear long-term trend.

The monthly distribution (Figure 3-6) of unimpaired NDO and historical NDO for water years 1930 to 2003 reveals that for all months except September and October (when NDO is low), average unimpaired NDO is greater than average monthly historical NDO. The tendency in the average historical NDO toward greater flow in September and October is influenced strongly by the period prior to about 1975 when reservoir operations resulted in more flow in those months (see Figure 3-7 and related discussion below). On average from 1930-2003, water management practices reduced Delta outflows in the months of November through August (and in all months since about 1975, see Figure 3-7). The greatest reduction in Delta outflow relative to unimpaired conditions occurs in the months of March through June, when spring snow melt is captured in reservoirs and a portion of the river flow is diverted for direct use.

As also shown in Figure 3-6, water management practices also shift the peak flow periods to earlier in the year. The unimpaired NDO hydrograph peaks in May when snow melt contributes to high river flows, with at least 4.1 MAF in May in 50% of the years (averaging 4.2 MAF in May over all years). The historical NDO peaks in February with at least 2.9 MAF/month in 50% of the years (averaging 3.7 MAF/month over all years). The variability between years, represented by the vertical bars and '+' marks, indicates the distribution is positively skewed, which means a relatively few years have excessively high flows.

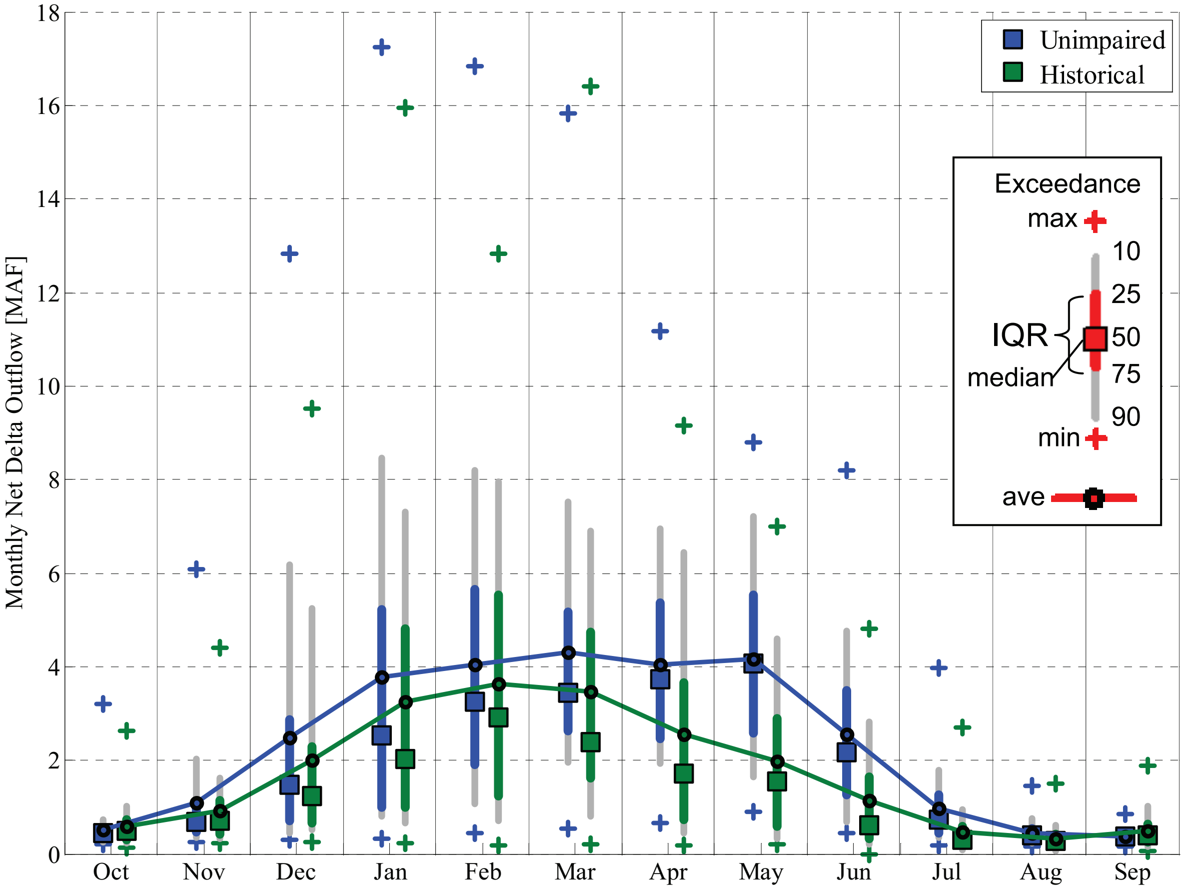

Figure 3-6 – Monthly distribution of Net Delta Outflow

Distribution of monthly NDO for water years 1930 through 2008. Monthly averages are indicated by the lines with black circles. Monthly median is given by the squares, while the interquartile range is indicated by the vertical line for each month and the vertical grey line extends to the 10th and 90th percentiles. Maximum and minimum values are indicated by '+' marks.

Figure 3-7 shows the long-term trends in the difference between historical (actual) monthly NDO and unimpaired monthly NDO. Increased water usage and increased diversion of water to storage has reduced historical NDO relative to unimpaired NDO in most months of the year. In July (and August, not shown in Figure 3-7), the deficit is reduced, likely due to reservoir releases which provide a portion of the water diverted by upstream users prior to reservoir construction. The 1994 Bay-Delta Accord called for higher minimum Delta outflows in July and August to protect Delta fish species, which should also serve to reduce the deficit. However, historical (actual) NDO still remains less than unimpaired NDO.

In September (and October, not shown in Figure 3-7), historical (actual) NDO exceeded unimpaired NDO from about 1945 to 1975, with an increasing trend in the percent change. Since 1975, the percent change has shown a downward trend with a deficit (historical NDO less than unimpaired NDO) during most years since 1975.

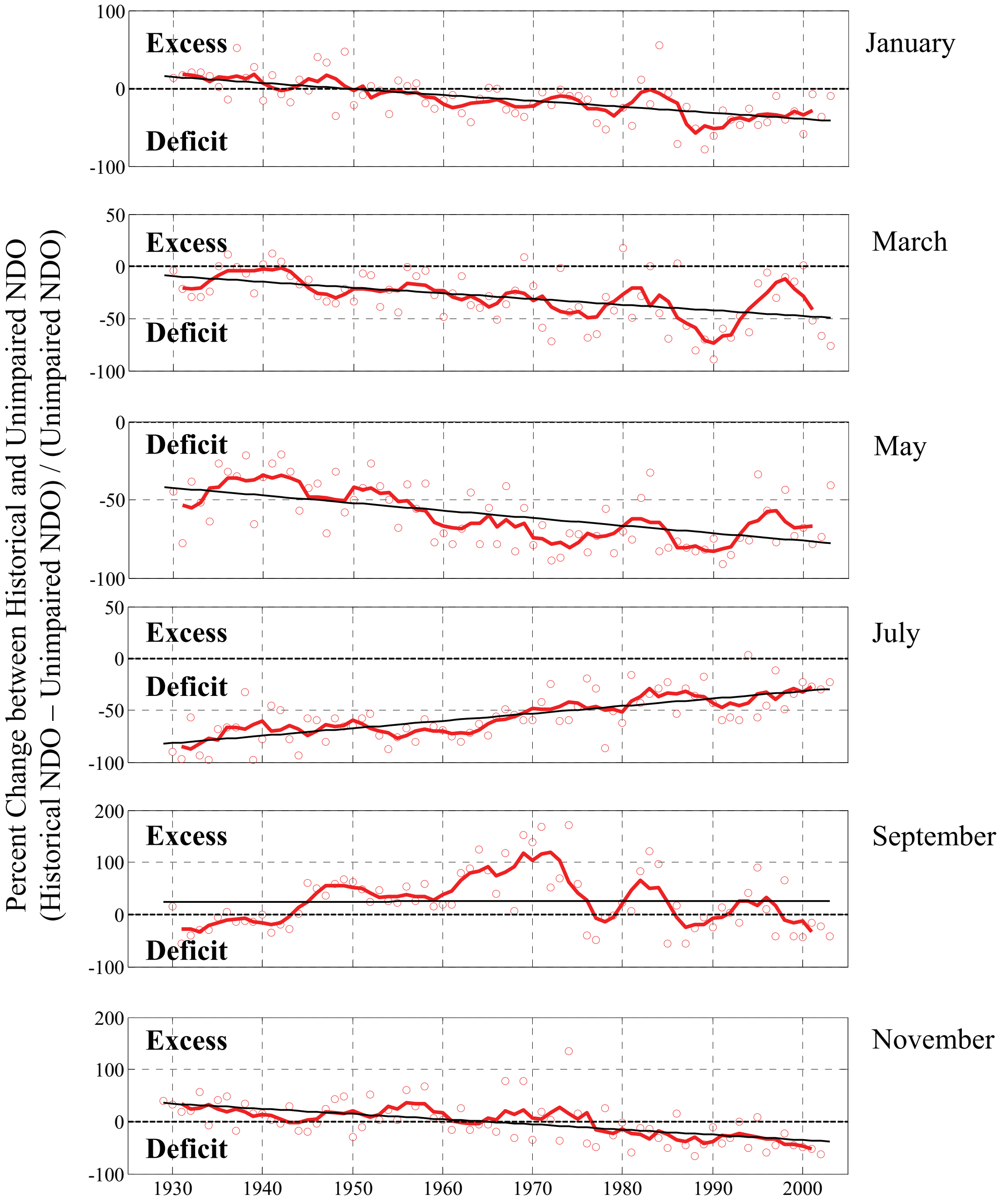

Figure 3-7 – Long-term trends in monthly NDO

Percent change of NDO relative to unimpaired conditions. Circles indicate the percent change for each month of the period of record. The red line indicates a moving 5-year average of the percent change, while the black line indicates the long-term linear trend over the entire period of record.

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Conclusions

Anthropogenic water management practices have altered NDO in the following ways:

- Long-term data demonstrate that the difference between historical (actual) NDO and unimpaired NDO is increasing over time, indicating that water management actions have reduced Delta outflow significantly.
- During most months, water management practices have reduced Delta outflow relative to unimpaired conditions. From the mid-1940's to the mid-1980's, reservoir operations resulted in historical (actual) NDO slightly greater than unimpaired NDO slightly in a number of months, largely in the fall. However, since 1985, reservoir operations have resulted in increased NDO only in the wettest years, and NDO has declined in all other months.
- On average, water management practices have resulted in reduced Delta outflows in all months except September and October. The greatest reduction in Delta outflow relative to unimpaired conditions occurs in the months of March through June, when spring snow melt is captured in reservoirs and some of the remaining river flows are diverted for direct use.

3.3. Salinity in the Western Delta and Suisun Bay

Observations and model-based estimates can be used to examine historical variations in salinity in the western Delta and Suisun Bay. The observations examined in this section include records from the early 1900's from the California & Hawaiian Sugar Refining Corporation in Crockett (C&H) and long-term monitoring data published online by the Interagency Ecological Program (IEP). Estimates of salinity intrusion were obtained using the Kimmerer-Monismith equation describing X2 (Kimmerer and Monismith, 1992).

Section 3.3.1 addresses the importance of consistency among salinity comparisons. The spatial variability of a specific salinity level is examined in Section 3.3.2 and Section 3.3.3, while the temporal variability of salinity at specific fixed locations is explored in Section 3.3.4 and Section 3.3.5.

3.3.1. Importance of Consistency among Salinity Comparisons

Water salinity in this report is specified either as electrical conductivity (EC) or as a concentration of chloride in water. EC is a measure of the ability of an aqueous solution to carry an electric current and is expressed in units of microSiemens per centimeter (µS/cm)[15]. Chloride concentration is specified in units of milligrams of chloride per liter of water (mg/L). Conversion between EC and chloride concentration can be accomplished using site-specific empirical relationships such as those developed by Kamyar Guivetchi (DWR, 1986).

Previous studies have evaluated the level of salinity in the Bay and Delta, using a variety of salinity units (e.g. EC, chloride concentration, or concentration of total dissolved solids in water) and various salinity parameters (e.g. annual maximum location 1,000 µS/cm EC, monthly average location of 50 mg/L chloride, or daily average EC at a specific location). Therefore, when comparing studies, it is critical to use consistent salinity units, parameters, and timing, including the phase of tide and time of year. These concepts are discussed further in Appendix D.

3.3.2. Distance to Fresh Water from Crockett

The California & Hawaiian Sugar Refining Corporation (C&H) is located in Crockett, near the western boundary of Suisun Bay (see Figure 3-8). C&H either obtained its freshwater supply in Crockett, or, when fresh water was not available at Crockett, from barges that traveled upstream on the Sacramento and San Joaquin Rivers. The barges generally travelled upstream twice a day beginning in 1908 (DPW, 1931). C&H recorded both the distance traveled by its barges to reach fresh water and the quality of the water they obtained. This provides the most detailed quantitative salinity record available prior to the initiation of salinity monitoring by the State of California in 1920. The distance traveled by the C&H barges serves as a surrogate for the prevailing salinity conditions in the western Delta and

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[15] The reported EC values are actually specific conductance, i.e., the electrical conductivity of the water solution at a reference temperature of 25° centigrade, as is standard practice.

Suisun Bay. Operations by C&H required water with less than 50 mg/L chloride concentration.[16] Additional detail on C&H operations and the detailed barge travel data are included in Appendix D.

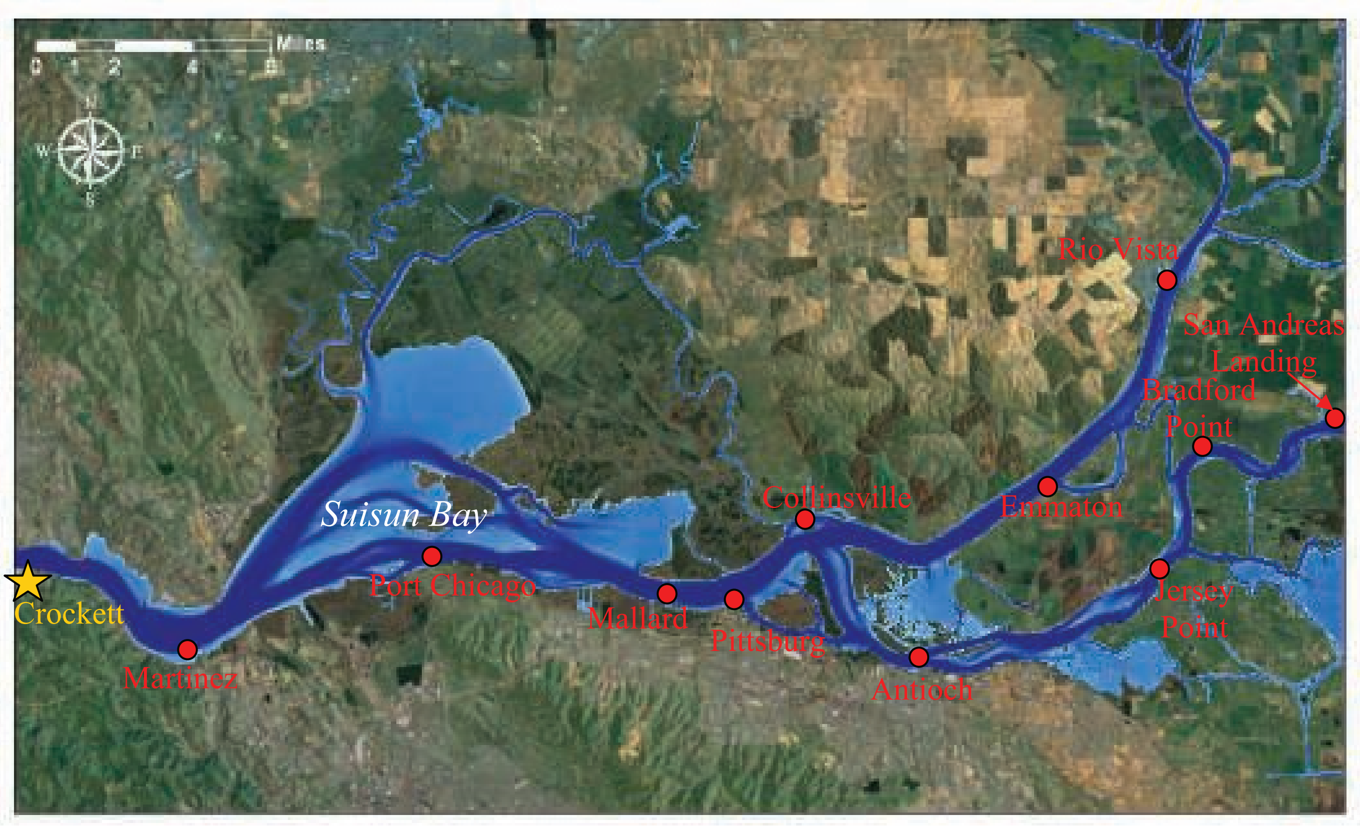

Figure 3-8 – Map of Suisun Bay and Western Delta with locations of continuous monitoring stations

C&H barges traveled up estuary from Crockett (yellow star). Locations of IEP continuous monitoring stations are shown in red. Scale in miles is indicated in the upper left corner of the map.

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[16] In comparison, the 50 mg/L concentration required for C&H operations is one-third the concentration of the industrial water quality standard under current conditions in the Delta.

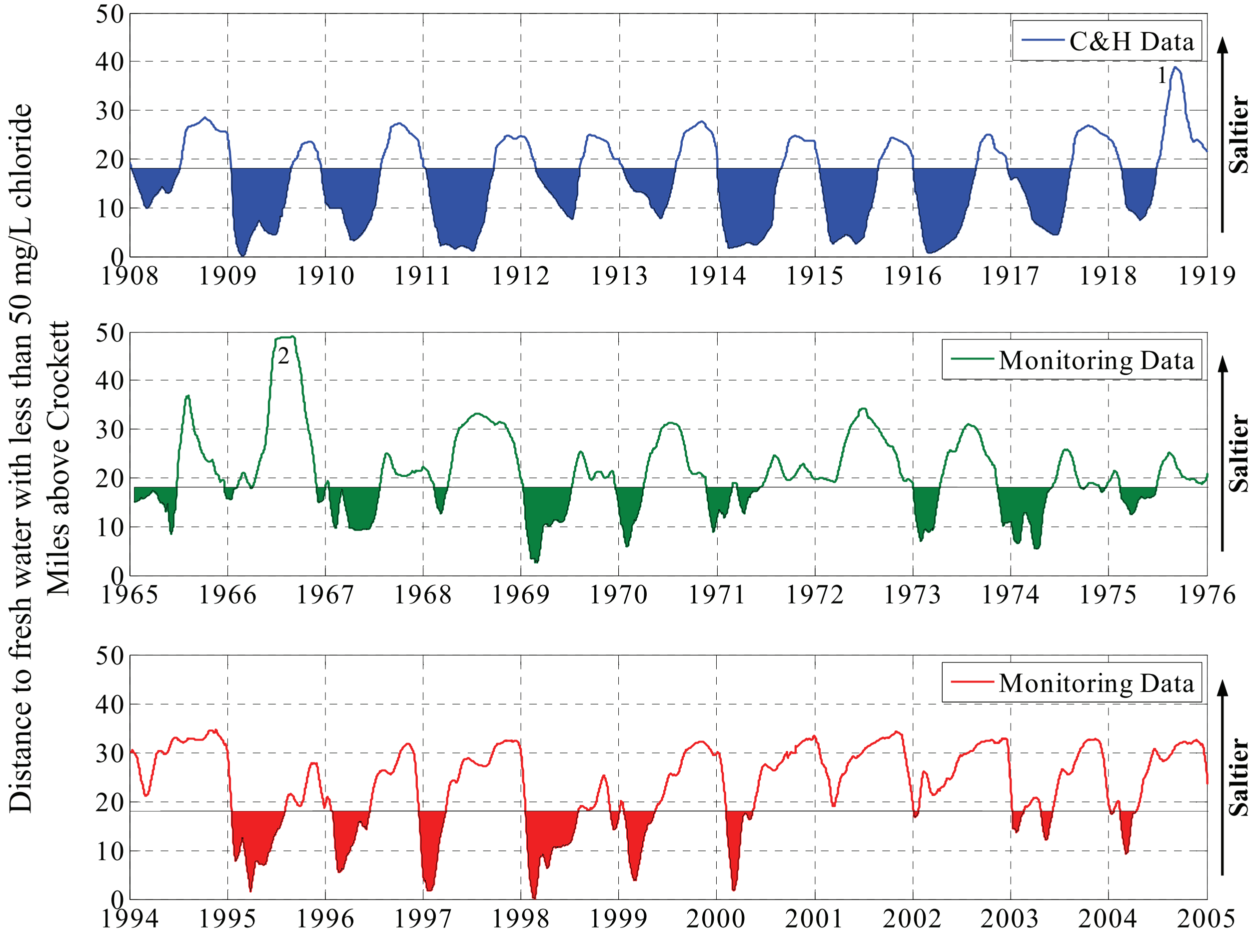

Figure 3-9 – Distance to fresh water from Crockett

"Distance to fresh water" is defined as the distance in miles upstream of Crockett to water with less than 50 mg/L chloride concentration. The horizontal line, at approximately 18 miles, is the distance from Crockett to the Delta. The shading represents the spatial extent and duration of the presence of fresh water within Suisun Bay, downstream of the Delta.

Data notes: (1) During August and September 1918, average water quality obtained by C&H exceeded 110 mg/L chlorides; (2) Salinity during 1966 is likely an overestimate due to relatively sparse spatial coverage of IEP monitoring stations. During 1966, salinity at Emmaton (28 miles from Crockett) exceeded 3,000 µS/cm; the nearest station upstream of Emmaton is near Courtland (58 miles from Crockett) and had a salinity of ~ 300 µS/cm. Location of 350 µS/cm isohaline based on data interpolation between these two stations (which are 30 miles apart) is not likely to be representative of the true location.

Figure 3-9 compares surface[17] salinity data from C&H with estimates derived from a network of continuous surface salinity monitoring stations (Figure 3-8) within Suisun Bay and the western Delta dating back to 1964. The monitoring data are published online by the Interagency Ecological Program (IEP, see http://iep.water.ca.gov/dss). The location of the 350 µS/cm EC isohaline, which approximately coincides with the C&H criterion of 50 mg/L chloride concentration, was estimated from the IEP measurements by linear interpolation between the average daily values at IEP monitoring stations.

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[17] Due to the method of collection, C&H water samples are assumed to be from near the water surface.

As a cautionary note, depending on the source of information, the C&H barges are said to have traveled with the tide, indicating they either took water at high tide (moving up river on the flood and down on the ebb) or at low tide (traveling against the tide, but moving a shorter distance). Thus, the C&H records either represent the daily maximum or daily minimum distance traveled. In contrast, the distances to fresh water calculated from recent monitoring data are based on the average daily values of EC measured at fixed locations. The difference between daily average distance and daily minimum or maximum is approximately 2 to 3 miles. However, since the difference between the data from the early 1900's and the more recent time periods exceed this 2 to 3 mile uncertainty, the conclusions of this section remain unchanged regardless of the specific barge travel timing.

From 1908 through 1918, C&H was able to collect fresh water for a large portion of the year within Suisun Bay, without having to travel all the way from Crockett to the Delta. However, as can be seen in Figure 3-9, that would no longer be possible in many years (e.g., 2001-2004).

Figure 3-10 shows the monthly distribution of distance traveled by C&H barges during water years 1908 through 1917, and the equivalent distance from determined from observed data for water years 1966 through 1975 (top panel) and water years 1995 through 2004 (bottom panel). These two latter periods have similar hydrologic characteristics to the period of the C&H data.[18] The monthly distribution for each dataset illustrates the seasonal fluctuations of the salt field as well as the variability between years for each month.

During the early 1900's, the median distance traveled by C&H barges to procure fresh water was less than 8 miles in the spring (March-June) and about 25 miles (between Collinsville and Emmaton) in the fall (September-October). In contrast, due to water management conditions from 1995 to 2005, the equivalent distances would be 13 to 23 miles in the spring and up to 30 miles in the fall. It is worth noting that from 1966 to 1977, the distance to fresh water in the fall and early winter months (September through January) was generally less than the equivalent distance in the early 1900's, indicating that large-scale water management operations circa 1970 tended to reduce salinity in the fall and early winter. However, this trend has reversed in the more recent water management period (1995-2005), with salinity intrusion significantly increased over levels in the early 1900's during all months.

Figure 3-10 also shows that the range of the average annual distance from Crockett to fresh water from 1995 to 2005 was approximately 15 miles (from about 13 to 30 miles), while the range during the early 1900's was approximately 20 miles (from 6 to 25 miles). This analysis indicates that large-scale water management activities limit the fluctuating nature of the salt field by preventing fresh water from reaching as far downstream as it did in the early 1900's.

Finally, Figure 3-10 indicates that salinity intrusion in the Delta occurred later in the year (beginning in July) in the early 1900's than under more recent time period conditions (beginning in March).

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[18] This similarity in hydrological characteristics between the periods was established by approximately matching the distribution of annual Sacramento River flow during these periods (see Appendix E).

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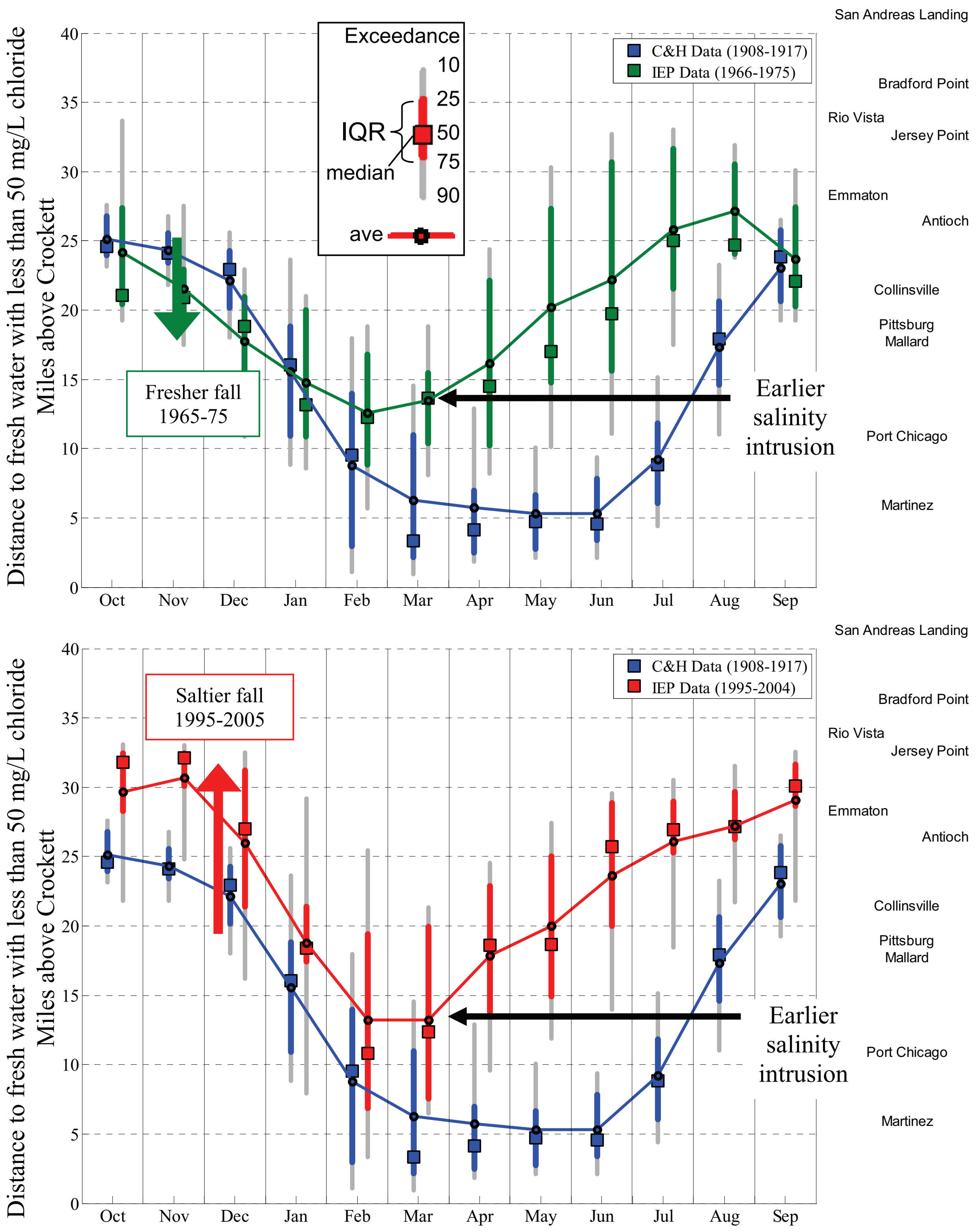


Figure 3-10 – Monthly distribution of distance to fresh water from Crockett

These comparisons (and other relevant comparisons in Appendix D) show that, on average, C&H barges would have had to travel up to 19 miles farther to procure fresh water under recent large-scale water management conditions than in the early 1900's. These comparisons also indicate that fresh water was present for significantly longer time periods, and over a larger area of the western Delta, in the early 1900's than during similar hydrological periods under current water management conditions. Abrupt changes in salinity just prior to 1920 caused C&H to abandon the Sacramento and San Joaquin Rivers and switch to a water supply contract with Marin County beginning in 1920 (Appendix D).

The distance to fresh water during individual wet years and during individual dry years is presented in Appendix D. The data in Appendix D also show that salinity has been generally higher in recent times than in the early 1900's and that water management has restricted the range in salinity experienced during a water year. The periods when fresh water is present at given locations have been reduced, or, in some cases, eliminated.

Conclusions

The records of the distance traveled upstream from Crockett by C&H barges to procure fresh water and estimates of this distance under large-scale water management conditions (reservoir operations and water diversions) show that:

- Fresh water was present farther downstream and persisted for longer periods of time in the western Delta in the early 1900's than under recent time periods with similar hydrologic conditions;
- Water management practices result in greater salinity intrusion in the western Delta for most months of the year; and,
- Salinity intrusion begins earlier in the year, extends farther upstream, and persists for a longer period each year.

3.3.3. X2 Variability

An often-used indicator of fresh water availability and fish habitat conditions in the Delta is a metric called X2. X2 is defined as the distance from the Golden Gate to the 2 part-per-thousand isohaline (equivalent to a salinity of 2 grams of salt per kilogram of water), measured near the channel bed along the axis of the San Francisco Estuary. Higher values of X2 indicate greater salinity intrusion. Monthly values of X2 are estimated in this report using the monthly regression equation from Kimmerer and Monismith (1992):

$$\text{Monthly} \quad X2(t) = 122.2 + 0.3278 * X2(t-1) - 17.65 * \log_{10}(NDO(t))$$

The K-M equation expresses X2 (in units of kilometers) in terms of Net Delta Outflow (NDO, see Section 3.2) during the current month and the X2 value from the previous month. The monthly K-M equation was based on a statistical regression of X2 values (interpolated from EC measurements at fixed locations) and estimates of NDO from IEP's DAYFLOW computer program. Hence, the K-M equation is only valid for the existing Delta channel configuration and existing sea level conditions.

The K-M equation can be used to transform unimpaired and historical NDO data into the corresponding X2 values for unimpaired (without reservoir operations or water diversions) and historical (with historical water management) conditions, respectively.

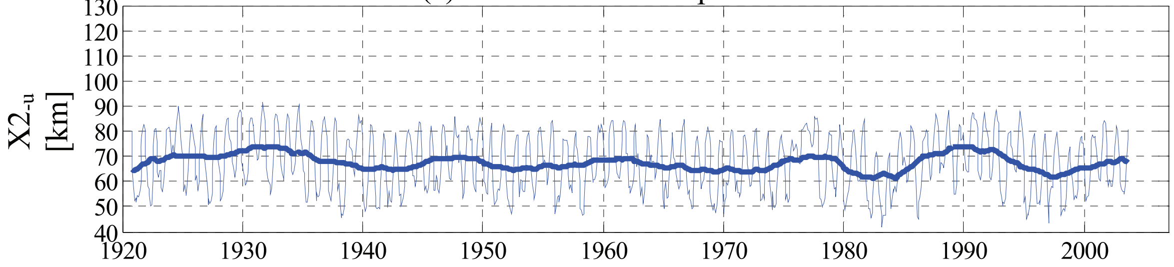
The seasonal and annual variations of X2 are dependent on the corresponding variations of NDO under both historical and unimpaired flow conditions (Figure 3-11). X2 under historical flow conditions is shifted landward relative to unimpaired conditions by approximately 5 km. During the 1930's, historical NDO was often negative, sometimes averaging approximately -3,000 cfs for several months. This was due to relatively low runoff and significant upstream water diversions. Unfortunately, the K-M equation, which includes the logarithm (base 10) of NDO, is unable to account for negative values of NDO. In the case of historical flow conditions, this results in high variability of X2 in the 1930's. The values of X2 under historical flow conditions during 1930's in Figure 3-11 are likely underestimated.

Figure 3-12 compares X2 under unimpaired and historical conditions for the period from 1945-2003, following initiation of the Central Valley Project (i.e., after the completion of the Shasta Reservoir of the CVP). Figure 3-12 shows that, compared to unimpaired conditions, X2 under historical conditions was higher by about 10 km during April-July and by about 5 km during the rest of the year.

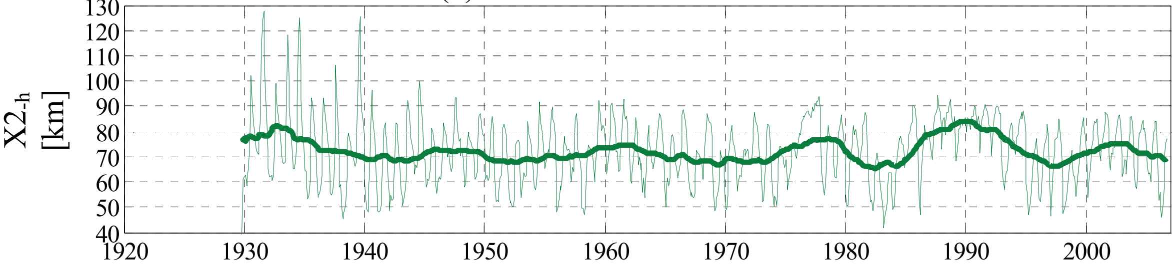
Salinity intrusion under historical water management conditions is, therefore, greater (higher X2) than the intrusion that would occur under unimpaired conditions. Moreover, the switch from declining X2 values during fall and winter months to increasing X2 values (increasing salinity intrusion) occurs in March under historical water management conditions and in June under unimpaired conditions. Thus, recent water management practices have resulted in a saltier Delta with earlier occurrence of salinity intrusion in the year.

Although current water management practices operate to provide salinity control, both the extent and duration of salinity intrusion are greater under current water management practices than under historical conditions. Likewise, current water management practices have changed the overall annual range in salinity (i.e., the difference between the highest and lowest salinity values during the year).

(a) X2 based on unimpaired NDO



(b) X2 based on historical NDO



(c) Change in X2 due to water management

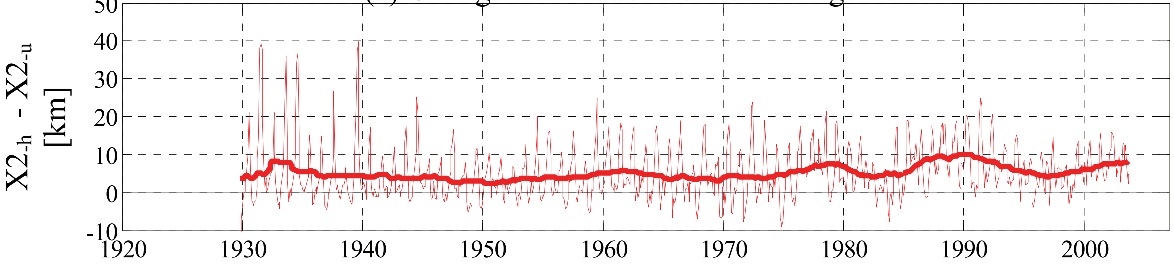


Figure 3-11 – Location of X2 under unimpaired and historical conditions

X2 has a strong seasonal and decadal variability under both unimpaired (top panel) and historical (middle panel) flow conditions reflecting the strong seasonal and decadal variability of NDO. The difference between historical and unimpaired conditions (bottom panel) illustrates the net effect of water management activities.

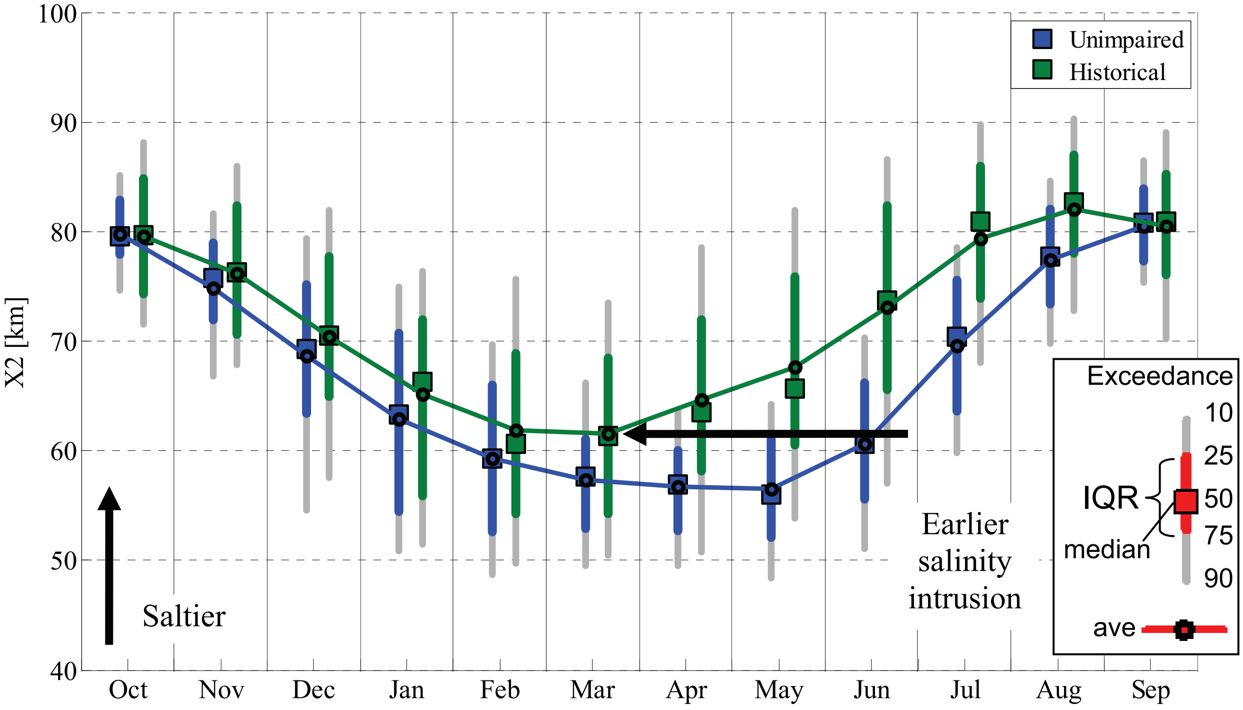


Figure 3-12 – Monthly distribution of X2 from 1945 through 2003

Figure 3-13 presents a comparison of unimpaired X2 and historical X2 during the 10 driest and the 10 wettest years of the CVP period (1945-2006).[19] During dry years (top panel), X2 is substantially greater under historical water management conditions than under unimpaired conditions (i.e., without water management); these effects are less dramatic but still occur during the wet years (bottom panel). Additionally, the annual range in salinity variability is significantly reduced under dry conditions (from approximately 22 km with unimpaired flows to 14 km with historical flows), but not wet conditions. The result of water management practices is a saltier Delta during both wet and dry years, with the greatest amount of salinity intrusion and reduced seasonal variability occurring in dry years.

Conclusions

The analysis of X2 (a measure of salinity intrusion in the Delta) shows that:

- Water management practices (reservoir operations and water diversions) result in a saltier Delta, with earlier salinity intrusion in the year.
- Water management practices result in a saltier Delta during both wet and dry years, but the effect is more pronounced in the dry years when the seasonal variability of salinity is also significantly reduced.

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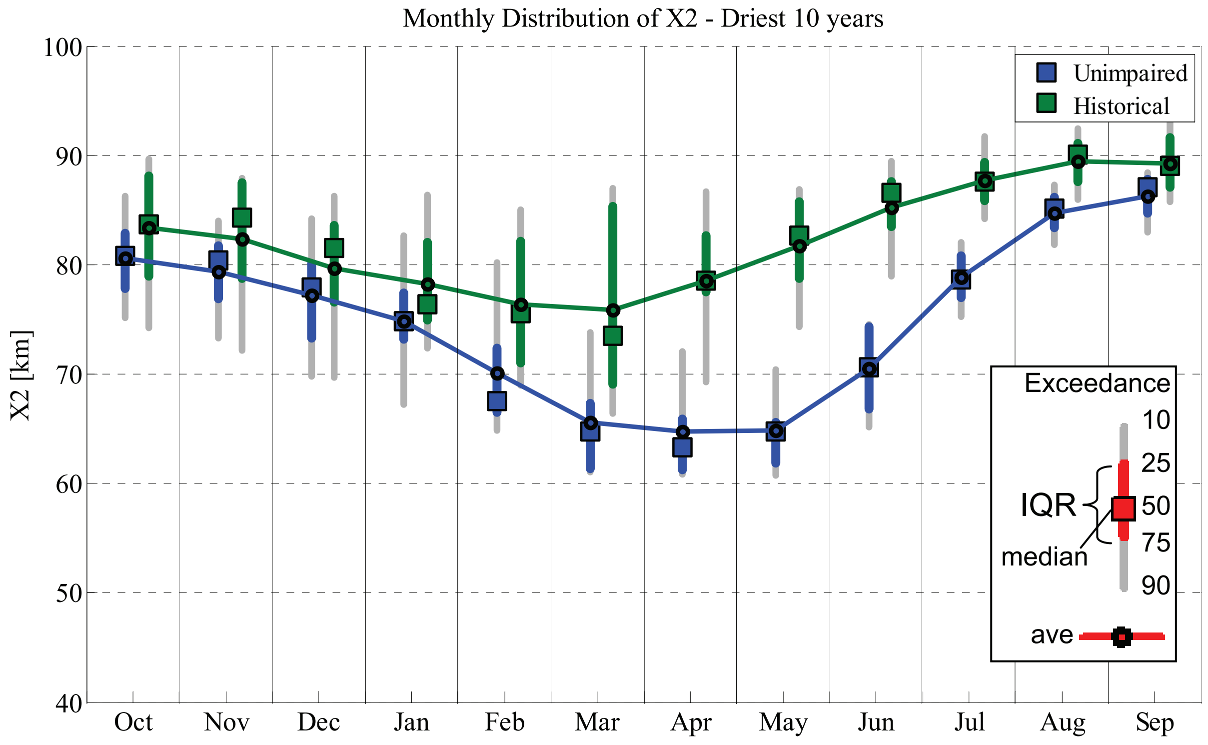
[19] Determination of the ten wettest and driest years is based on the total annual unimpaired Net Delta Outflow. The ten wettest years are 1952, 1956, 1958, 1969, 1974, 1982, 1983, 1986, 1995, and 1998. The ten driest years are 1947, 1976, 1977, 1987, 1988, 1990, 1991, 1992, 1994, and 2001.



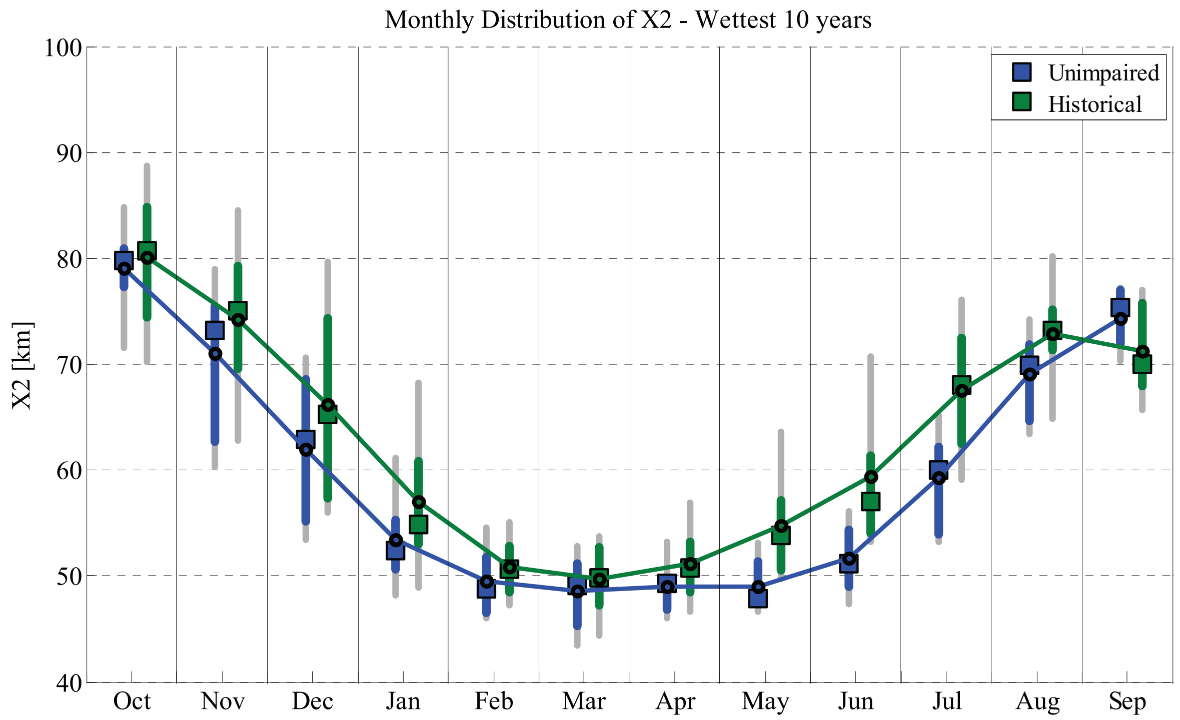


Figure 3-13 – Monthly X2 variability during wet and dry years (1945-2003)

Determination of the ten wettest and driest years is based on the total annual unimpaired Net Delta Outflow. The ten wettest years are 1952, 1956, 1958, 1969, 1974, 1982, 1983, 1986, 1995, and 1998. The ten driest years are 1947, 1976, 1977, 1987, 1988, 1990, 1991, 1992, 1994, and 2001.

3.3.4. Salinity at Collinsville

Collinsville, near the confluence of the Sacramento and San Joaquin Rivers, was one of the first long-term sampling locations implemented by the State of California. The Suisun Marsh Branch[20] of the DWR estimated monthly average salinity at Collinsville for the period 1920-2002, using a combination of 4-day TDS (total dissolved solids) grab samples from 1920-1971 and EC measurements from 1966-2002. Data from the overlap period of 5 years between the TDS grab samples and EC measurements were used in a statistical regression model, and the monthly averaged 4-day TDS samples were converted to monthly average EC (Enright, 2004). The result of this regression analysis was a time series of monthly EC values at Collinsville for the period of 1920-2002.

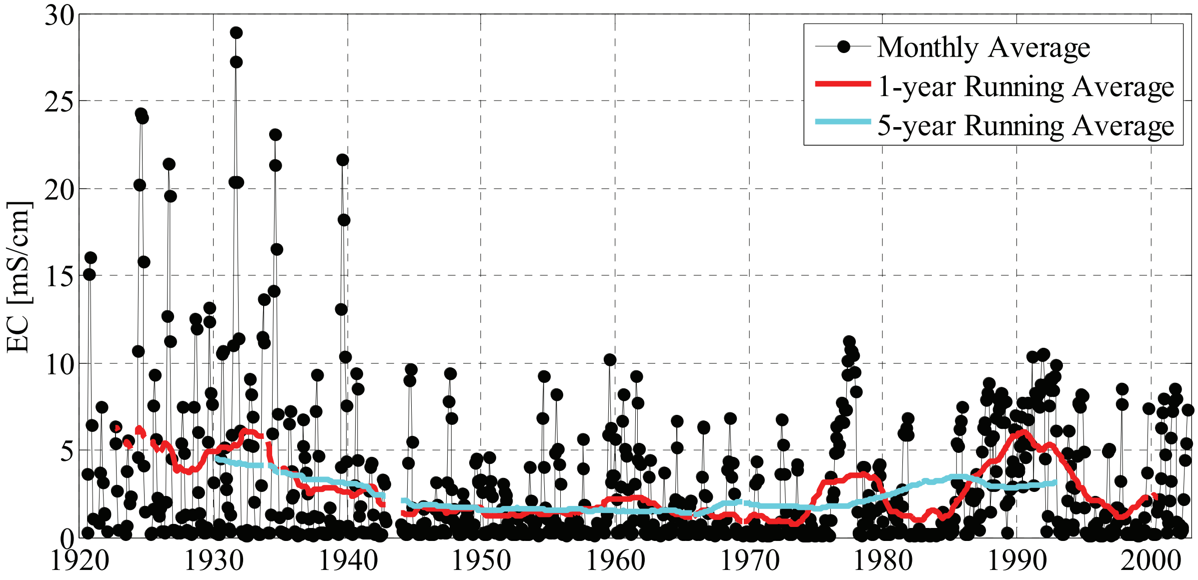


Figure 3-14 – Observed salinity at Collinsville

Monthly average salinity at Collinsville (black dots and black line), with the 12-month running average (red line) and 5-year running average (blue line).

Figure 3-14 shows the monthly average salinity at Collinsville for the period of 1920-2002, and Figure 3-15 shows the long-term trends in monthly salinity at Collinsville. Although the maximum values of salinity in the 1920's and 1930's far exceed subsequent salinity measurements at Collinsville, during the winters and springs of the 1920's and 1930's, the water at Collinsville freshened considerably. During the dry periods of 1920's and 1930's, monthly average salinity was below 350 µS/cm EC (approximately 50 mg/L chloride) for at least one month in every year. The one exception is 1924 which is inconclusive because no data were available from November through March. Monthly average EC data are missing for a portion of the winters and springs prior to 1926, and data for 1943 are missing entirely.

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[20] Data provided by Chris Enright (DWR), personal communication, 2007.

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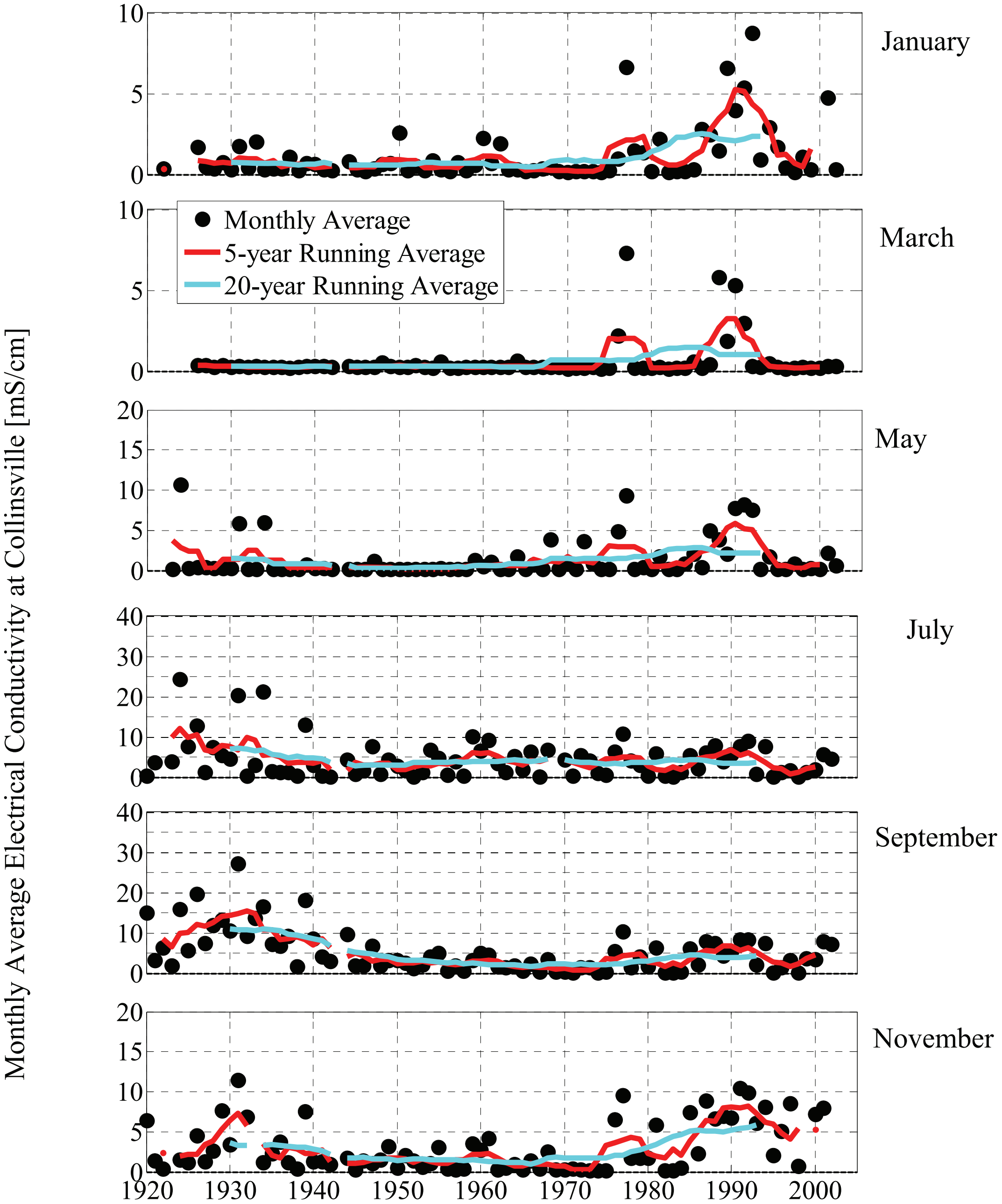


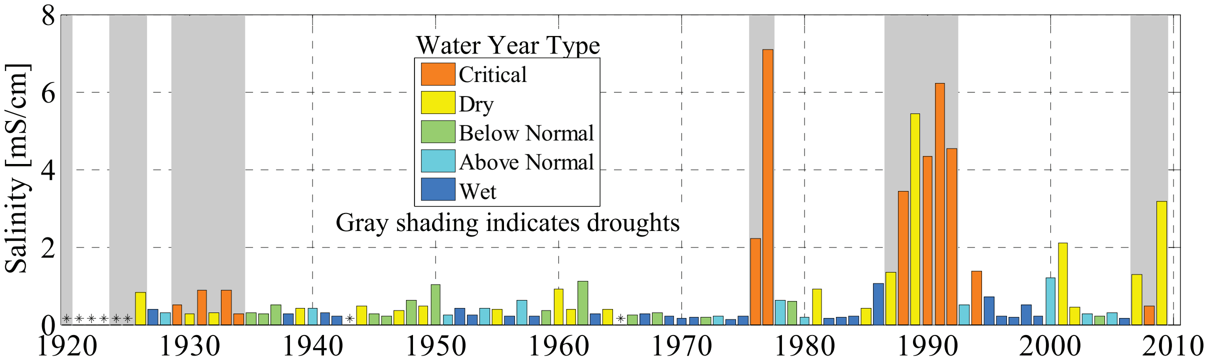
Figure 3-15 – Year-to-year trends in monthly-average salinity at Collinsville, 1920-2002

Monthly average salinity at Collinsville (black dots), with the 12-month running average (red line) and 5-year running average (blue line) for individual months.

Relatively fresh winters and springs during the 1920's are consistent with observations by C&H during that time period. However, monthly EC at Collinsville during the recent droughts (1976-1977 and 1987-1993) was always greater than 350 µS/cm EC, except for one month in both 1989 and 1992. These monthly observations of EC at Collinsville indicate that during the recent dry periods (1976-1977 and 1987-1993), EC at Collinsville was higher than that during similar dry periods in the 1920's and 1930's.

Enright and Culberson (2009) analyzed the trend in salinity variability at Collinsville from 1920-2006. They found increasing salinity variability in eleven of twelve months and attributed it to water operations. In seven months (January-May, September-October) the increasing trend was significant ($p<0.05$).

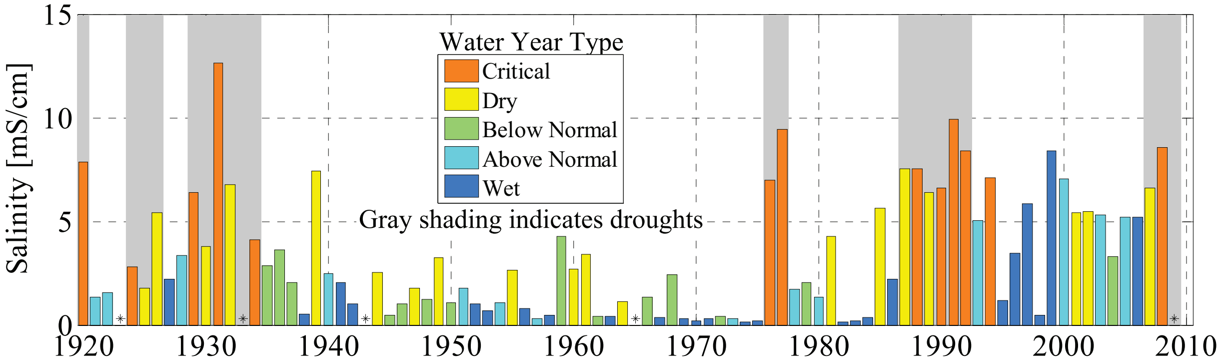
Even in the six-year drought from 1928 to 1934, the Delta still freshened every winter (Figure 3-16). However, as shown in Figure 3-16, the Delta has not freshened during more recent droughts (1976-1977, 1987-1994, and 2007-2009). This indicates that the historical "flushing" of the Delta with fresh water is no longer occurring. This lack of flushing can also allow waste from urban and agricultural developments upstream of and within the Delta to accumulate. Contaminants and toxics have been identified as factors in the decline of the Delta ecosystem (Baxter *et al.* 2007). The data indicate the effect of managing to the X2 standard (implemented in 1995), as the salinity levels attained in the most recent drought are not as high as the 1976-77 and 1987-1992 droughts.



* Indicates no data are available

Figure 3-16 – Average Winter salinity at Collinsville

Annual average salinity during the winter (January through March) for water years 1927 to 2009. Bars are colored by water year type as defined by the Sacramento 40-30-30 index. Grey shading indicates multi-year droughts that include at least one critical water year.



* Indicates no data are available

Figure 3-17 – Average Fall salinity at Collinsville

Annual average salinity during the fall months (October through December) for water years 1920 to 2009. Bars are colored by water year type as defined by the Sacramento 40-30-30 index. Grey shading indicates multi-year droughts that include at least one critical water year.

Figure 3-17 presents the variation in average fall salinity at Collinsville from 1920 to 2008 (October-December). Fall salinity is now high almost every year, while in the past, fall salinity was only high in dry and critical years. High salinity in the fall has been identified as a factor in the decline of the Delta ecosystem. Baxter *et al.* (2008) noted that "fall salinity has been relatively high during the POD years, with X2 positioned further [sic] upstream, despite moderate to high outflow conditions during the previous winter and spring of most years."

Conclusions

- In the 1920's and 1930's, the Delta freshened annually, even during droughts. In recent droughts, the Delta does not always freshen during the winter.
- Prior to 1976, fall salinity was high only in relatively dry years. Recently, fall salinity is high almost every year.

3.3.5. Salinity at Mallard Slough

A 1967 agreement between the Contra Costa Water District (CCWD) and the State of California requires the State to reimburse CCWD for the decrease in availability of usable river water, defined as water with less than 100 mg/L chlorides, at the Mallard Slough intake (CCWD, 1967). The 1967 agreement, and similar agreements between the State and other Delta water users, recognized the State Water Project (SWP) would increase salinity at Mallard Slough. The agreement defined a baseline of 142 days of usable water per year, based on the average number of days of usable water at the Mallard Slough intake from 1926-1967. Since 1967, the average number of days of usable water[21] (for the period 1967-2005) has declined to 122, indicating a 20-day (14%) reduction in the number of days of high quality water at Mallard Slough since the completion of the SWP.

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[21] The data are from the USBR-CVO record of EC at Pittsburg, approximately 2 km upstream of Mallard Slough from 1967-2005. Since this station is located upstream of Mallard Slough, the number of days of usable water at Mallard Slough since the SWP was built may be overestimated.

4. Qualitative Observations of Historical Freshwater Flow and Salinity Conditions

In this section, qualitative observations of salinity conditions in the western Delta and Suisun Bay from the lawsuit filed by the Town of Antioch in 1920 and from various literature reports are discussed to provide a perspective of the salinity conditions prevailing in the late 1800's and early 1900's. Qualitative observations from early explorers and settlers are discussed in Appendix E.

4.1. Town of Antioch Injunction on Upstream Diverters

In 1920, the Town of Antioch filed a lawsuit (hereinafter referred to as the "Antioch Case") against upstream irrigation districts, alleging that upstream water diversions were causing increased salinity intrusion at Antioch. An overview of the Antioch Case is provided in Appendix E. The court decision, legal briefings, and petitions provide qualitative salinity observations from a number of witnesses. Although testimony in the Antioch Case is generally anecdotal, not quantitative, it provides a perspective of the salinity conditions prevailing in the early 1900's. Because the proceedings were adversarial in nature, this report focuses on the testimony of the upstream interests, who were trying to demonstrate that salinity intrusion was common near Antioch prior to their diverting water (prior to 1920). Consequently, the testimony may be biased in support of this "more saline" argument.

The upstream interests in the Antioch Case provided information on the operation of pumping plants along the San Joaquin River at Antioch for domestic water supply and the quality of water obtained from the pumping plants, summarized in Table 4-1.

Table 4-1 – Testimony regarding pumping plant operations and water quality in the 1920 Antioch Case

Time period of observation	Relevant information from the testimony
1866-1878	Mr. Dodge ran a pumping/delivery operation at Antioch ▪ Dodge pumped water into a small earthen reservoir at Antioch and then hauled the water to residents in a wagon. ▪ Cary Howard testified that while he was living in Antioch (1867-1876), the water became <u>brackish one or two years in the fall</u>, when they had to drive into the country to get water. This likely occurred during the drought of 1870-71.
1878-1880	Mr. Dahnken bought and operated the Dodge operation ▪ Dahnken testified that the water became <u>brackish at high tide every year in the late summer</u>, and remained brackish at high tide until it rained "in the mountains."

Time period of observation	Relevant information from the testimony
1880-1903	Belshaw Company provided water ▪ Dahnken testified that Belshaw Company pumped only at low tide.
1903-1920	Municipal Plant ▪ William E. Meek (resident since 1910) testified the water is brackish at high tide every year, for some months in the year. ▪ James P. Taylor testified that for at least the last 5 years, insufficient storage required the plant to pump nearly 24 hours per day, regardless of tidal phase. ▪ Dr. J. W. DeWitt testified that during October of most years between 1897 and 1918, the water was too brackish to drink. Even when the city only pumped at low tide, the water was occasionally so brackish that it would be harmful to irrigate the lawns.

This testimony suggests that, in the late 1800's, water at Antioch was known to be brackish at high tide during certain time periods, but Antioch was apparently able to pump fresh water at low tide year-round. A possible exception was the fall season during a few dry years. Water at Antioch was apparently fresh at low tide until at least around 1915. At that time, due to increased demand and inadequate storage, the pumping plants started pumping continuously, regardless of tidal stage. The window of time each year when Antioch is able to pump fresh water from the river has been substantially reduced in the last 125 years.

As shown in Appendix A, DWR (1960) estimated that water with a chloride concentration of 350 mg/L or less would be available about 85% of the time if there were no water management effects. DWR (1960) estimated that chloride concentrations at Antioch would be less than 350 mg/L about 80% of the time in 1900 and about 60% of the time by 1940. DWR also projected further deterioration of water quality by 1960 and beyond but did not include the effects of reservoir releases for salinity control.

Observations of salinity at Antioch during recent years indicate that salinity is strongly dependent on ocean tides, and the diurnal range in salinity can be as much as the seasonal and annual ranges in salinity. This is discussed in more detail in Appendices D and E. For instance, salinity at high tide can be more than five times the salinity at low tide (Figures D-1, D-2, and D-3), and the salinity during the course of a single day may vary up to 6,000 µS/cm EC (Figure D-1). Average daily salinity at low tide during the period of 1983-2002 exceeded 1,000 µS/cm[22] EC for about four and a half months of the year (Figure D-3). During the driest 5 years between 1983 and 2002, salinity at low tide was always greater than 1,000 µS/cm EC (i.e., no fresh water was available at any time of day) for about eight months of the year. Fresh water is currently available at Antioch far less frequently than prior to the 1920's.

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[22] The current water quality criterion for municipal and industrial use is 250 mg/L, equivalent to about 1,000 µS/cm EC.

Available data and observations indicate that, prior to about 1918, fresh water was available at least at low tide during almost the entire year, in all but a few dry years. Around 1918, an abrupt change to higher salinity occurred. Although a prolonged and severe drought also began about this time, salinity conditions at Antioch did not return to pre-drought levels when the drought ended, indicating that water management activities (increased upstream diversions and later storage of water in upstream reservoirs) were the primary causes of this increased salinity.

4.2. Reports on Historical Freshwater Extent

Several literature reports discuss the spatial extent and duration of salinity conditions in the western Delta and Suisun Bay during the late 1800’s and early 1900’s. Salinity conditions at several key Delta locations are summarized below.

Location: **Western Delta**
Source(s): DPW (1931)
Quotation: “*The dry years of 1917 to 1919, combined with increased upstream irrigation diversions, especially for rice culture in the Sacramento Valley, had already given rise to invasions of salinity into the upper bay and lower delta channels of greater extent and magnitude than had ever been known before.*” (DPW, 1931, pg. 22)
Quotation: “*It is particularly important to note that the period 1917-1929 has been one of unusual dryness and subnormal stream flow and that this condition has been a most important contributing factor to the abnormal extent of saline invasion which has occurred during this same time.*” (DPW, 1931, pg. 66)
Summary: Salinity intrusion into the Delta during the period 1917-1929 was much larger than experienced prior to that time.

Location: **Pittsburg, CA**
Source(s): Tolman and Poland (1935) and DPW (1931)
Quotation: “*From 1880 to 1920, Pittsburg (formerly Black Diamond) obtained all or most of its domestic and municipal water supply from New York Slough offshore.*” (DPW, 1931, pg. 60)
Quotation: “*There was an inexhaustible supply of river water available in the New York Slough* [near Pittsburg at the confluence of the Sacramento and San Joaquin Rivers]*, but in the summer of 1924 this river water showed a startling rise in salinity to 1,400 ppm of chlorine, the first time in many years that it had grown very brackish during the dry summer months.*” (Tolman and Poland, 1935, pg. 27)
Summary: Prior to the 1920’s, the water near the City of Pittsburg was sufficiently fresh for the City to obtain all or most of its fresh water directly from the river.

Location: **Antioch, CA**
Source(s): DPW (1931)

Quotation: “*From early days, Antioch has obtained all or most of its domestic and municipal water supply from the San Joaquin River immediately offshore from the city. This supply also has always been affected to some extent by saline invasion with the water becoming brackish during certain periods in the late summer and early fall months. However, conditions were fairly satisfactory in this respect until 1917, when the increased degree and duration of saline invasion began to result in the water becoming too brackish for domestic use during considerable periods in the summer and fall.*” (DPW, 1931, pg. 60)

Summary: Until 1917, the City of Antioch obtained all or most of its freshwater supplies directly from the San Joaquin River. Salinity intrusion has prevented domestic use of water at the Antioch intake in summer and fall after 1917.

Location: **Benicia, CA (Suisun Bay)**

Source(s): Dillon (1980) and Cowell (1963)

Quotation: “*In 1889, an artificial lake was constructed. This reservoir, filled with fresh water from Suisun Bay during the spring runoff of the Sierra snow melt water ...*” (Dillon, 1980, pg. 131)

Quotation: “*…in 1889, construction began on an artificial lake for the* [Benicia] *arsenal which would serve throughout its remaining history as a reservoir, being filled with fresh water pumped from Suisun Bay during spring runoffs of the Sacramento and San Joaquin Rivers which emptied into the bay a short distance north of the installation.*” (Cowell, 1963, pg. 31)

Summary: In the late 19th Century, fresh water was available in the Suisun Bay and Carquinez Straits for use by the City of Benicia.

The reported presence of relatively fresh water in the western Delta and the Suisun Bay during the late 1800’s and early 1900’s is consistent with the relatively fresh conditions observed in the paleoclimate records for this time period (Section 2.3) and the relatively wet conditions observed in the Sacramento River runoff and precipitation records (Section 3.1).

Additional observations between 1775 and 1841 are included in Appendix E. These qualitative observations indicated the presence of “*sweet*” water near the confluence of the Sacramento and San Joaquin Rivers in the vicinity of Collinsville in August 1775 (a period of average or above-average Sacramento River flow), and September 1776 (a period of below-average Sacramento River flow). The presence of “*very clear, fresh, sweet, and good*” water was reported in April 1776 (a dry year). Historical observations from 1796 and August 1841 (dry periods) indicated salinity “*far upstream*” at high tide and the presence of brackish (undrinkable) water in Threemile Slough. Current salinity controls and regulations put brackish water (averaged over 14 days) near Jersey Point and Emmaton, each about 2.5 miles below Threemile Slough, on a regular basis annually.

5. Conclusions

1. Measurements of ancient plant pollen, carbon isotope and tree ring data show that the Delta was predominately a freshwater marsh for the past 2,500 years, and that the Delta has become far more saline in the past 100 years because of human activity. Salinity intrusion during the last 100 years is comparable to the highest levels over the past 2,500 years.
2. Human activities during the last 150 years, including channelization of the Delta, elimination of tidal marsh, construction of deep water ship channels, and diversions of water, have resulted in increased salinity levels in the Delta. Today, salinity typically intrudes 3 to 15 miles farther into the Delta than it did in the early 20th Century.
3. Before the substantial increase in freshwater diversions in the 1940's, the Delta and Suisun Bay would freshen every winter, even during the extreme drought of the 1930's. However, that pattern has changed. During the most recent droughts (1976-1977, 1987-1994, and 2007-2009), the Delta did not always freshen in winter. Without seasonal freshening, contaminants and toxics can accumulate in the system and young aquatic species do not experience the same fresh conditions in the spring that occurred naturally.
4. While half of the past 25 years have been relatively wet, the fall salinity levels in 21 of those 25 years have resembled dry-year conditions. In terms of salinity, the Delta is now in a state of drought almost every fall because of human activity, including water diversions.
5. Seasonal and inter-annual variation in salinity has also been changed; however, this change is the result of reduced freshwater flows into the Delta. At any given location in the western Delta and Suisun Bay, the percentage of the year when fresh water is present has been greatly reduced or even eliminated.
6. The historical record and published studies show the Delta is far saltier now, even after the construction of reservoirs that have been used in part to meet State Water Resources Control Board water quality requirements in the Delta. Operation of reservoirs and water diversions for salinity management somewhat ameliorates the increased salinity intrusion, but the levels still exceed pre-1900 salinities.

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Historical Fresh Water and Salinity Conditions in the Western Sacramento-San Joaquin Delta and Suisun Bay

A summary of historical reviews, reports, analyses and measurements

Appendices

Water Resources Department

Contra Costa Water District

Concord, California

February 2010

Technical Memorandum WR10-001

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Appendix A. Factors Influencing Salinity Intrusion

Salinity intrusion in the Delta is the result of the interaction between tidally-driven saline water from the Pacific Ocean and fresh water from rivers flowing into the Delta. Regional climate change (e.g., sea level rise and change in precipitation regime), physical changes to the Central Valley landscape (e.g., creation of artificial channels and land use changes), and water management practices (e.g., reservoir storage, water diversions for agricultural and municipal and industrial use) affect this interaction between the ocean tides and the freshwater flow, in turn affecting salinity intrusion in the Delta (The Bay Institute (TBI), 1998, Department of Public Works (DPW), 1931, Nichols *et al.*, 1986, Conomos, 1979, and Knowles, 2000).

These factors are grouped into three categories (Table A-1) and discussed individually and qualitatively to provide context for observed salinity variability, which is necessarily due to the cumulative impact of all factors.

Table A-1 – Factors Affecting Salinity Intrusion into the Delta

Natural and artificial factors affect the salinity of the Delta. The factors are grouped into three categories: regional climate change, physical changes to the landscape, and water management practices.

Category	Factors affecting salinity intrusion and specific effect on Delta salinity
Regional Climate Change	• Precipitation regime o Long-term reduction of spring (April-July) snowmelt runoff may increase salinity in the spring, summer, and fall. o A shift to more intense winter runoff may not decrease salinity in the winter because outflows are typically already high during winter storms. • Ocean conditions o Added periodic variability to precipitation (via mechanisms such as the El Niño/Southern Oscillation (ENSO) or Pacific Decadal Oscillation (PDO)) • Sea level rise o Expected to increase salinity intrusion (DWR, 2006). Actual salinity response to rising sea level will depend upon actions taken to protect against flooding or overtopping (e.g., new tidal marsh vs. sea walls or dykes).
Physical Changes to the Landscape	• Deepening, widening, and straightening of Delta channels o Generally increase salinity, but response will depend upon location within the Delta (DWR, 2006)

Category	Factors affecting salinity intrusion and specific effect on Delta salinity

	• Separation of natural floodplains from valley rivers
	  o Confining peak flows to river channels would reduce salinity during flood events.
	  o Preventing floodplains from draining back into the main channel would increase salinity after floods (late spring and summer).
	• Reclamation of Delta islands
	  o Varies (the effect on salinity depends on marsh vegetation, depth, and location), but marshes generally dampen tides, reducing salinity intrusion
	• Creation of canals and channel "cuts"
	  o Generally creates more efficient routes for tidal flows to enter the Delta, thereby increasing salinity intrusion relative to native conditions
	• Deposition and erosion of sediments in Suisun Bay (Cappiella *et al.*, 1999)
	  o Deposition of mining debris (occurred from 1860's to approximately 1887) reduced salinity in Suisun Bay and the western and central Delta (Enright, 2004, Enright and Culberson, 2009)
	  o Erosion (occurring since 1887) increases salinity in Suisun Bay and the western and central Delta (Enright, 2004, Enright and Culberson, 2009)

Water Management Practices (reservoir operations, water diversions, and exports from the Delta)	• Decreasing Net Delta Outflow (NDO) by increasing upstream and in-Delta diversions as well as exports
	  o Increases salinity
	• Increasing upstream storage capacity
	  o Generally increases salinity when reservoirs are filling. Reservoir releases may decrease salinity if they increase outflow. Historically, this occurred when flood control or other releases were required in wetter years. However, as this study shows, this has generally been small and intermittent; salinity measurements indicate it occurred occasionally prior to 1985, and very seldom since. Increased early winter diversion of runoff to storage will maintain or increase high salinities in the winter.

A.1. Climatic Variability

Changes in precipitation regimes and sea levels, brought about by a changing climate, can affect the spatial and temporal salinity conditions in the Delta. Long-term variations in river runoff, precipitation and sea level are discussed below.

A.1.1. Regional Precipitation and Runoff

Precipitation in the Bay-Delta watershed sets the amount of water available within the system which could ultimately reach the Bay and affect salinity conditions. However, since precipitation falls as both rain and snow, runoff to river channels is spread over more months than the precipitation events themselves; any runoff from rain generally reaches the river channels within days of the precipitation event, but runoff resulting from snow is delayed until the spring snowmelt. For this reason, estimates of unimpaired flow (runoff), rather than precipitation, are generally used to characterize hydrological variability. Unimpaired runoff represents the natural water production of a river basin, unaltered by water diversions, reservoir storage and operation, and export of water to or import of water from other basins.

Knowles (2000) determined that variability in freshwater flows accounts for the majority of the Bay's salinity variability. The spatial distribution, seasonal timing, annual magnitude, decadal variability, and long-term trends of unimpaired flow all affect the hydrology and salinity transport in the Delta. Total annual unimpaired flow in the Sacramento and San Joaquin basins from 1872 through 2009 is presented in Section 3.1, with the seasonal distribution provided for 1921 through 2003.

The total annual unimpaired flow of the upper Sacramento Basin for water years 1906 through 2006 exhibits substantial year-to-year variability with a strong decadal oscillation in the 5-year running average (see Figure 3-1). On average, over the last 100 years, the total annual unimpaired Sacramento River flow is increasing by about 0.06% or 11 thousand-acre feet (TAF) each year. However, increased total annual unimpaired flow does not necessarily reduce salinity intrusion. Knowles (2000) illustrated that the seasonal timing of runoff can significantly alter salinity intrusion without any change to the total annual runoff.

Typically, most precipitation in California occurs during winter in the form of snow in the Sierra Nevada. The subsequent melting of this snow, beginning in the spring, feeds the rivers that flow into the Delta. The four months from April through July approximately span the spring season and represent the period of runoff due to snow melt. The long-term trend in spring (April-July) runoff decreased by approximately 1.3 MAF from 1906 to 2006 (Figure A-1). This effect is believed to be caused by climate change; as temperatures warm, more precipitation falls as rain instead of snow, and what snowpack that does accumulate tends to melt earlier in the year. This leads to higher runoff during winter months, but lower runoff in spring or summer, resulting in the potential for greater salinity intrusion. These observed changes in the magnitude and timing of spring runoff of the Sacramento River watershed are consistent with similar changes in spring runoff observed across river watersheds of the western United States (e.g., Dettinger, 2005; Mote *et al.*, 2005; Stewart *et al.*, 2005). Note that, from 1920 to 2006, the long-term trend in spring runoff actually increased slightly (approximately 0.5 MAF).

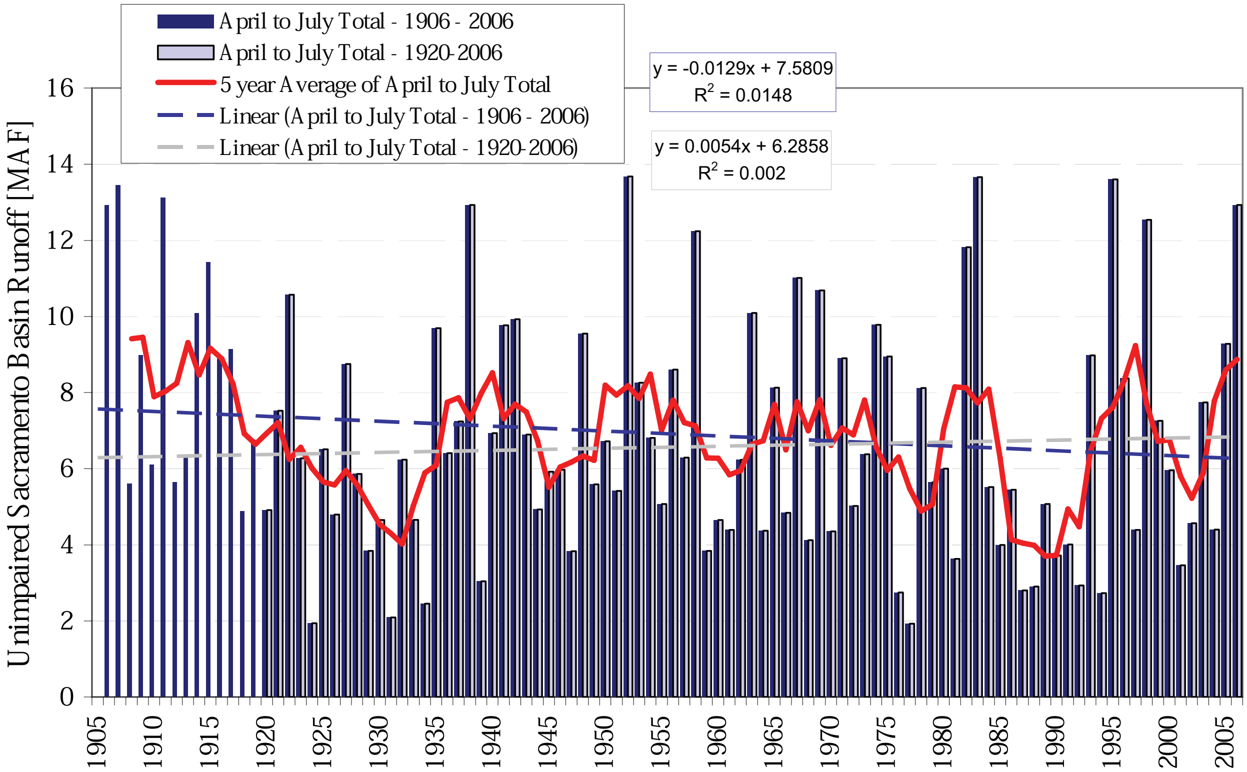

Figure A-1 – Unimpaired runoff from the Sacramento River basins from April to July

Data source: http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST.

Precipitation and runoff are influenced by regional events such as the Little Ice Age (about 1300 to 1850 CE) and the Medieval Warm Period (about 800 to about 1300 CE). During the Little Ice Age, the winter snowline in the Sierra was generally at a lower elevation, and spring and summer nighttime temperatures were significantly lower. This temperature pattern would allow the snowmelt to last further into the summer, providing a more uniform seasonal distribution of runoff such that significantly less salinity intrusion than occurs today would be expected. This expectation is borne out by paleosalinity studies (see Section 2.3).

At shorter time scales, oceanic conditions such as the Pacific Decadal Oscillation (PDO) and El Niño/Southern Oscillation (ENSO) also impact precipitation and runoff patterns. Runoff in the upper watershed is the primary factor that determines freshwater outflow from the Delta. Anthropogenic flow management (upstream diversions, reservoir operations, in-Delta diversions, and south-of-Delta exports) alters the amount and timing of flow from the upper watershed (see Section 2.3). Changes to the physical landscape further alter the amount and timing of flow (see Section 2.2).

A.1.2. Sea Level Rise

Sea level fluctuations resulting from the repeated glacial advance and retreat during the Pleistocene epoch (extending from 2 million years ago to 15,000 years ago) resulted in deposition of alternating layers of marine and alluvial sediments in the Delta (TBI, 1998). A warming trend starting about 15,000 years ago ended the last glacial advance and triggered rapid sea-level rise. At the end of this period (known as the "Holocene Transgression") approximately 6,000 years ago, sea level had risen sufficiently to inundate the Delta at high tide (Atwater *et al.*, 1979).

Sea level is estimated to have risen at an average rate of about 5 cm/century during the past 6,000 years and at an average rate of 1-2 cm/century during the past 3,000 years (Cayan *et al.*, 2008). Observations of sea level at the Golden Gate in San Francisco reveal that the mean sea level has risen at an average rate of 2.2 cm/decade (or 0.22 mm/yr) over the past 100 years (Cayan *et al.*, 2008). Future increases in sea level are expected to increase salinity intrusion into the Delta (DWR, 2006); actual salinity response to rising sea level will depend upon actions taken to protect against flooding or levee overtopping (e.g. new tidal marsh would generally reduce salinity intrusion, while construction of sea walls or dykes may further increase salinity).

A.2. Physical Changes to the Delta and Central Valley

Creation of artificial channels, reclamation of marshlands, land use changes and other physical changes to the landscape of the Delta and Central Valley have significantly altered water movement through the Delta and the intrusion of salinity into the Delta. Major physical changes to the Delta and Central Valley landscape have occurred over the last 150 years. As many of these physical changes were made prior to flow and salinity monitoring (which began in the 1920's), only a qualitative discussion is presented below.

A.2.1. Deepening, Widening, and Straightening Channels (early 1900's-present)

The lower Sacramento River was widened to 3,500 feet and straightened (creating Decker Island) around 1910 (Lund *et al.,* 2007). Progressive deepening of shipping channels began in the early 1900's. Original channel depths were less than 10 feet; channels were gradually dredged to depths exceeding 30 feet, and maintenance dredging continues today.

These changes to the river channels have increased salinity intrusion. Deepening the river channels increases the propagation speed of tidal waves, leading to increased salinity intrusion. Similarly, straightening the river channels provides a shorter path for the passage of the tidal waves and increases salinity intrusion. Widening of the river channels increases the tidal prism (the volume of water in the channels), resulting in further salinity intrusion. Larger cross-sections reduce velocities, lowering friction losses and maintaining more tidal energy, which is the driving force for dispersing salinity into the Delta.

A.2.2. Reclamation of Marshland (1850-1920)

In the Central Valley

The original natural floodplains captured large winter flows, gradually releasing the water back into the river channels throughout the spring and summer, resulting in a more uniform flow into the Delta (reduced peak flow and increased low flow) compared to current conditions. The increased surface area of water stored in these natural floodplains increased total evaporation and groundwater recharge, reducing total annual inflow into the Delta.

Even with less Delta inflow, the difference in the seasonal flow pattern may have limited salinity intrusion. The drainage of floodplains back into rivers during the spring and groundwater seepage back to the rivers in the summer and fall provided a delayed increase in river flows during the low flow period. Raising and strengthening natural levees in the Central Valley effectively disconnected the rivers from their floodplains, removing this natural water storage, increasing the peak flood flows and reducing the low flows. The net effect of these changes in the Central Valley was to reduce salinity during floods, when salinity is typically already low, and increase salinity during the following summers and falls, which is likely to have led to increased maximum annual salinity intrusion.

In the Delta

Reclamation of Delta marshland began around 1850. By 1920, almost all land within the legal Delta[1] had been diked and drained for agriculture (DPW, 1931). Before the levees were armored and the marshes were drained, the channels would have been shallower and longer (more sinuous), which would have slowed propagation of the tides into the Delta, reduced tidal energy and reduced salinity intrusion.

The natural marsh surface would have increased the tidal prism. However, the shallow marsh depth and native vegetation would have slowed the tidal wave progression. The combined effect on salinity intrusion depends on the location and depth of the marsh, the native vegetation distribution, and the dendritic channels that were removed from the tidally active system.

Figure A-2 shows the western, central, and southern portions of the Delta in 1869. For comparison, Figure A-3 shows the same area in 1992, with man-made channels highlighted grey.

A.2.3. Mining debris

Hydraulic mining in the Sierra Nevada began in the 1860's and produced large quantities of debris which traveled down the Sacramento River, through the Delta and into the Bay. Mining debris may have contributed to the extensive flooding reported in 1878 and 1881. Cappiella *et al.* (1999) estimate that, from 1867 to 1887, approximately 115 million cubic meters (Mm3) of sediment were deposited in Suisun Bay. This deposition was due to the inflow of hydraulic mining debris.

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[1] The legal Delta is defined in California Water Code Section 12220.

Figure A-2 - Map of the Delta in 1869

Channels of the western, central, and southern Delta in 1869, prior to extensive reclamation efforts (Gibbes, 1869)

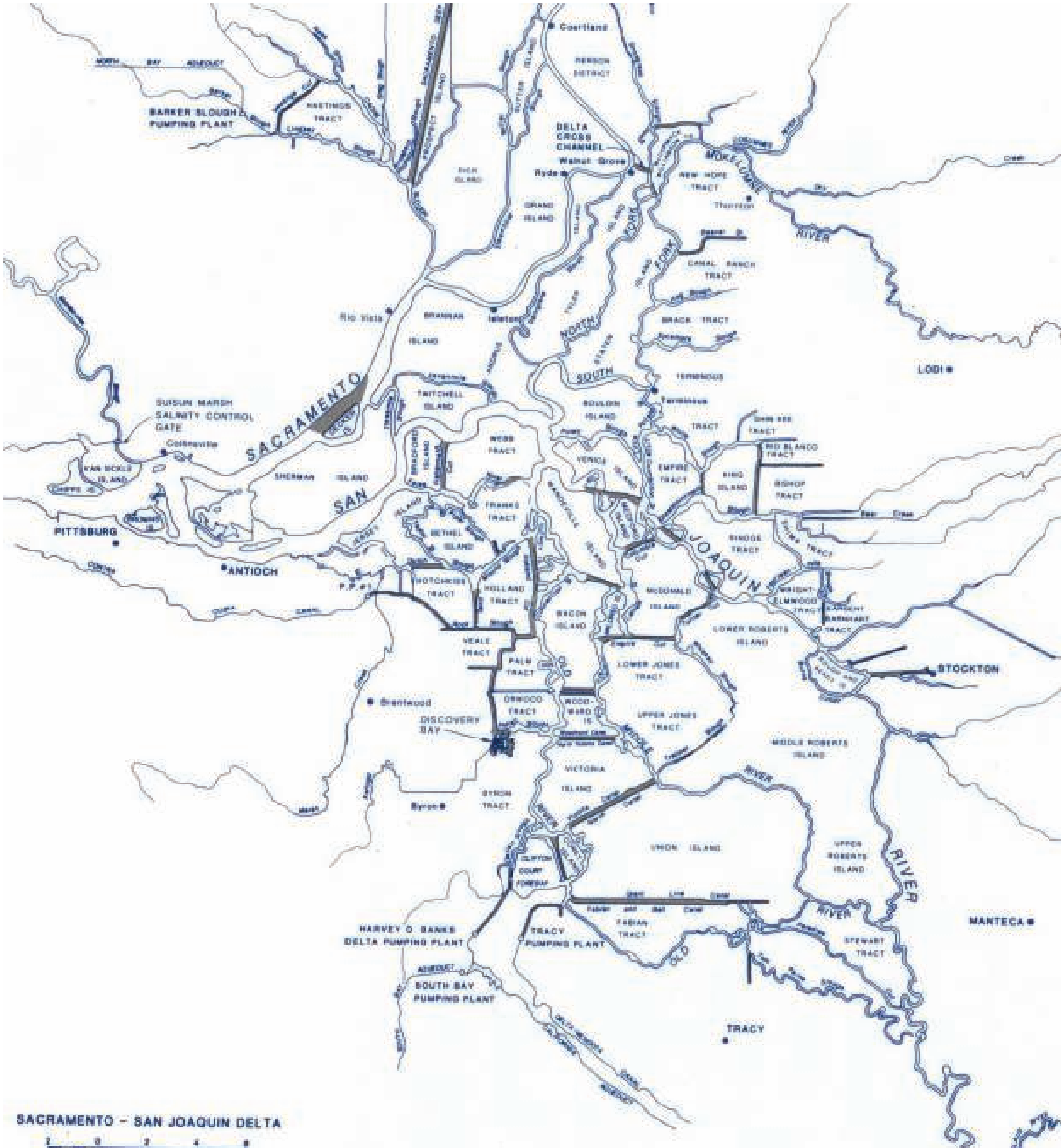

Figure A-3 – Map of the Delta in 1992

Channels of the western, central, and southern Delta from the Delta Atlas (DWR, 1992) Constructed waterways (highlighted in grey) generally create more efficient routes for tidal flows to enter the Delta, thereby increasing salinity intrusion relative to the native tidal marshes.

Cessation of hydraulic mining around 1884 resulted in erosion of Suisun Bay, which continues to erode even today. From 1887 to 1990, approximately 262 Mm3 of sediment were eroded from Suisun Bay. The net change in volume of sediment during 1867-1887 was 68 Mm3 (net deposition) and during 1887-1990 was -175 Mm3 (net erosion). As a result of these changes, the tidal flat of Suisun Bay increased from about 41 km^2 in 1867 to 52 km^2 in 1887, but decreased to 12 km^2 by 1990 (due to erosion subsequent to the cessation of hydraulic mining). Cappiella *et al.* (1999) attributed the change in the Suisun Bay area from being a largely depositional environment to an erosional environment not only to the hydraulic mining practices of the late 1800's but also to increased upstream water management practices. The Suisun Marsh Branch of the DWR estimated that erosion of Suisun Bay (modeled as a uniform change in depth of 0.75 meters) has increased salinity in Suisun Bay and the western Delta by as much as 20% (Enright, 2004; Enright and Culberson, 2009).

A.3. Water Management Practices

Extensive local, state, and federal projects have been built to move water around the state, altering the natural flow patterns throughout the Delta and in upstream watersheds. For clarity in the discussion that follows, definitions and discussions of actual flow and salinity, unimpaired flow and salinity, and natural flow and salinity, are given below.

Historical (actual) flow and salinity

Historical (or actual) flow and salinity refer to the flow and electrical conductivity, total dissolved solids concentration, or chloride concentration that occurred in the estuary. Historical conditions have been observed, measured, or estimated at various times and locations; they are now measured at monitoring stations throughout the estuary. Historical data are also used to estimate flow and water quality conditions at other locations with the following tools: the DAYFLOW program from IEP, the DSM2 model from the California Department of Water Resources, the X2[2] equation (Kimmerer and Monismith, 1992) and Contra Costa Water District's salinity outflow model (also referred to as the G-model) (Denton, 1993; Denton and Sullivan, 1993). The use of these tools to estimate flow and water quality is necessarily dependent upon the Delta configuration to which they were calibrated. Use of these tools in hypothetical configurations (such as pre-levee conditions, flooding of islands, etc) is subject to un-quantified error.

Unimpaired flow and salinity

Unimpaired flows are hypothetical flows that would have occurred in the absence of upstream diversions and storage, but with the existing Delta and tributary configuration. Unimpaired flows are estimated by the California Department of Water Resources (DWR) for the 24 basins of the Central Valley; the Delta is one of the 24 basins. Additionally, DWR estimates unimpaired in-Delta use and unimpaired net Delta outflow (NDO). Unimpaired NDO estimates can be used to estimate unimpaired water quality using a salinity-outflow relationship such as the X2 or G-model tools discussed above.

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[2] X2 is defined as the distance from the Golden Gate to the 2 part-per-thousand isohaline (equivalent to a salinity of 2 grams of salt per kilogram of water), measured along the axis of the San Francisco Estuary. X2 is often used as an indicator of freshwater availability and fish habitat conditions in the Delta (Jassby *et al.*, 1995; Monismith, 1998).

Since unimpaired flows assume the existing Delta configuration, the use of these tools should not violate their basic assumptions. However, the results should be taken in context. Water quality based on unimpaired flows compared to water quality based on historical (actual) flows shows how water management activities affect water quality. Water quality based on unimpaired flows cannot be considered natural.

Natural flow and salinity
Natural flow and salinity reflect pre-European settlement conditions, with a virgin landscape in both the Central Valley and the Delta, native vegetation, and no diversions or constructed storage. As discussed above, the natural landscape included natural storage on the floodplains and extensive Delta marsh. Estimation of natural flow requires assumptions regarding the pre-European landscape and vegetation throughout the Central Valley. Estimation of natural salinity requires development of new models to account for pre-European Delta geometry, incorporating the estimates of natural flow. These assumptions induce an unknown level of error. For this reason, no attempt is made in this report to calculate natural flow or the resulting salinity. Instead, paleosalinity studies are examined to provide evidence of salinity in the pre-European era.

Water management practices have continually evolved since the mid-1850's. As discussed in Section 1.1, anthropogenic modification include diversion of water upstream and within the Delta, construction of reservoirs, and system operations to meet regulatory requirements.

The irrigated acreage in the Central Valley has been steadily increasing since 1880 (Figure 1-3), increasing the upstream diversions of water. There were two periods of rapid growth in irrigated acreage: from 1880 to 1920 and from 1940 to 1980. In-Delta diversions (Figure 1-3) began in 1869 with reclamation of Sherman Island; from 1869 to 1930, in-Delta diversions are assumed to have grown in proportion to the area of reclaimed marshland (from Atwater *et al.*, 1979).

Upstream diversions first became an issue with respect to Delta salinity around 1916 with the rapid growth of the rice cultivation industry (Antioch Case, Town of Antioch v. Williams Irrigation District, 1922, 188 Cal. 451; see Appendix E.2). These early "pre-project" diversions for irrigation had particularly large impacts because of the seasonality of water availability and water use. Diversions for agriculture typically start in the spring and continue through the early fall (when river flow is already low). These early irrigation practices, combined with the decrease in spring and summer flow due to the separation of rivers from their natural floodplains, resulted in a significant reduction of the spring and summer river flow, leading to increased salinity intrusion.

Figure A-4 shows the Department of Water Resources' estimates of the effects of upstream diversions and south-of-Delta exports on the salinity in the San Joaquin River at Antioch (DWR, 1960). DWR's 1960 report indicated that water with less than 350 mg/L chlorides would be present at Antioch approximately 88% of the time on average "naturally," and that availability decreased to approximately 62% by 1940 due to upstream diversions. This illustrates that upstream depletions had a significant effect on salinity at Antioch during 1900-1940, prior to the construction of large upstream reservoirs. (For reference, Shasta Dam was completed in 1945.)

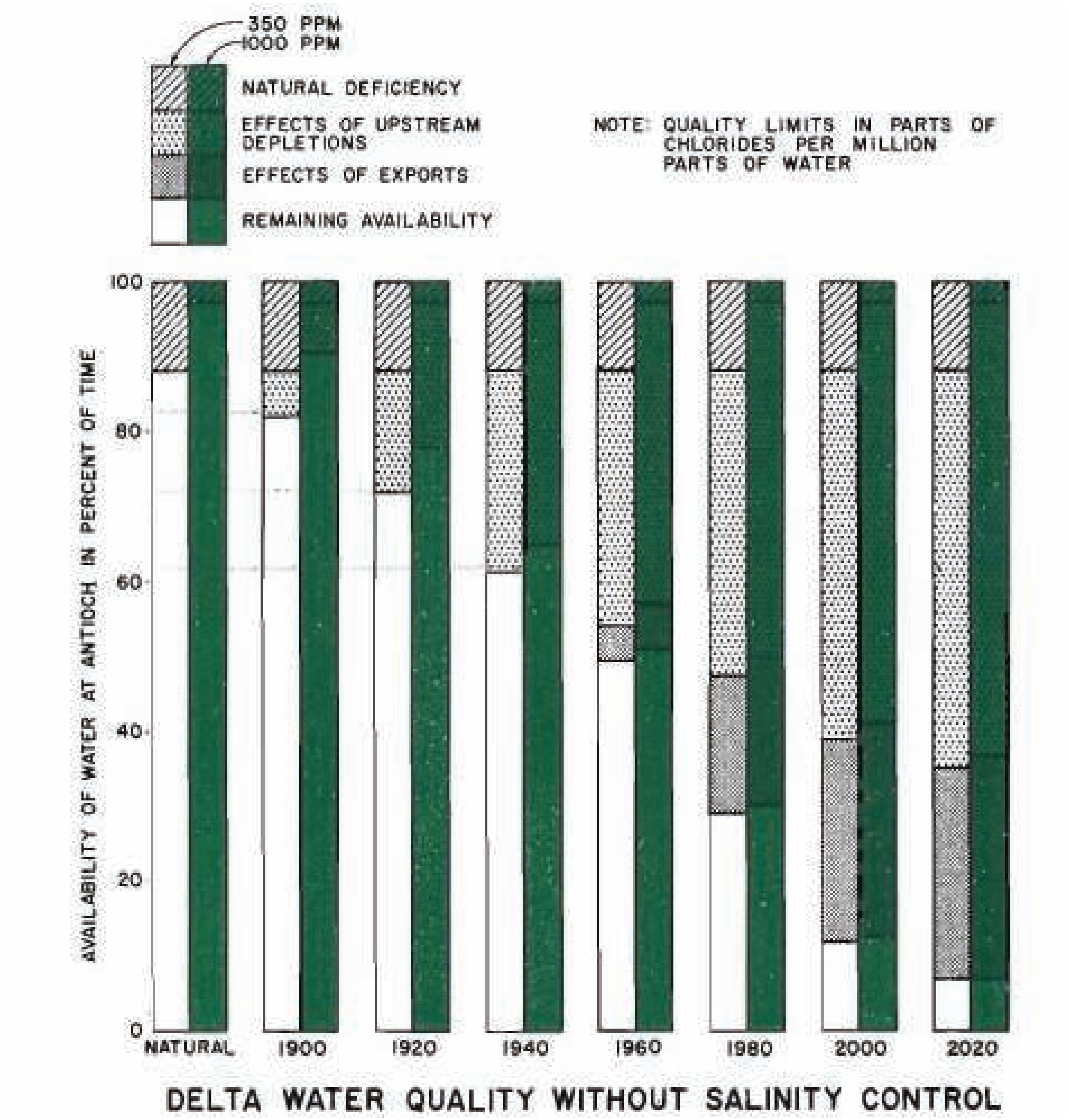

Figure A-4 - Salinity on the San Joaquin River at Antioch (DWR, 1960)

The Department of Water Resources examined the effects of upstream depletions and south-of-Delta exports on salinity in the San Joaquin River at Antioch, estimating the percent of time water that a certain quality of water (with less than 350 mg/L chlorides; or less than 1,000 mg/L chlorides) would be available in the river without reservoir releases to provide salinity control. The estimates for 1960, 1980, 2000, and 2020 assume the reservoirs do not make releases for salinity control and therefore underestimate the actual quality of water during these years.

Figure A-4 also shows estimates of the availability of water in 1960, 1980, 2000, and 2020, without reservoir releases to provide salinity control, demonstrating that upstream depletions and in-Delta exports would have continued to degrade water quality at Antioch.

Exports from the south Delta started in 1951 with the completion of the federal Central Valley Project pumping facility near Tracy, California. Exports from the State Water Project Banks Pumping Plant, just to the west of the federal facility, began in 1967. As shown in Figure 1-3, south-of-Delta exports increased rapidly from 1951 through the mid-1970s, and since then the combined exports have averaged more than 4 million acre-feet per year.

Construction of upstream reservoirs also altered natural patterns of flow into the Delta. Figure A-5 and Figure A-6 show the extent and rapid rise of constructed reservoirs in the upstream watersheds of the Delta (DWR, 1993). The location, year of completion and approximate storage capacities (in acre-feet, AF) are shown in Figure A-5. Figure A-6 shows the temporal development of reservoir capacity. Reservoir construction began in 1850. The major reservoirs of the Central Valley Project (CVP) and State Water Project (SWP) are the Shasta (4.5 MAF capacity) and Oroville (3.5 MAF) reservoirs, respectively. These reservoirs capture the flow in the wet season (reducing the flow into the Delta in the wet season) and release water for irrigation and diversions.

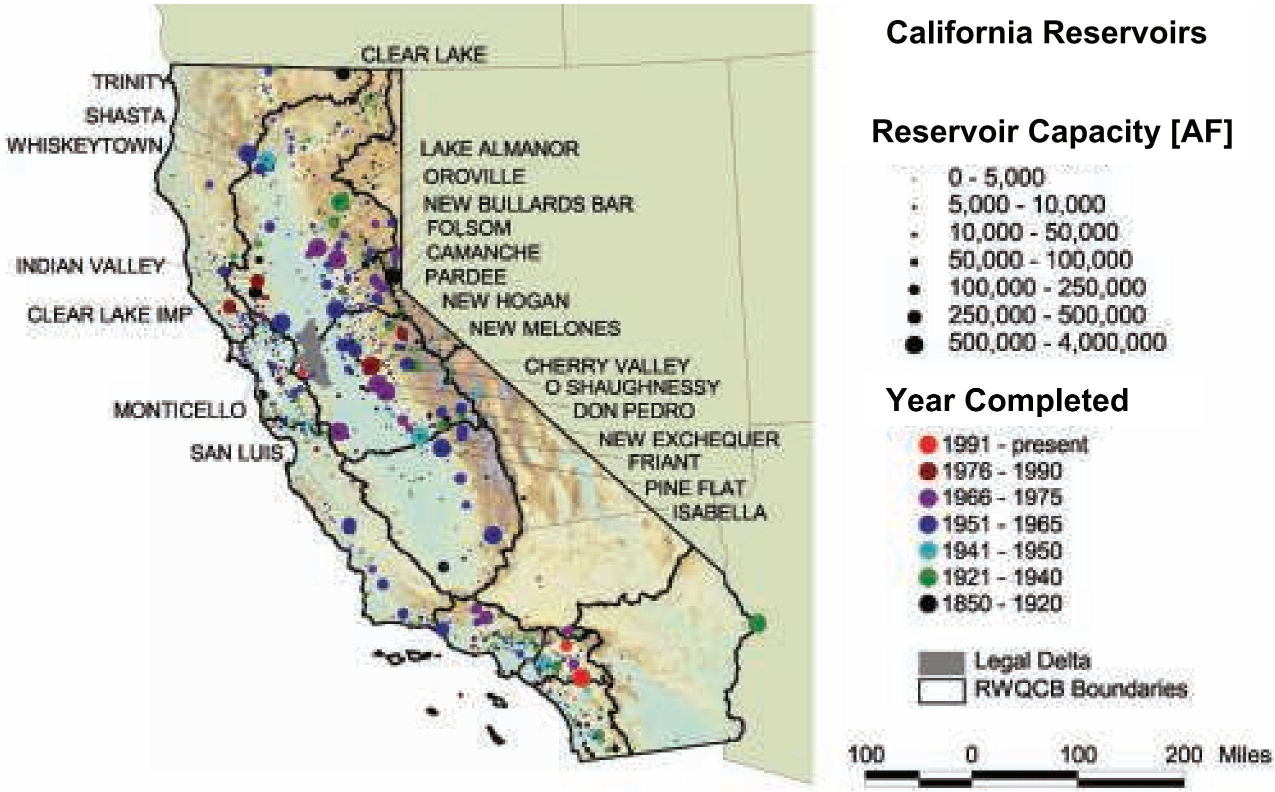

Figure A-5 – Storage reservoirs in California

Location of storage reservoirs within California. Reservoir capacity is indicated by the size of the circle, while the year construction was completed is indicated by color.

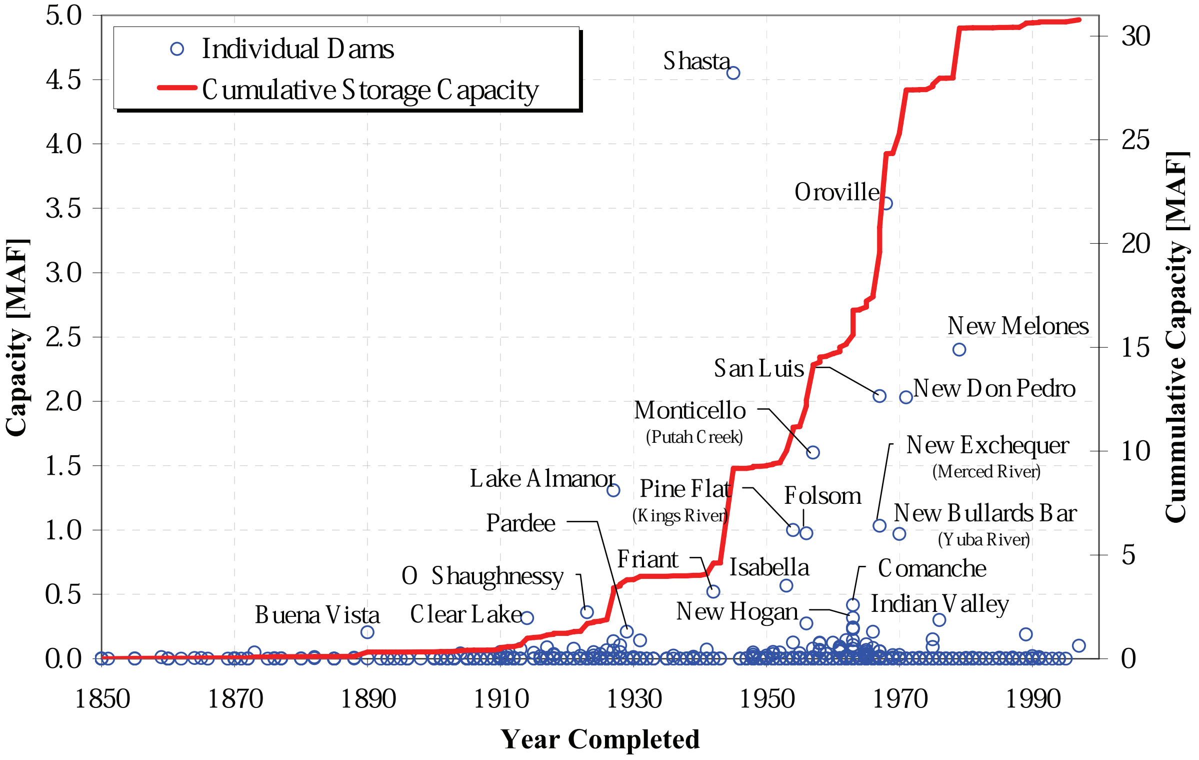

Figure A-6 – Surface Reservoir Capacity

Timeline of reservoir development in California. Individual reservoir capacity is indicated by the blue circles (left axis), while the cumulative capacity is indicated with the red line (right axis).

Water management practices have been altered by regulations that require maintenance of specified flow and salinity conditions at locations in the Bay-Delta region during certain periods of the year. The 1978 Water Quality Control Plan and State Water Resources Control Board (SWRCB) Decision 1485 established water quality standards to manage salinity to protect Delta agriculture and municipal and industrial (M&I) uses. The listing of delta smelt as a threatened species under the Endangered Species Act in 1993, followed by the Bay-Delta Accord in 1994 and the adoption of a new water quality control plan by the State Water Resources Control Board in 1995 changed the amount and timing of reservoir releases and south-of-Delta exports. California's Rice Straw Burning Act was enacted in 1992 to reduce air pollution by phasing out the burning of rice field stubble; by 1999, Sacramento Basin rice farmers were diverting additional water to flood harvested fields to decompose the stubble.

Changes in water diversions and reservoir operations have altered the magnitude and timing of river flows to the Delta, and anthropogenic modifications to the Delta landscape have altered the interaction of fresh water from the rivers with salt water from the ocean, thus changing patterns of salinity intrusion into the Delta.

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Appendix B. Paleoclimatic Records of Hydrology and Salinity

This section presents paleoclimate records of hydrology (precipitation and unimpaired runoff) and salinity in the Bay-Delta region, in addition to those presented in Section 2 of the main report.

B.1. Methods of Paleoclimatic Reconstruction

The field of paleoclimatology aims to deduce climatological information from natural "archives" in order to reconstruct past global climate. These archives are created by such Earth processes as the formation of ice sheets, sediments, rocks, and forests. Examples of information sampled from such archives include atmospheric temperatures from ice cores and precipitation cycles from tree rings. When samples are dated, through radiometric or other methods, the data preserved therein become proxy indices, establishing a timeline of major events in the local environment of the sample. Multiple samples collected over larger spatial scales can be cross-dated to create regional climate and landscape process chronologies.

The material sampled for paleoclimatic reconstructions has limitations that decrease the resolution and confidence of data going back in time. Although paleoclimatic reconstructions have a coarser temporal resolution than modern measurements, the variations in climate and landscape responses to change are reliably described "in the first person" because the evidence of localized climate change is preserved as a time series *in situ*, absent of human influence.

The San Francisco Bay-Delta has been the focus of several paleoclimatic reconstructions. Surveys have sampled from Browns Island (Goman and Wells, 2000; May, 1999; Malamud-Roam and Ingram, 2004), Roe Island (May, 1999; Malamud-Roam and Ingram, 2004) Rush Ranch (Starratt, 2001; Byrne *et al.*, 2001; Starratt, 2004), and China Camp and Benicia State Parks (Malamud-Roam and Ingram, 2004).

Sediment cores are the predominate archive used to reconstruct Bay-Delta climate. Changes in wetland plant and algae communities are the dominant response in the Bay-Delta to climate change and associated fluctuations in temperature and precipitation. Proxies of plant and algae response to environmental conditions are preserved in the sediment cores and determined by quantification and taxonomic identification of diatom frustules (Byrne *et al.*, 2001; Starratt, 2001; Starratt, 2004), plant seeds and roots (Goman and Wells, 2000) and plant pollen (May, 1999; Byrne *et al.*, 2001; Malamud-Roam and Ingram, 2004) and measurement of peat carbon isotope ratios (Byrne *et al.*, 2001; Malamud-Roam and Ingram, 2004).

Plant communities in the Delta are characterized by salt tolerance. Salt-tolerant plant communities are dominated by pickleweed (*Salicornia* spp.) while freshwater plant assemblages are dominated by tule (*Scirpus* spp.) and cattail (*Typha* spp.) (Atwater *et al.,* 1979). Plants contribute pollen, seeds, and vegetative tissue in the form of peat to the sediment archive. Plant material deposited to surface sediments are significantly correlated to the surrounding standing vegetation, and thus plant material preserved in sediment cores are considered autochthonous to the type of wetland existent at the time of sediment deposition, allowing reconstruction of the salinity conditions in the Delta over time.

Diatom taxa are classified according to their salinity preference expressed as the Diatom Salinity Index (DSI) (Eq 1) (Starratt, 2004). Starratt (2001) classified salinity preference as freshwater (F; 0-2‰), freshwater and brackish water (FB; 0-30‰), brackish (B; 2-30‰), brackish and marine (BM; 2-35‰), and marine (M; 30-35‰). Samples dominated by marine taxa have a DSI range of 0.00 to 0.30.

$$DSI = \frac{F + FB + 0.5B}{F + FB + B + BM + M} \tag{1}$$

Carbon-isotope ratios ($^{13}C/^{12}C$) (Eq 2) are measured by spectrometry and the δ notation calculated as

$$\delta^{13}C = \left[\left(\frac{{}^{13}C/{}^{12}C_{sample}}{{}^{13}C/{}^{12}C_{std}}\right) - 1\right] \times 1000 \tag{2}$$

The $\delta^{13}C$ value of peat samples is a proxy for the composition of the plant assemblages contributing vegetation to the formation of the peat. Plants utilizing the C_4 mechanism have higher $\delta^{13}C$ values (~-14‰) than those utilizing the C_3 or CAM (~-27‰) (Table B-1). Using the $\delta^{13}C$ proxy can detect the presence of upland bunchgrasses such as *Spartina* and *Distichlis.*

Pollen can be classified to the taxonomic family level. *Chenopodiaceae (*now *Salicornioideae*) is representative of salt-tolerant *Salicornia. Cyperaceae* is representative of freshwater species including *Scirpus.* The ratio of *Chenopodiaceae* to the sum of *Chenopodiaceae* and *Cyperaceae* (Eq. 3) is a proxy of the percent relative abundance of salt-tolerant species (May, 1999).

$$\% ST = \frac{Chenopodiaceae}{Chenopodiaceae + Cyperaceae} \tag{3}$$

To establish chronologies for sediment archives, dates must be established for when material was deposited through the length of the sediment cores. Radiocarbon dating by Accelerator Mass Spectrometry (AMS) determines age by counting the ^{14}C content of plant seeds or carbonate shells calibrated against a northern hemisphere atmospheric carbon calibration curve (Malamud-Roam *et al.,* 2006). Radiocarbon dating is valid to about 40,000 years before present (BP)[3], making it an ideal method for establishing dates through the period of interest for the Bay and Delta. When archived proxies are correlated with the sediment core chronology, a timeline is established reconstructing past climate and landscape response.

Table B-1 – Carbon Isotope Ratios ($\delta^{13}C$) of Plant Species in the San Francisco Estuary

(adapted from Byrne et al. 2001)

Species	Common Name	Photosynthetic Pathway	δ13C (‰)
Distichlis spicata	Saltgrass	C4	-13.5
Spartina foliosa	California cordgrass	C4	-12.7
Cuscuta salina	Salt-marsh dodder	C3	-29.8
Frankenia grandifolia	Alkali heath	C3	-30.2
Grindelia stricta	Gumplant	C3	-26.4
Jaumea carnosa	Marsh jaumea	C3	-27.2
Juncus balticus	Baltic rush	C3	-28.4
Lepidium latifolium	Perennial pepperweed	C3	-26.6
Scirpus californicus	California bulrush	C3	-27.5
Scirpus maritimus	Alkali bulrush	C3	-25.5
Typha latifolia	Cattail	C3	-27.8
Salicornia virginica	Pickleweed	CAM	-27.2

A large number of paleoclimatic reconstructions exist for California and the western U.S., but a complete discussion is beyond the scope of this report. These reconstructions are reviewed by Malamud-Roam *et al.* (2006; 2007) and provide important context to events in the Bay and Delta by recording major non-localized events and larger regional climate shifts. Important examples include: Central Valley oaks, Sierra Nevada giant sequoias, and White Mountain Bristlecone pines used to establish precipitation and temperature from the location of the tree line and tree rings; Mono Lake sediments and submerged tree stump rings for precipitation; and Sacramento and San Joaquin River floodplain deposits for flood events. These studies establish a record of environmental conditions in the Bay and Delta from their formation to the present.

B.2. Major Regional Climatic Events

Formation of the Sacramento-San Joaquin Delta

The Holocene epoch began approximately 8000 BCE at the end of Pleistocene glaciations (Malamud-Roam *et al.*, 2007). In the early Holocene, a general warming and drying period in California accompanied high orbitally driven insolation until insolation reached current values at approximately 6000 BCE. In the Sierra Nevada, western slopes were in the early stages of ecological succession following the retreat of glaciers. The modern river floodplain systems were forming in the Central Valley. Parts of the Delta and Bay were river valleys

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[3] Before Present (BP) is a time scale, with the year 1950 as the origin, used in many scientific disciplines. Thus, 100 BP refers to the calendar year 1850.

prior to approximately 8000 to 6000 BCE, when rapidly rising sea level entered the Golden Gate and formed the early Bay estuary (Atwater *et al.*, 1979). A fringe of tidal marshes retreated from a spreading Bay until approximately 4000 BCE when the rate of submergence slowed to 1 to 2 cm per year, allowing the formation of extensive Delta marshes over the next 2000 years (Atwater *et al.*, 1979). Sedimentation from upstream sources kept up with subsidence from increasing sea-level rise.

2000 – 1 BCE

After 2000 BCE, information from archives indicates climate in the Bay and Delta was cooler with greater freshwater inflows. The Sierra Nevada became more moist and cooler during a period ca. 4000-3500 BP (Malamud-Roam *et al.*, 2006).

1 BCE - Present

The cooler and wetter period ended approximately 1 BCE, replaced by more arid conditions (Malamud-Roam, 2007). Major climatic events, known from other parts of the world, are captured in the regional paleoclimatic reconstructions and help to calibrate or correlate these reconstructions to global events. Unusually dry conditions prevailed during the Medieval Warm Period (approximately 800-1300 CE). Wetter and cooler conditions existed during the Little Ice Age (approximately 1400-1700 CE). These climate variations are reflected in variations in the plant communities.

Droughts

Two extreme droughts occurred in the region from about 900 to 1150 CE and from 1200 to 1350 CE. Low freshwater inflows to the Delta occurred during periods 1230-1150, 1400-1300, 2700-2600, and 3700-3450 B.P.

Flood Events

Periods of increase moisture occurred from 800-730 BP and 650-300 BP. Massive flooding inundated the Central Valley in the winter of 1861 (Malamud-Roam *et al.*, 2006). High periods of inflow occurred during 1180-1100, 2400-2200, 3400-3100, and 5100-3800 BP.

Sampling for paleoclimatic reconstructions captures the modern era, enabling a comparison of current conditions with conditions over the past several thousand years. The erratic nature of precipitation in California observed over the past century have been normal and small compared to natural variations over the past millennia.

Reconstructed River Flow and Precipitation Records

Meko *et al.* (2001a) used tree-ring chronologies in statistical regression models to reconstruct time series of annual unimpaired Sacramento River flow for approximately the past 1,100 years (see Section 2.1). Similarly, Graumlich (1987) used tree ring data from the Pacific Northwest to reconstruct precipitation records for the period of 1675-1975 (Figure B-1). Compared to the average observed precipitation from 1899 to 1975, the reconstructed record has above-average precipitation during the latter half of the nineteenth century (1850-1900) (Figure B-1). These relatively wet conditions during the late 1800's and the severe dry conditions from the 1920's trough the 1930's in the reconstructed precipitation record are consistent with the annual unimpaired Sacramento River flow reconstruction from Meko *et al.* (2001) presented in Section 2.1.

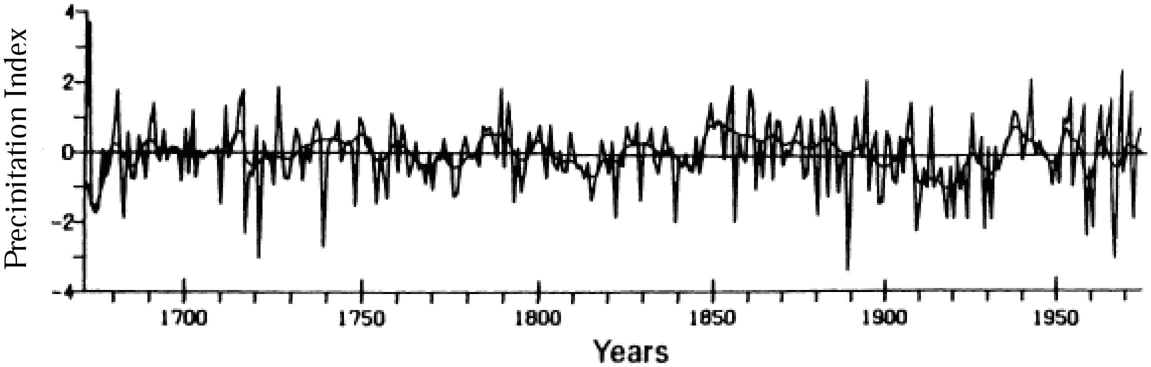

Figure B-1 – Reconstructed annual precipitation, 1675-1975
Data from Graumlich (1987). Precipitation index is presented in units of standard deviation from the 1899-1975 observed mean value.

Estimates of annual precipitation (Graumlich, 1987) and unimpaired runoff (Meko *et al.*, 2001a) from tree ring analysis are used in this study to provide hydrological context, indicating the relative hydrology (e.g. wet or dry) of a specific year and surrounding decade. The reconstructed hydrological data are not used to estimate salinity intrusion for two reasons. First, the seasonal distribution of hydrology is critical in determining salinity variability; two years with the same total annual flow could have significantly different salinity intrusion due to the timing of the flow (Knowles, 2000). Second, since 1850, anthropogenic modifications to the landscape and river flows alter the hydrodynamic response to freshwater flow, somewhat decoupling the unimpaired hydrology from the downstream response (i.e. salinity intrusion).

Malamud-Roam *et al.* (2005) and Goman *et al.* (2008) review paleoclimate as it relates to San Francisco Bay. Generally, they found that paleoclimatic studies showed that a wetter (and fresher) period existed from about 4000 BP to about 2000 BP. In the past 2,000 years, the climate has been cooling and becoming drier, with several extreme periods, including decades-long periods of very wet conditions and century-long periods of drought. As discussed in the next section, the century-long periods of drought are found in paleosalinity records in Suisun Bay and Rush Ranch in Suisun Marsh, but are much less evident in Browns Island, indicating a predominately freshwater marsh throughout the Delta. Citing Meko *et al.* (2001), they note that only one period had a six-year drought more severe than the 1928-1934 period: a seven-year drought ending in 984 CE. They also not the most extreme dry year was in 1580 CE, and state that it was almost certainly drier than 1977. On the whole, however, the last 600 years have been a generally wet period. This is reflected in the salinity records discussed in the next section.

B.3. Reconstructed Salinity in the Bay-Delta

Starratt (2001) reconstructed historical salinity variability at Rush Ranch, in the northwestern Suisun Marsh, over the last 3,000 years by examining diatoms from sediment cores. The taxa were classified according to their salinity preference: freshwater (< 2‰), freshwater and brackish water (0‰ to 30‰), brackish (2‰ to 30‰), brackish and marine (2‰ to > 30‰), and marine (> 30‰). Based on the composition of the diatom assemblages, Starrat identified centennial-scale salinity cycles (Table B-2).

Table B-2 – Salinity Intervals over the last 3,000 years at Rush Ranch

Salinity intervals determined from the diatom populations in a sediment core in northwestern Suisun Marsh.

Approximate Years	*Type of Interval* [a]
1850 CE – present	[not classified]
1250 CE – 1850 CE	fresh
250 CE – 1250 CE	brackish
500 BCE – 250 CE	fresh
1000 BCE – 500 BCE	brackish

[a] Classification according to Starratt (2001)

These results correspond well to other paleoclimatic reconstructions. The most recent broad-scale freshwater interval roughly corresponds to the Little Ice Age, and the most recent brackish interval corresponds to the Medieval Warm Period.

Starratt notes that the post-1850 interval indicates an increase in the percentage of diatoms that prefer brackish and marine salinities compared to the last freshwater interval, indicating an increase in salinity during the last 150 years, in comparison to the previous 600 years. During the post-1850 period, diatoms that prefer "marine" environments constitute as much as 50% of the total diatom population, a percentage that is at or above that of any other period. During the most recent years, "freshwater" assemblages constitute about 20% of the total population, a percentage that is only about 10% higher than the most recent *brackish* interval from 250 to 1250 CE.

Malamud-Roam *et al.* (2006) compared reconstructed salinity records for the past three thousand years from four locations (three tidal marsh locations and one location in the Bay) in the Bay-Delta region (Figure B-2(a)). Figure B-2(b) shows several periods with higher than average salinity (e.g., 1600-1300 and 1000-800 BP and 1900 CE to present) and several periods with lower than average salinity (e.g., 1300 to 1200 BP and 150 to 100 BP). These paleosalinity records are consistent with each other and with the paleoclimatic records of river flow and salinity presented in Section 2.

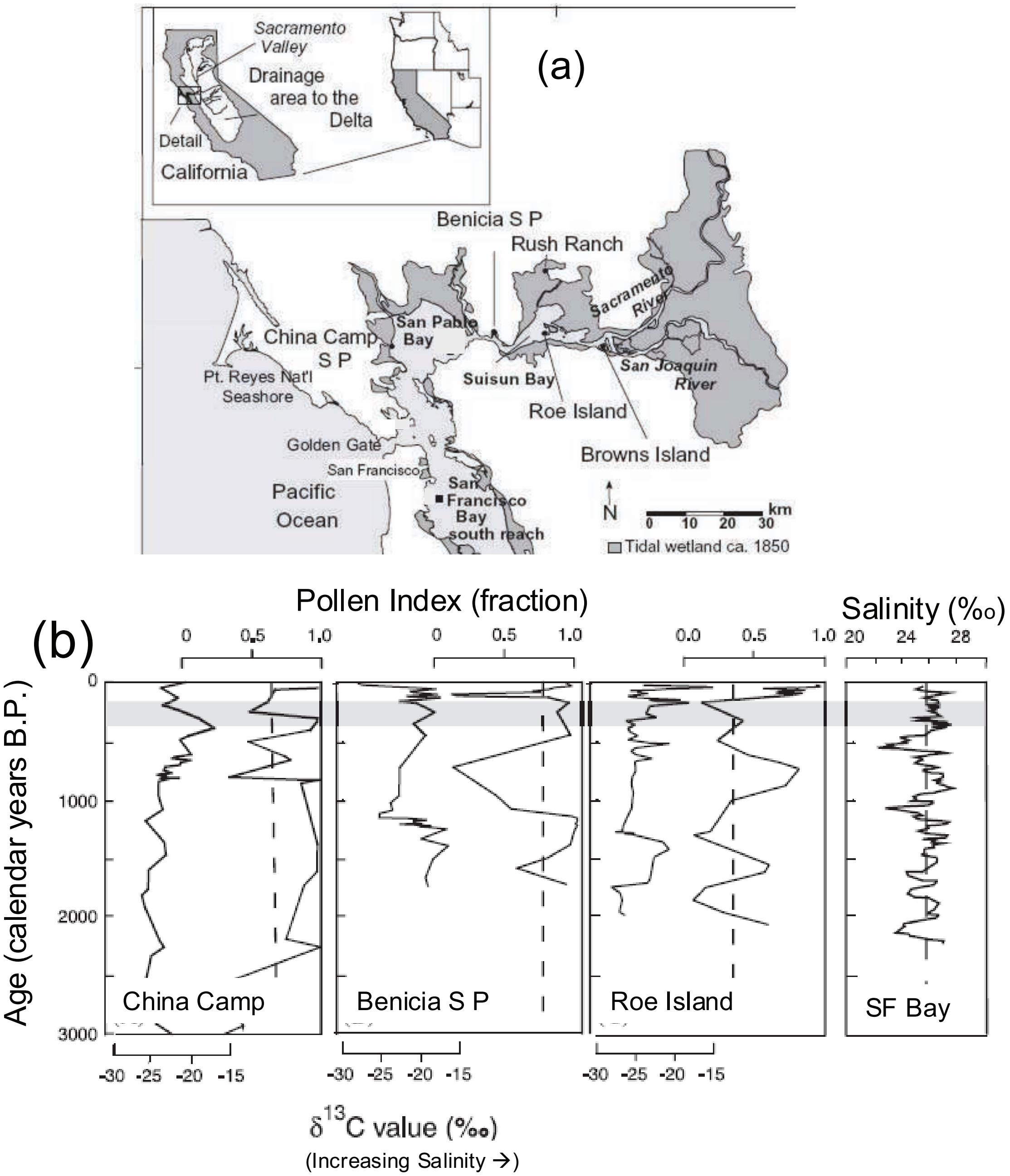

Figure B-2 – Paleosalinity records at selected sites in the San Francisco Estuary

(a) location of the three tidal marsh sites (China Camp, Benicia State Park and Roe Island) and one site in the Estuary (Oyster Point in San Francisco Bay) where sediment cores were obtained.
(b) time series for the pollen index (ranging from 0 to 1, higher values corresponding to higher salinity) and the δ13C values at the tidal marsh sites; salinity at Oyster Point, San Francisco Bay (inferred from δ13O values) is also shown. The broken line shows the estimated mean pollen index prior to European disturbance. (modified from Malamud-Roam and Ingram (2004) and Malamud-Roam et al. (2006))

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Appendix C. Quantitative Hydrological Observations

Long-term records of river runoff are useful in understanding hydroclimatic variations. Section 3.1 discusses the long-term variations of the unimpaired Sacramento River runoff and unimpaired San Joaquin River runoff. The estimates of these variables from early 1900's to the present are available on the internet . Estimates prior to the early 1900's (late 1800's to early 1900's) were obtained from a 1923 California Department of Public Works report (DPW, 1923). Table C-1 through Table C-4 present estimates of Sacramento River runoff and San Joaquin River runoff for the period of 1872-2008, obtained from DPW (1923) and http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST.

The unimpaired Sacramento River runoff is the sum of the flows from the Sacramento River at Bend Bridge, Feather River inflow to Lake Oroville, Yuba River at Smartville, and the American River inflow to Folsom Lake. The unimpaired San Joaquin River runoff is the sum of the flows from the Stanislaus River inflow to New Melones Lake, Tuolumne River inflow to New Don Pedro Reservoir, Merced River inflow to Lake McClure, and San Joaquin River inflow to Millerton Lake.

Table C-1 – Annual unimpaired Sacramento River runoff for 1872-1905
Data source: DPW (1923

Water Year	**Sacramento River @ Bend Bridge**	**Feather River @ Lake Oroville**	**Yuba River @ Smartville**	**American River @ Folsom Lake**	**Sacramento River Runoff**
	Acre-feet (AF)				Million acre-feet (MAF)
1872	10,200,000	7,254,000	4,352,000	4,215,600	**26.0**
1873	4,780,000	3,347,000	1,638,400	1,862,200	**11.6**
1874	7,300,000	5,571,000	3,340,800	3,079,800	**19.3**
1875	4,390,000	2,747,000	1,561,600	1,391,600	**10.1**
1876	14,500,000	6,867,000	3,594,000	4,450,900	**29.4**
1877	9,870,000	2,437,000	1,292,800	1,289,200	**14.9**
1878	17,800,000	4,836,000	2,528,000	2,721,700	**27.9**
1879	8,380,000	5,513,000	2,796,800	3,304,900	**20.0**
1880	12,300,000	7,061,000	3,641,600	4,502,100	**27.5**
1881	15,400,000	5,610,000	3,104,000	3,540,300	**27.7**
1882	8,000,000	4,797,000	2,150,400	3,264,000	**18.2**
1883	6,670,000	3,714,000	1,804,800	2,169,200	**14.4**
1884	11,400,000	6,190,000	3,104,000	4,103,000	**24.8**
1885	6,460,000	3,482,000	2,304,000	1,780,400	**14.0**
1886	14,400,000	6,384,000	3,174,400	3,918,900	**27.9**
1887	6,670,000	2,611,000	1,561,600	1,862,200	**12.7**
1888	5,430,000	2,669,000	998,400	1,575,700	**10.7**
1889	10,600,000	5,126,000	1,612,800	1,903,200	**19.2**
1890	22,700,000	12,090,000	6,176,000	7,725,200	**48.7**

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Water Year	Sacramento River @ Bend Bridge	Feather River @ Lake Oroville	Yuba River @ Smartville	American River @ Folsom Lake	Sacramento River Runoff
1891	6,460,000	3,482,000	1,747,200	1,944,100	**13.6**
1892	7,250,000	5,416,000	1,945,600	2,568,200	**17.2**
1893	12,400,000	7,177,000	3,488,000	4,399,800	**27.5**
1894	8,640,000	4,410,000	2,432,000	3,304,900	**18.8**
1895	12,300,000	7,177,000	4,160,000	4,737,400	**28.4**
1896	11,343,200	7,738,000	3,641,600	3,857,500	**26.6**
1897	10,391,400	5,610,000	3,040,000	3,632,400	**22.7**
1898	5,135,800	2,805,000	1,184,000	1,186,900	**10.3**
1899	5,977,400	3,288,000	1,984,000	2,362,600	**13.6**
1900	8,712,500	6,500,000	2,956,800	3,683,500	**21.9**
1901	9,020,900	6,229,000	2,854,400	3,714,200	**21.8**
1902	11,380,600	4,468,000	2,432,000	3,079,800	**21.4**
1903	9,941,800	4,483,500	2,368,000	3,038,900	**19.8**
1904	16,095,800	9,377,000	4,101,800	5,249,000	**34.8**
1905	10,775,200	4,529,200	2,403,500	2,050,000	**19.8**

Table C-2 – Annual unimpaired Sacramento River runoff for 1906-2009

Data Source: http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST

Water Year	Sacramento River Runoff (MAF)	Water Year	Sacramento River Runoff (MAF)	Water Year	Sacramento River Runoff (MAF)	Water Year	Sacramento River Runoff (MAF)
1906	26.7	1936	17.4	1966	13.0	1996	22.3
1907	33.7	1937	13.3	1967	24.1	1997	25.4
1908	14.8	1938	31.8	1968	13.6	1998	31.4
1909	30.7	1939	8.2	1969	27.0	1999	21.2
1910	20.1	1940	22.4	1970	24.1	2000	18.9
1911	26.4	1941	27.1	1971	22.6	2001	9.8
1912	11.4	1942	25.2	1972	13.4	2002	14.6
1913	12.9	1943	21.1	1973	20.1	2003	19.3
1914	27.8	1944	10.4	1974	32.5	2004	16.0
1915	23.9	1945	15.1	1975	19.2	2005	18.6
1916	24.1	1946	17.6	1976	8.2	2006	32.1
1917	17.3	1947	10.4	1977	5.1	2007	10.3
1918	11.0	1948	15.8	1978	23.9	2008	10.3
1919	15.7	1949	12.0	1979	12.4	2009	12.9
1920	9.2	1950	14.4	1980	22.3		
1921	23.8	1951	23.0	1981	11.1		
1922	18.0	1952	28.6	1982	33.4		
1923	13.2	1953	20.1	1983	37.7		
1924	5.7	1954	17.4	1984	22.4		
1925	16.0	1955	11.0	1985	11.0		
1926	11.8	1956	29.9	1986	25.8		
1927	23.8	1957	14.9	1987	9.3		
1928	16.8	1958	29.7	1988	9.2		
1929	8.4	1959	12.1	1989	14.8		
1930	13.5	1960	13.1	1990	9.3		
1931	6.1	1961	12.0	1991	8.4		
1932	13.1	1962	15.1	1992	8.9		
1933	8.9	1963	23.0	1993	22.2		
1934	8.6	1964	10.9	1994	7.8		
1935	16.6	1965	25.6	1995	34.6		

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Table C-3 – Annual unimpaired San Joaquin River runoff for 1872-1900

Data source: DPW (1923)

Water Year	Stanislaus River @ New Melones Lake	Tuolumne River @ New Don Pedro Reservoir	Merced River @ Lake McClure	San Joaquin River @ Millerton Lake	San Joaquin River Runoff
	units of acre-feet (AF)				units of million acre-feet (MAF)
1872	1,860,000	2,624,000	1,511,000	2,627,000	**8.6**
1873	959,000	1,543,000	769,000	1,122,000	**4.4**
1874	970,000	1,576,000	791,000	1,862,000	**5.2**
1875	482,000	982,000	439,000	887,000	**2.8**
1876	2,930,000	4,059,000	2,384,000	2,862,000	**12.2**
1877	408,900	561,000	220,000	809,000	**2.0**
1878	1,570,000	2,286,000	1,274,000	2,218,000	**7.3**
1879	823,000	1,353,000	659,000	470,000	**3.3**
1880	1,390,000	2,071,000	1,132,000	3,349,000	**7.9**
1881	970,000	1,576,000	791,000	2,740,000	**6.1**
1882	944,000	1,526,000	764,000	1,000,000	**4.2**
1883	1,020,000	1,600,000	813,000	1,392,000	**4.8**
1884	2,250,000	3,152,000	1,840,000	5,732,000	**13.0**
1885	582,000	1,097,000	505,000	1,218,000	**3.4**
1886	2,070,000	2,929,000	1,692,000	5,211,000	**11.9**
1887	619,000	1,139,000	538,000	1,479,000	**3.8**
1888	540,000	1,048,000	478,000	957,000	**3.0**
1889	718,000	1,262,000	599,000	1,574,000	**4.2**
1890	3,580,000	5,099,000	2,955,000	4,349,000	**16.0**
1891	959,000	1,543,000	769,000	1,227,000	**4.5**
1892	1,050,000	1,650,000	846,000	1,931,000	**5.5**
1893	2,150,000	3,036,000	1,758,000	1,914,000	**8.9**
1894	1,860,000	2,624,000	1,511,000	1,331,000	**7.3**
1895	2,700,000	3,795,000	2,236,000	2,786,700	**11.5**
1896	1,380,000	1,588,100	1,110,000	1,985,700	**6.1**
1897	1,920,000	2,437100	1,566,000	2,219,700	**8.1**
1898	498,000	960,500	450,000	922,300	**2.8**
1899	1,030,000	1,334,700	824,000	1,269,500	**4.5**
1900	1,350,000	1,628,100	1,099,000	1,343,000	**5.4**

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Table C-4 – Annual unimpaired San Joaquin River runoff for 1901-2009

Data Source: *http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST*

Water Year	San Joaquin River Runoff (MAF)	Water Year	San Joaquin River Runoff (MAF)	Water Year	San Joaquin River Runoff (MAF)	Water Year	San Joaquin River Runoff (MAF)
1901	9.4	1931	1.7	1961	2.1	1991	3.2
1902	5.1	1932	6.6	1962	5.6	1992	2.6
1903	5.7	1933	3.3	1963	6.2	1993	8.4
1904	7.6	1934	2.3	1964	3.1	1994	2.5
1905	5.3	1935	6.4	1965	8.1	1995	12.3
1906	12.4	1936	6.5	1966	4.0	1996	7.2
1907	11.8	1937	6.5	1967	10.0	1997	9.5
1908	3.3	1938	11.2	1968	2.9	1998	10.4
1909	9.0	1939	2.9	1969	12.3	1999	5.9
1910	6.6	1940	6.6	1970	5.6	2000	5.9
1911	11.5	1941	7.9	1971	4.9	2001	3.2
1912	3.2	1942	7.4	1972	3.6	2002	4.1
1913	3.0	1943	7.3	1973	6.5	2003	4.9
1914	8.7	1944	3.9	1974	7.1	2004	3.8
1915	6.4	1945	6.6	1975	6.2	2005	9.2
1916	8.4	1946	5.7	1976	2.0	2006	10.4
1917	6.7	1947	3.4	1977	1.1	2007	2.5
1918	4.6	1948	4.2	1978	9.7	2008	3.5
1919	4.1	1949	3.8	1979	6.0	2009	5.0
1920	4.1	1950	4.7	1980	9.5		
1921	5.9	1951	7.3	1981	3.2		
1922	7.7	1952	9.3	1982	11.4		
1923	5.5	1953	4.4	1983	15.0		
1924	1.5	1954	4.3	1984	7.1		
1925	5.5	1955	3.5	1985	3.6		
1926	3.5	1956	9.7	1986	9.5		
1927	6.5	1957	4.3	1987	2.1		
1928	4.4	1958	8.4	1988	2.5		
1929	2.8	1959	3.0	1989	3.6		
1930	3.3	1960	3.0	1990	2.5		

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Appendix D. Instrumental Observations of Salinity

In Section 3, historical variations in the net quantity of water flowing from the Delta to the Suisun Bay (called net Delta outflow or NDO) and salinity in the western Delta were discussed using available observations and a suite of commonly used modeling tools. This section presents additional information on the historical variations of NDO and salinity in the western Delta and Suisun Bay discussed in Section 3.

D.1. Introduction

D.1.1. Salinity Units

Salinity is specified in this report either as electrical conductivity (EC, in units of microSiemens per centimeter, or µS/cm) or as a concentration of chloride in water (in units of milligrams of chloride per liter of water, or mg/L). Conversion between EC and chloride concentration is accomplished using site-specific empirical relationships developed by Kamyar Guivetchi (DWR, 1986). Table D-1 presents a sample of typical EC concentrations and their approximate equivalent chloride concentrations.

Table D-1 – Typical electrical conductivity (EC) and equivalent chloride concentration

Electrical Conductivity (µS/cm)	Chloride (mg/L)
350	50
525	100
1,050	250
1,900	500
2,640	700
3,600	1,000

Qualitative terms such as "fresh" and "brackish" are often used to describe relative salinity. The quantitative thresholds of average chloride concentration that distinguish fresh water from brackish water and the averaging time period vary among studies. For instance, chloride concentrations of 1,000 mg/L, 700 mg/L, and 50 mg/L have been used by different studies (Table D-2).

D.1.2. Temporal and Spatial Variability of Salinity

The main variability in salinity along the length of the Bay-Delta system is due to the gradient from saline Pacific Ocean water (EC of approximately 50,000 µS/cm) to fresh water of the Central Valley rivers (EC of approximately 100 µS/cm). However, the salinity in the Bay-Delta varies both in space and time. It is important to clarify which time scales and measurement locations are being used when comparing and discussing salinity trends.

Table D-2 – Metrics used to distinguish between "fresh" and "brackish" water

Description	Sample timing or averaging	Salinity Value Chloride (mg/L)	EC (µS/cm)
Isohalines in Delta Atlas (DWR, 1995)	Annual maximum of the daily maximum	1,000 mg/L	3,700 µS/cm
X2 position (Jassby *et al.*, 1995)	Daily average (or a 14-day average)	700 mg/L	2,640 µS/cm
Barge travel by C&H[4]	Monthly average of the daily maximum	50 mg/L	350 µS/cm

Salinity in the western Delta is strongly influenced by tides. The hourly or daily variability of salinity can be much larger than the seasonal or annual variability. For instance, during the fall of 1999 (following a relatively wet year[5]), hourly EC in the San Joaquin River at Antioch varied by about 6,000 µS/cm (from about 3,000 µS/cm to 9,000 µS/cm) while the daily-averaged EC for all of 1999 ranged from about 100 µS/cm to 6,000 µS/cm (Figure D-1).

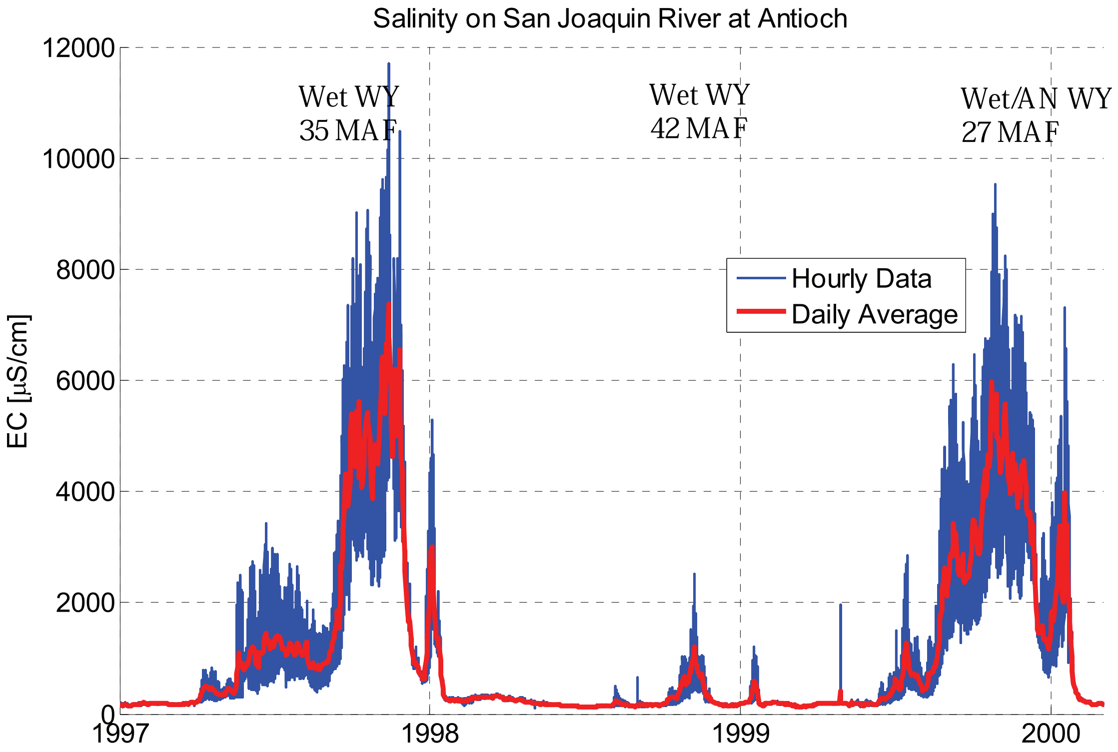

Figure D-1 – Hourly and daily salinity variability in the San Joaquin River at Antioch

Total annual unimpaired Sacramento River flow and water year type is indicated for each water year.
Data Source: IEP Data Vaults (http://www.iep.ca.gov/dss/)

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[4] The California & Hawaiian Sugar Refining Corporation in Crockett (C&H) obtained its freshwater supply from barges traveling up the Sacramento and San Joaquin Rivers, generally twice a day beginning in 1908 (DPW, 1931).

[5] Water year 1999 was classified as wet using the Sacramento Valley 40-30-30 index and above-normal using the San Joaquin Valley 60-20-20 index; indices are defined in D-1641.

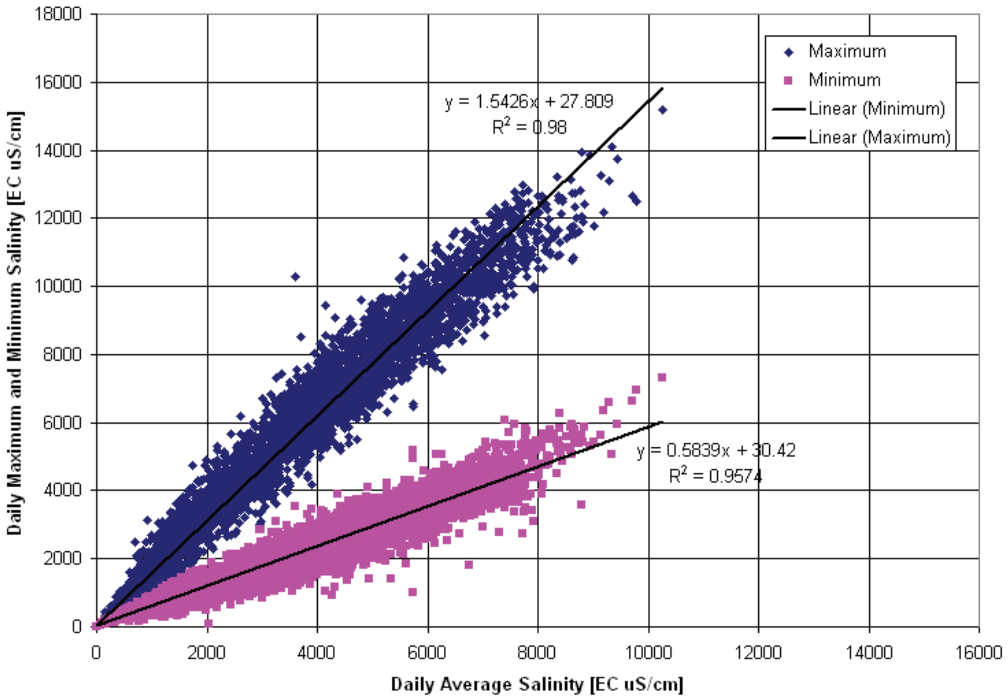


Figure D-2 – Tidal Variability in Salinity at Antioch (1967 to 1992)

Data Source: IEP Data Vaults (http://www.iep.ca.gov/dss/)

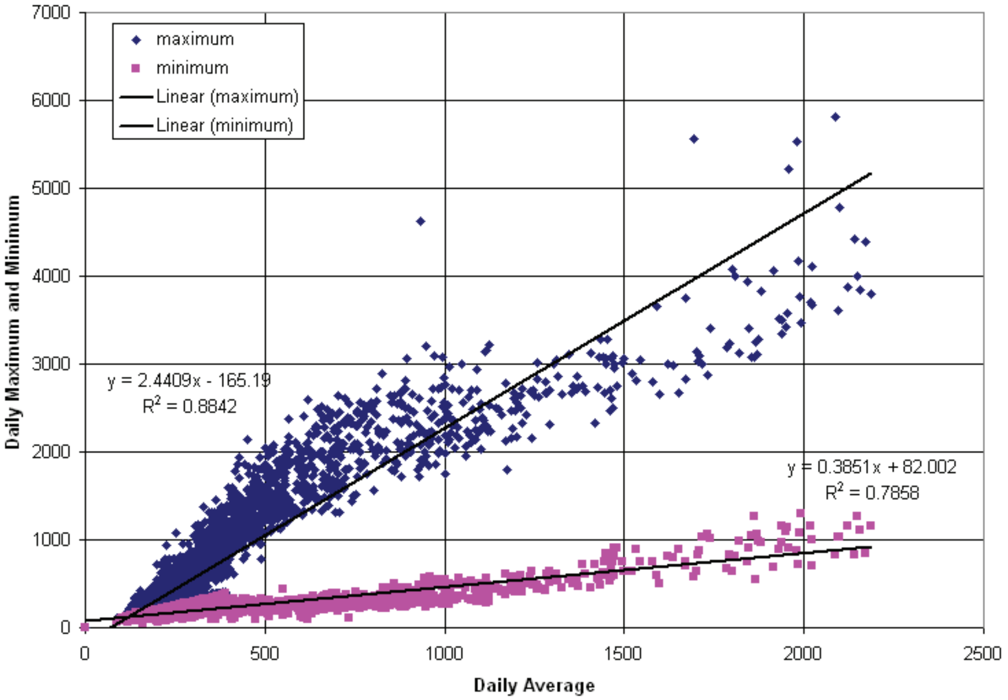


Figure D-3 – Tidal Variability in Salinity at Rio Vista (1967 to 1992)

Data Source: IEP Data Vaults (http://www.iep.ca.gov/dss/)

The high tide maximum, low tide minimum, and daily-averaged salinity at a given location are very different. As shown in Figure D-2, the daily maximum salinity in the San Joaquin River at Antioch can be double the daily-averaged salinity. Because of the large tidal variability in salinity, any comparisons of salinity observations should be at the same phase of the tide, or at least take into account tidal variability.

Similarly, as shown in Figure D-3, the daily maximum salinity in the Sacramento River at Rio Vista can be 170-400% of the daily average salinity. The daily minimum at Rio Vista may be 10-65% of the daily average.

D.2. Variations in the Spatial Salinity Distribution

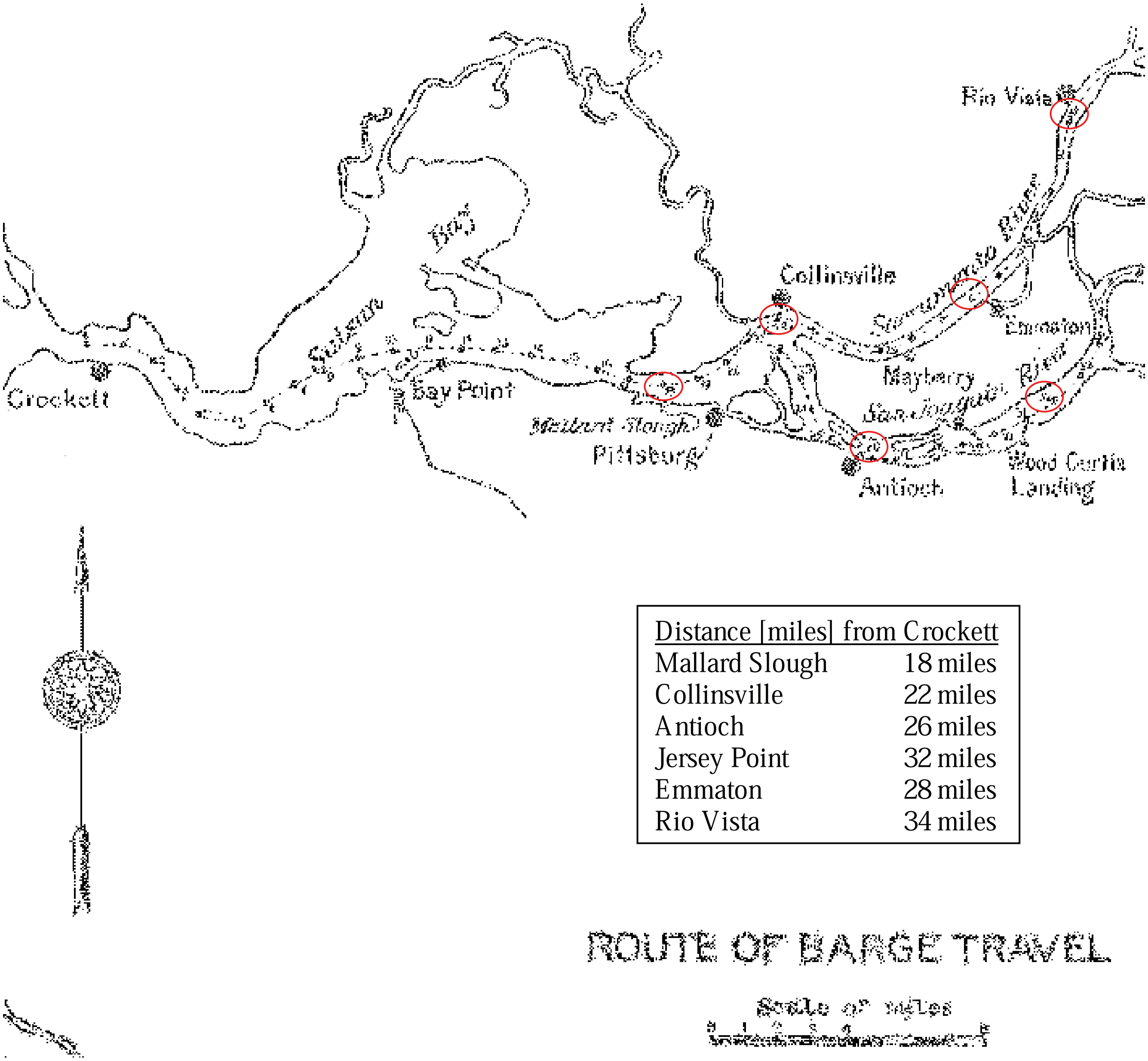
Observations examined in this section and Section 3.3 include records from the early 1900's from the California & Hawaiian Sugar Refining Corporation in Crockett (C&H) and the long-term monitoring data from the Interagency Ecological Program (IEP). Estimates of salinity at specific locations of interest were obtained from DWR's DSM2 model and Contra Costa Water District's salinity-outflow model (also known as the G-model) (Denton, 1993). Estimates of salinity intrusion were obtained using the K-M equation (Kimmerer and Monismith, 1992).

D.2.1. Distance to Freshwater from Crockett

The California & Hawaiian Sugar Refining Corporation in Crockett (C&H) obtained its freshwater supply from barges traveling up the Sacramento and San Joaquin Rivers, generally twice a day beginning in 1905 through 1929 or later (DPW, 1931). The salinity information recorded by C&H is the most detailed salinity record available prior to the intensive salinity monitoring by the State of California, which started in 1920. This section presents a comparison of the salinity observations of C&H with recent monitoring data and modeling results to determine how the managed salinity regime of the late 20th Century compares to the salinity regime of the early 1900's.

Data Sources and Methods

C&H data: C&H operations required water with less than 50 mg/L chloride concentration. According to DPW (1931), the C&H barges typically traveled up the river on flood tide and returned downstream on ebb tide. Since the maximum daily salinity for a given location in the river channel typically occurs about one to two hours after high slack tide, the distance traveled by the C&H barges represents approximately the daily maximum distance to 50 mg/L water from Crockett. The monthly minimum, average, and maximum distance traveled by C&H barges are shown in Figure D-4 and Figure D-5. For the following analysis, monthly averages of the C&H daily maximum distances were extracted from Figure D-5 for the period of 1908-1918 (after 1917, extensive salinity intrusion was reported and agricultural diversions reportedly started affecting flows into the Delta).



Distance [miles] from Crockett	
Mallard Slough	18 miles
Collinsville	22 miles
Antioch	26 miles
Jersey Point	32 miles
Emmaton	28 miles
Rio Vista	34 miles

Figure D-4 – C&H Barge Travel Routes

Map adapted from DPW (1931). Red circles indicate locations of landmarks, with distance from Crockett listed in the inset box.

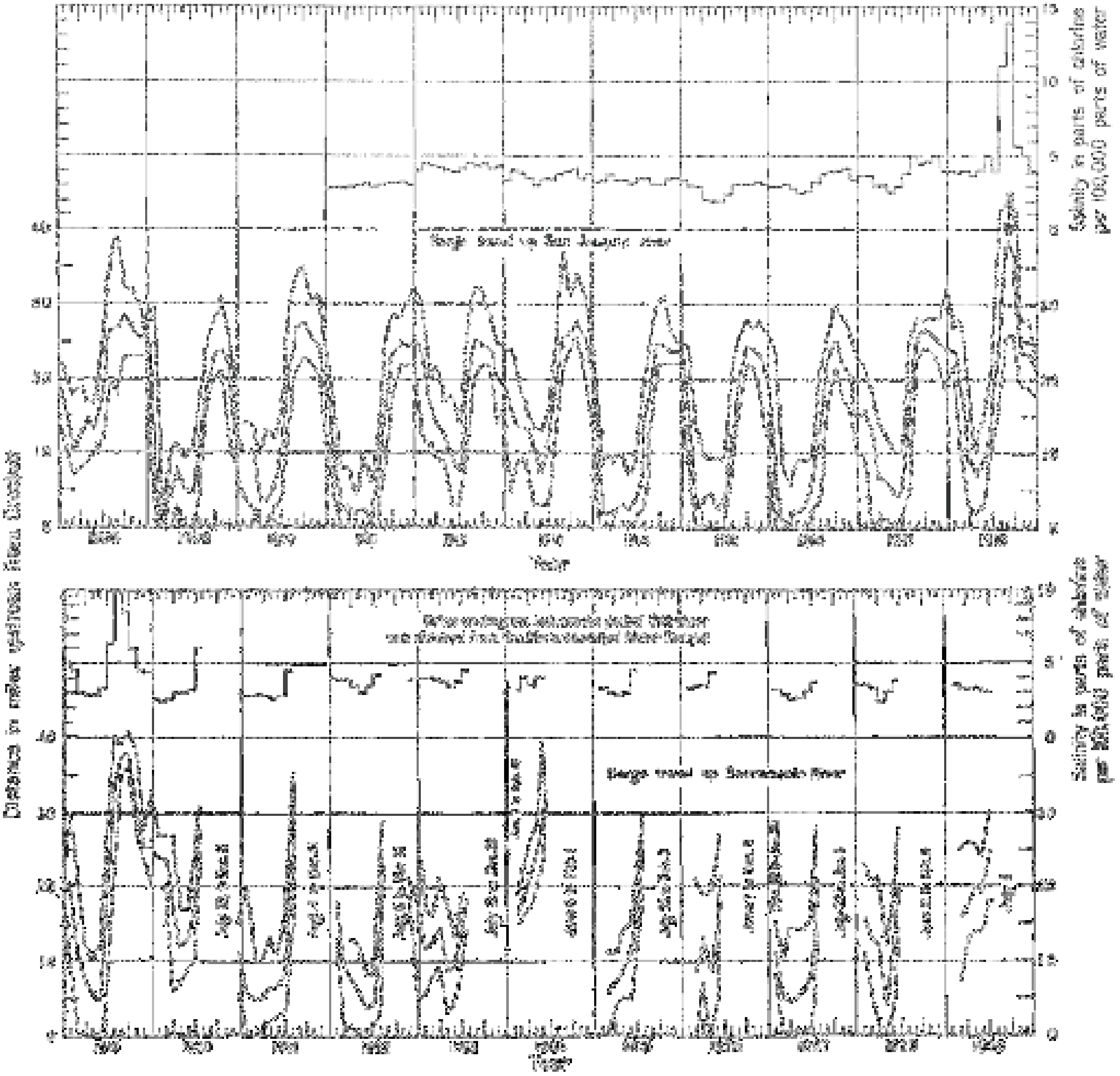


Figure D-5 – C&H Barge Travel and Quality of Water obtained

C&H barge travel up the San Joaquin River (1908 through 1918, top panel) and Sacramento River (1919 through 1929, bottom panel). The lower three lines on each panel (reference to the left axes) indicate the monthly minimum (dashed line), monthly maximum (dotted line), and monthly average (solid line) distance traveled by C&H barges to obtain their fresh water supply. The uppermost solid line on each panel (reference to the right axes) indicates the average monthly salinity of the water obtained by the barges. Figure adapted from DPW (1931)

From 1908 through 1917, C&H was able to obtain water with less than 50 mg/L chlorides within 30 miles of Crockett on average (below Jersey Point on the San Joaquin River). In 1918, the salinity of the water obtained by C&H barges had increased due to a combination of a lack of precipitation and upstream diversions (especially for newly introduced rice cultivation) (DPW, 1931). During August and September 1918, salinity exceeded 60 mg/L chloride, and the C&H barges traveled farther upstream than any time previously recorded.

In 1919, a wetter year than 1918, salinity was high for an even longer period of time, most likely due to increased upstream diversions for irrigation. Salinity exceeded 60 mg/L chloride during July, August, and September. Beginning in 1920, C&H abandoned the Sacramento and San Joaquin Rivers during the summer and fall seasons, replacing the water supply with a contract from Marin County. However, even during the driest years of the 1920's, C&H obtained water with less than 50 mg/L chloride below the confluence of the Sacramento and San Joaquin Rivers during a portion of every year.

Salinity observations from the Interagency Ecological Program (IEP): Long-term monitoring of electrical conductivity (EC) at multiple stations within the Bay and Delta began around 1964. Publicly-available daily-averaged data were obtained for this analysis from the Interagency Ecological Program (IEP) data vaults (Table D-3).

Table D-3 – Overview of long-term salinity observation records from IEP
(see http://www.iep.ca.gov/dss/)

Location	*Station*	*Source*	*Data*
Selby	RSAC045	USGS-BAY	Historical
Martinez	RSAC054	CDEC	Real-time
Benicia Bridge	RSAC056	USBR-CVO	Historical
Port Chicago	RSAC064	USBR-CVO	Historical
Mallard	RSAC075	CDEC	Real-time
Pittsburg	RSAC077	USBR-CVO	Historical
Collinsville	RSAC081	USBR-CVO	Historical
Emmaton	RSAC092	USBR-CVO	Historical
Rio Vista	RSAC101	USBR-CVO	Historical
		DWR-ESO-D1485C	Historical
Georgiana Slough	RSAC123	DWR-CD-SURFWATER	Historical
Greens Landing	RSAC139	USBR-CVO	Historical
Antioch	RSAN008	USBR-CVO	Historical
Jersey Pont	RSAN018	USBR-CVO	Historical
Bradford Point	RSAN024	USBR-CVO	Historical
San Andreas Landing	RSAN032	USBR-CVO	Historical

Delta Simulation Model (DSM2) Historical Simulation: The DSM2 historical simulation (1989-2006) was used to provide estimates of water quality to complement the limited field data from IEP. Because DSM2 has a very detailed spatial computational network covering the Delta and Suisun Bay, DSM2 can output much more detailed spatial and temporal salinity information than just the water quality at the IEP monitoring stations. DSM2 results include the daily-averaged EC at each model node along the lower Sacramento and San Joaquin Rivers. The location of the 350 μS/cm EC isohaline (corresponding to 50 mg/L chloride) was identified from the DSM2 results and compared with the equivalent C&H and IEP data.

Analysis time frame: The first decade of C&H barge travel (1908-1917) was a relatively wet period compared to the entire period of record (1906-2006) (Figure D-6). To compare conditions under similar hydrological conditions, specific recent decades (Figure D-6(a)) and select recent years (Figure D-6(b)) were selected that have comparable or slightly wetter hydrology than the C&H years. The periods 1966-1975 and 1995-2004 have similar annual unimpaired Sacramento River flow to the C&H data period (1908-1917) (see Figure D-6(a)). In addition, two wet years (1911 and 1916) and two dry years (1913 and 1918) selected from the C&H time period were compared with two wet years (1969 and 1998) and two dry years (1968 and 2002) from the IEP record.

Limitations of the analysis: The C&H data approximately represent the maximum daily salinity at a given location, whereas recent conditions (IEP or DSM2 data) are represented by the daily-averaged salinity. The estimates of the distance that must be traveled to reach fresh water under current conditions are, therefore, underestimated.

In addition, the C&H barges traveled up the San Joaquin River from 1908 through 1917, yet the equivalent travel distance for C&H barges under current conditions are estimated for the Sacramento River, and not the San Joaquin River. Under present-day conditions, the upstream distance to fresh water on the San Joaquin River is greater than for the Sacramento River, so this approach will also serve to underestimate the actual distance that C&H barges would have to travel under present-day conditions.

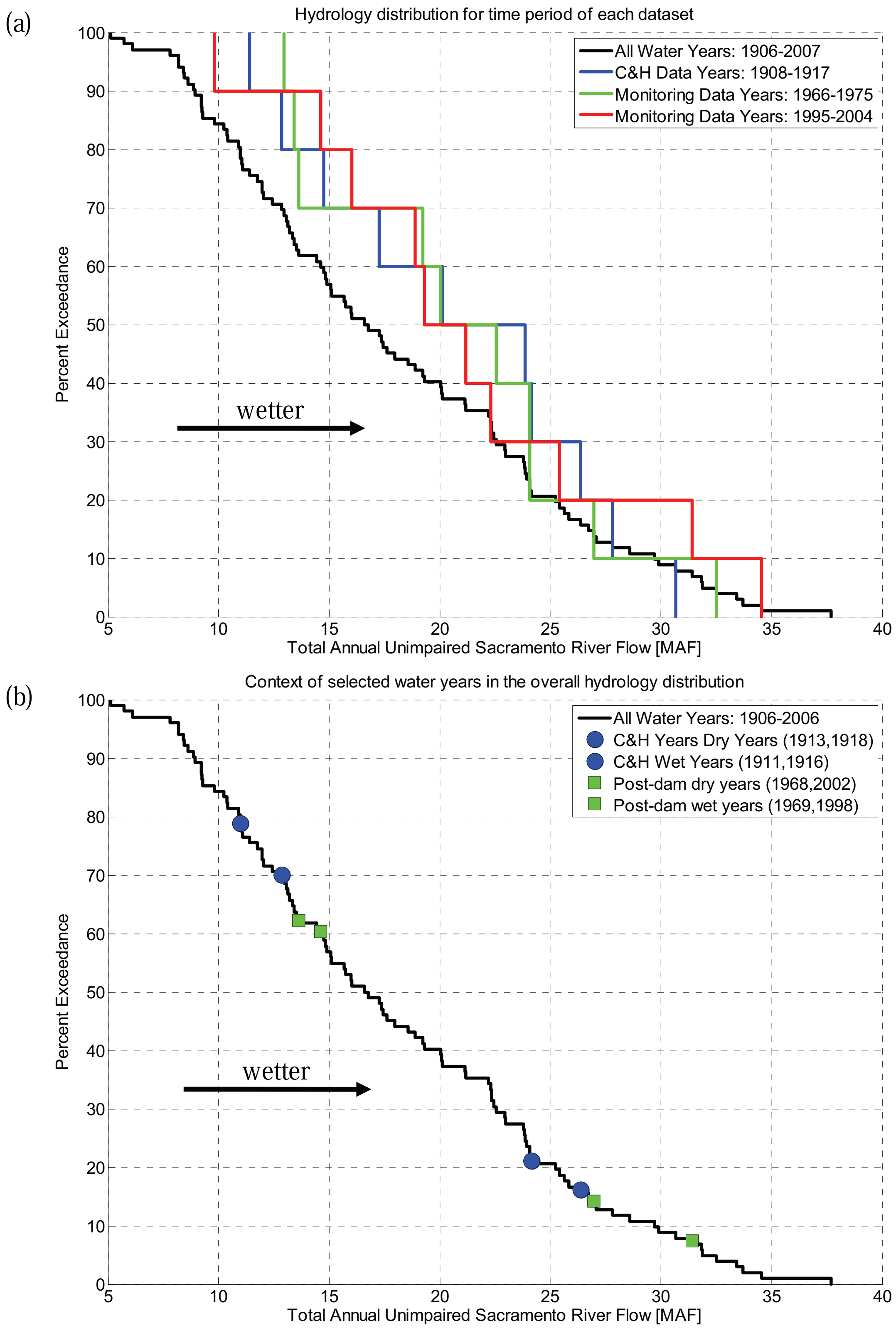


Figure D-6 – Hydrologic Context for Analysis of Distance to Fresh Water

(a) Hydrology distribution for water years 1906 to 2007, and select decades.

(b) Hydrology distribution for water years 1906 to 2007, with select water years shown for context.

Results and Discussion

Selected Wet Years

As shown in Figure D-7, the salinity patterns during the two selected C&H-era wet years, 1911 and 1916, are similar to each other. During these wet years, the location of 50 mg/L chloride water is west of Martinez for about 4-5 months (late February to early August in 1911 and from early February to late June in 1916). In contrast, during recent wet years 1969 and 1998, water with 50 mg/L chlorides or less was west of Martinez for only about 6 weeks in February and March. This comparison shows that in 1969 and 1998 the western Delta was saltier in the fall and spring than it was in 1911 and 1916, and salinity intrusion occurred much earlier in 1969 and 1998.

If barges were still traveling up the Sacramento River today to find fresh water, they would have to travel farther during the fall, spring, and summer than the C&H barges traveled during similar wet years. In 1916, fresh water retreated upstream about one month earlier than in 1911, possibly influenced by the increasing upstream diversions during 1911-1916 (see Figure 1-3). In recent years with even greater unimpaired runoff, fresh water retreats two to three months earlier than in 1916. Additionally, fresh water reaches Martinez for a much shorter period of time, about less than one month in recent years compared to four and five months during 1916 and 1911, respectively.

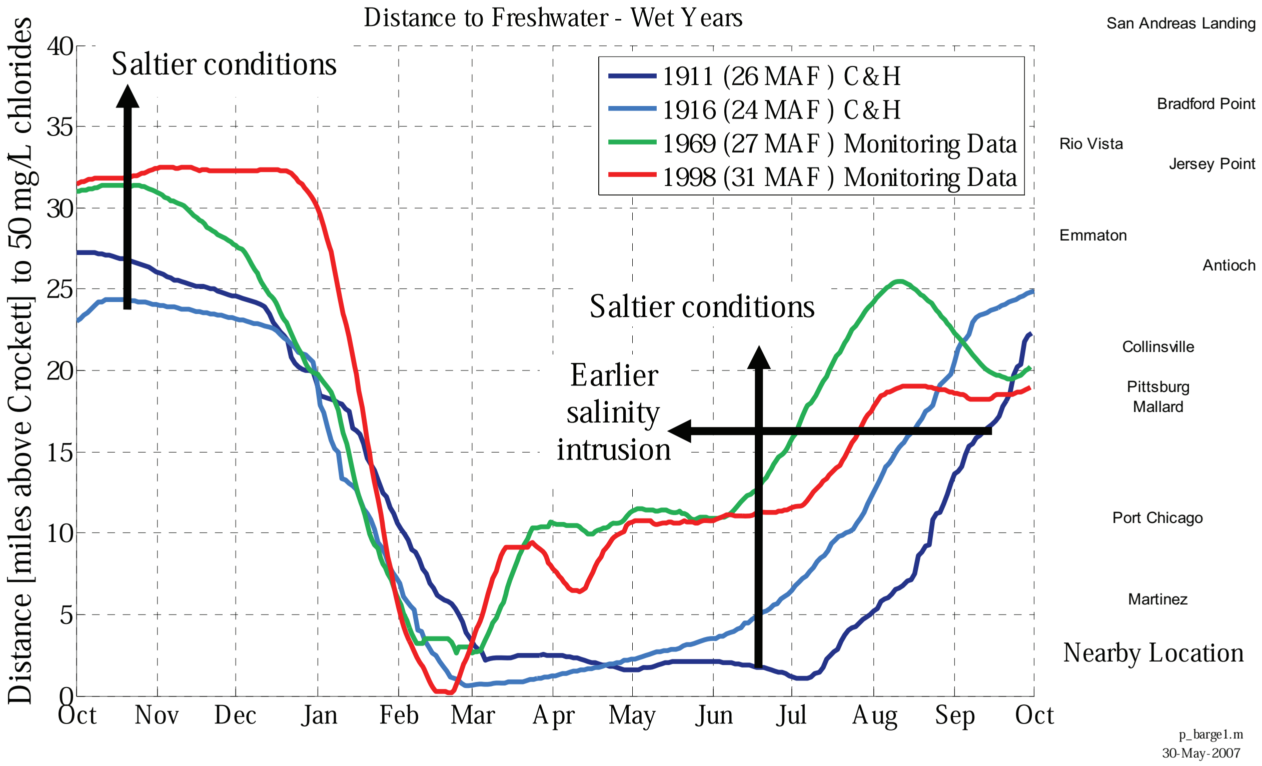
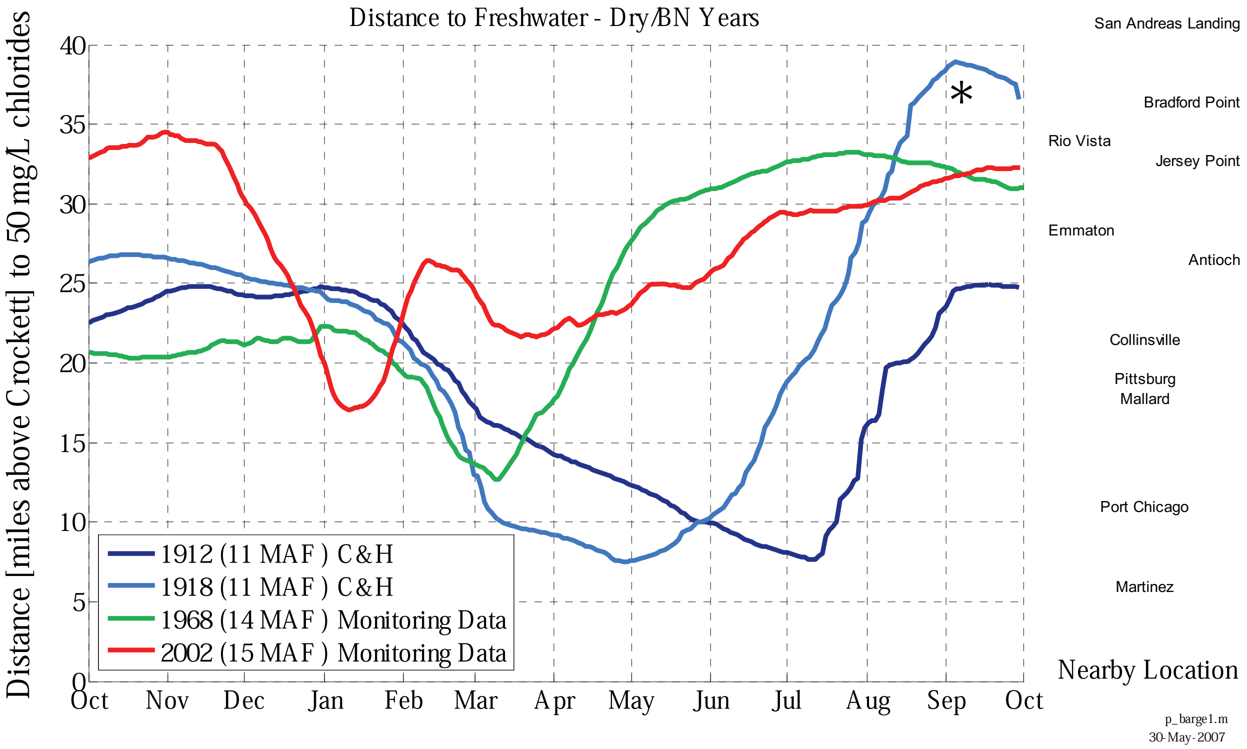


Figure D-7 – Distance to Fresh Water in Select Wet Years

Selected Dry Years

Figure D-8 shows that the most visible difference between the distance to fresh water in dry years of the early 1900's and more recent dry years is the substantial increase in distance to fresh water, particularly from April through June. This indicates the spring was much fresher during the dry years of the early 1900's, before large upstream reservoirs were built to capture the spring runoff. In dry and below-normal water years under today's conditions, barges would have to travel farther during spring, summer and fall than they traveled in the early 20th Century.

The C&H barge travel distance in the dry years of 1913 and 1918 are quite different, especially the additional 10 miles of distance to fresh water traveled in August and September of 1918. C&H recorded relatively high salinity (greater than 110 mg/L chlorides) above Bradford Point on the San Joaquin in 1918, which is greater than observed salinity on the Sacramento River near Rio Vista in similar water years. This may be partially explained by the development of the rice cultivation industry around 1912 (DPW, 1931) and increased upstream diversions when seasonal river flows were already low.



* During August and September 1918, average water quality obtained by C&H exceeded 110 mg/L chlorides

Figure D-8 – Distance to Fresh water in Select Dry or Below Normal Years

Figure D-9 shows the exceedance probabilities for distance traveled up the Sacramento River for different salinity levels. During 1908-1917, on a monthly-averaged basis, C&H barges had to travel above the confluence of the Sacramento and San Joaquin Rivers (approximately 22 miles above Crockett) about 26% of this time period to reach water with salinity less than

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350 µS/cm EC (about 50 mg/L chlorides). In contrast, from 1995-2006, DSM2 simulations suggest that barges would have to travel above the confluence approximately 56% of the time to reach water with salinity of 350 µS/cm EC.

The location of the 50 mg/L chloride isohaline during 1908-1917 approximately corresponds to the location of X2 (2,640 µS/cm EC, or 700 mg/L chlorides) during 1995-2006 (Figure D-9). This is equivalent to more than a 7-fold increase in salinity from the early 1900's to the present day.

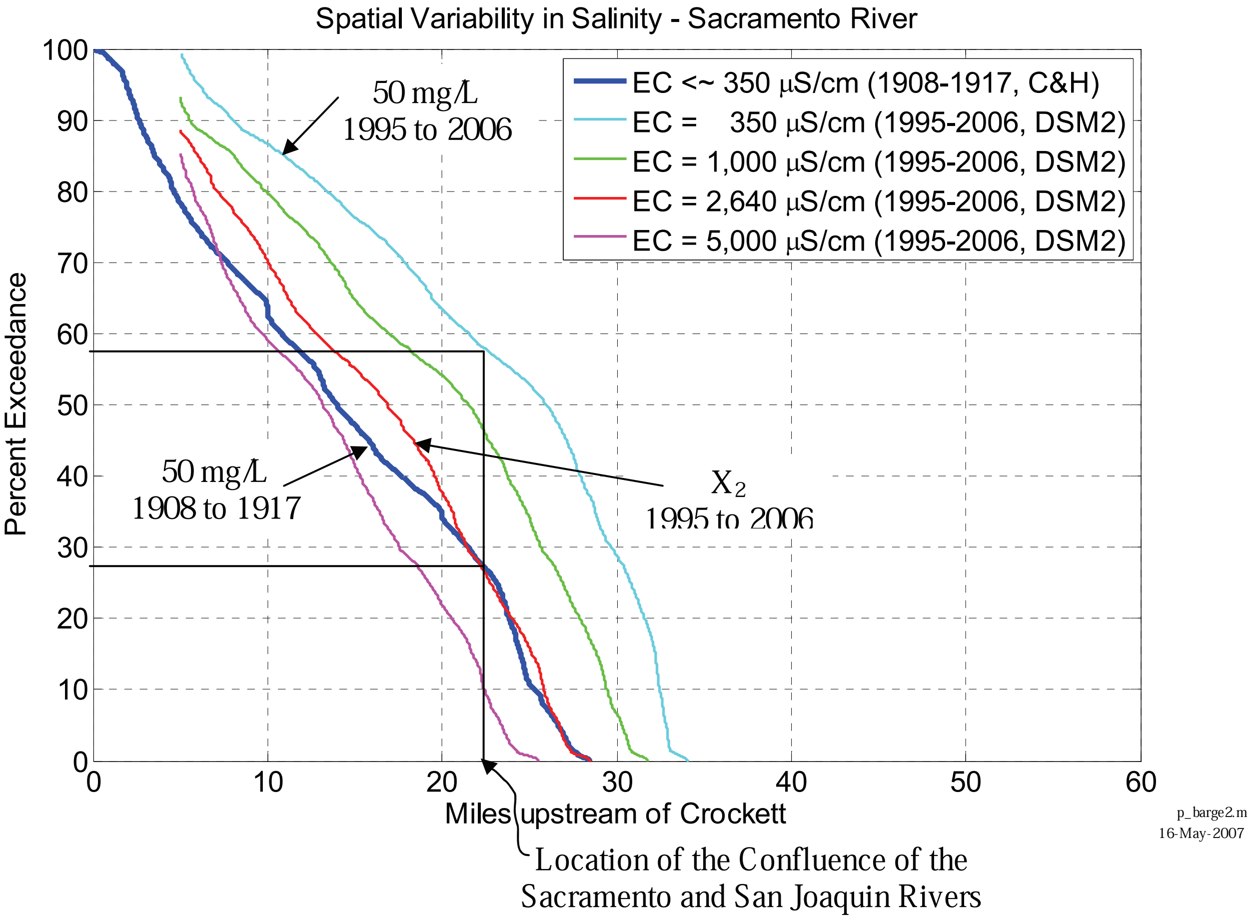

Figure D-9 – Distance along the Sacramento River to Specific Salinity Values

D.2.2. Maximum Annual Salinity Intrusion Before and After Large-scale Reservoir Construction

Figure D-10 shows maximum salinity intrusion during 1921-1943 (pre-CVP period), prior to the completion of the Shasta Dam of the Central Valley Project in 1945. Salinity intrusion is presented in terms of contours of 1,000 mg/L chlorides. Figure D-11 shows the maximum salinity intrusion during the post-CVP period of 1944-1990. These figures indicate the pre-CVP period experienced greater salinity intrusion than the post-CVP period, with seawater intruding farther into the Delta during 6 of the 24 pre-CVP years (1920, 1924, 1926, 1931, 1934, and 1939) than in any of the 47 years in the post-CVP period (1944-1990).

The extreme salinity intrusion during the pre-CVP period was due, in part, to relatively low runoff during these years. Meko *et al.* (2001a) determined that the period from 1917 through 1936 was the driest 20-year period in the past 400 years; this long-term drought encompassed 16 of the 24 years in the pre-CVP period. In addition, estimates of unimpaired runoff from the Sacramento River (obtained from http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST) indicate that the Sacramento River had 6 critical water years during the 24-year period of 1920-1943, whereas, the Sacramento River had only 4 critical water years during the 47-year period of 1944-1990.

Figure D-12 shows that the peak salinity intrusion during the pre-CVP period occurred between mid-August and mid-September, while peak salinity intrusion during the first portion of the the post-CVP period (1944-1960) occurred between late-July and late-August. Salinity intrusion during the pre-CVP period was not only affected by relatively low runoff, but also by extensive upstream diversions (DPW, 1931).

The salinity investigations of the pre-CVP era found that the extreme salinity intrusion was larger than any previous intrusions known to local residents and concluded the intrusion was due, in part, to the extensive upstream diversions. As observed in DPW (1931):

> "Under conditions of natural stream flow before upstream irrigation and storage developments occurred, the extent of saline invasion and the degree of salinity reached was much smaller than during the last ten to fifteen years." (DPW, 1931, page 15)
>
> "Beginning in 1917, there has been an almost unbroken succession of subnormal years of precipitation and stream flow which, in combination with increased irrigation and storage diversions from the upper Sacramento and San Joaquin River systems, has resulted in a degree and extent of saline invasion greater than has occurred ever before as far as known." (DPW, 1931, page 15)
>
> "The abnormal degree and extent of saline invasion into the delta during recent years since 1917 have been due chiefly to: first, subnormal precipitation and run-off with a subnormal amount of stream flow naturally available to the delta, and second, increased upstream diversions

> for irrigation and storage on the Sacramento and San Joaquin River systems, reducing the inflow naturally available to the delta. It is probable that the degree of salinity in the lower channels of the delta and the extent of saline invasion above the confluence of the Sacramento and San Joaquin rivers have been about doubled by reason of the second factor." (DPW, 1931, page 42)

Conclusions from DPW (1931) and similar investigations have been corroborated by paleosalinty studies (see Section 2.3), which indicate that Browns Island in the western Delta was a freshwater marsh for approximately 2,500 years until salinity intruded in the early 20th Century.

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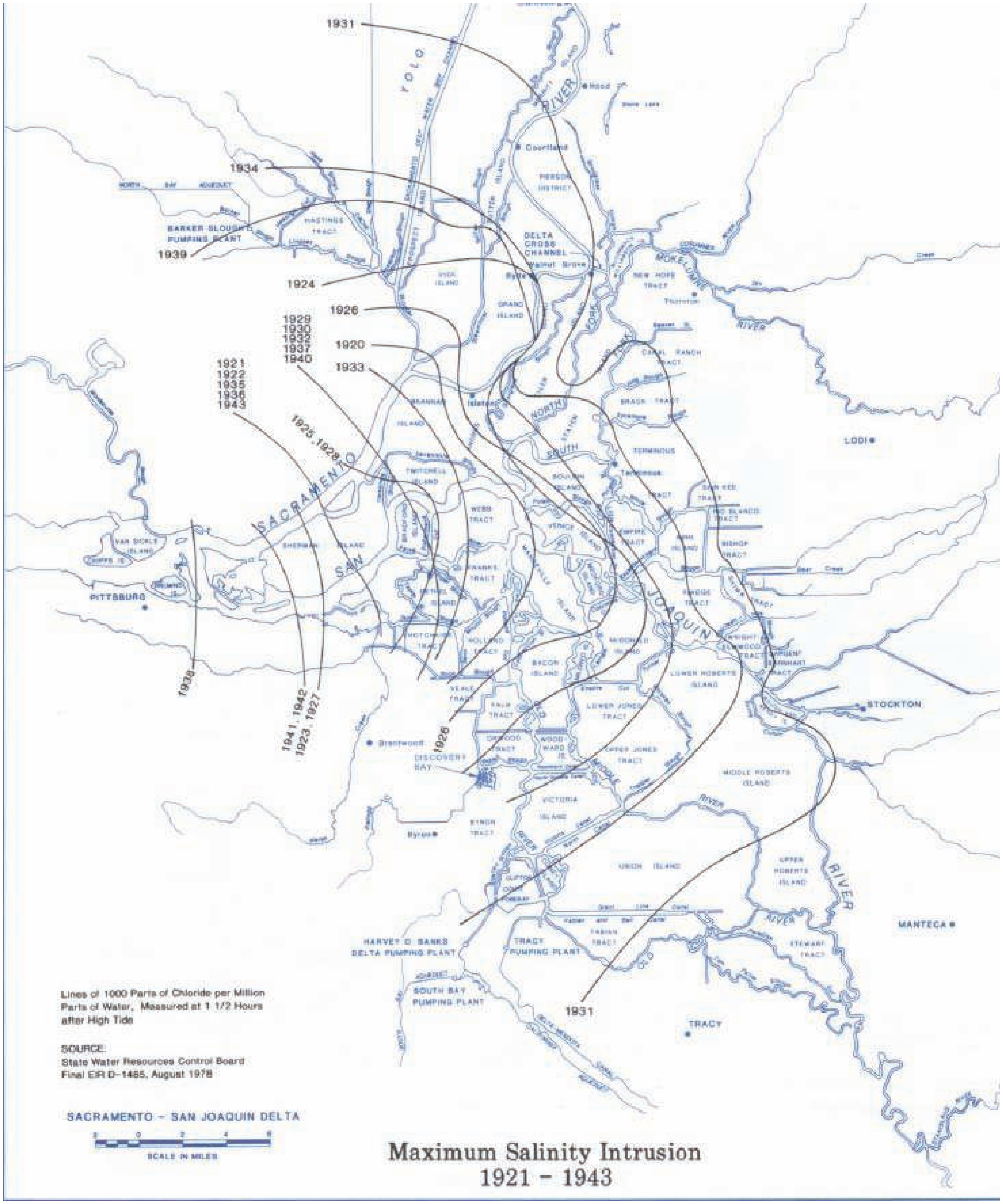
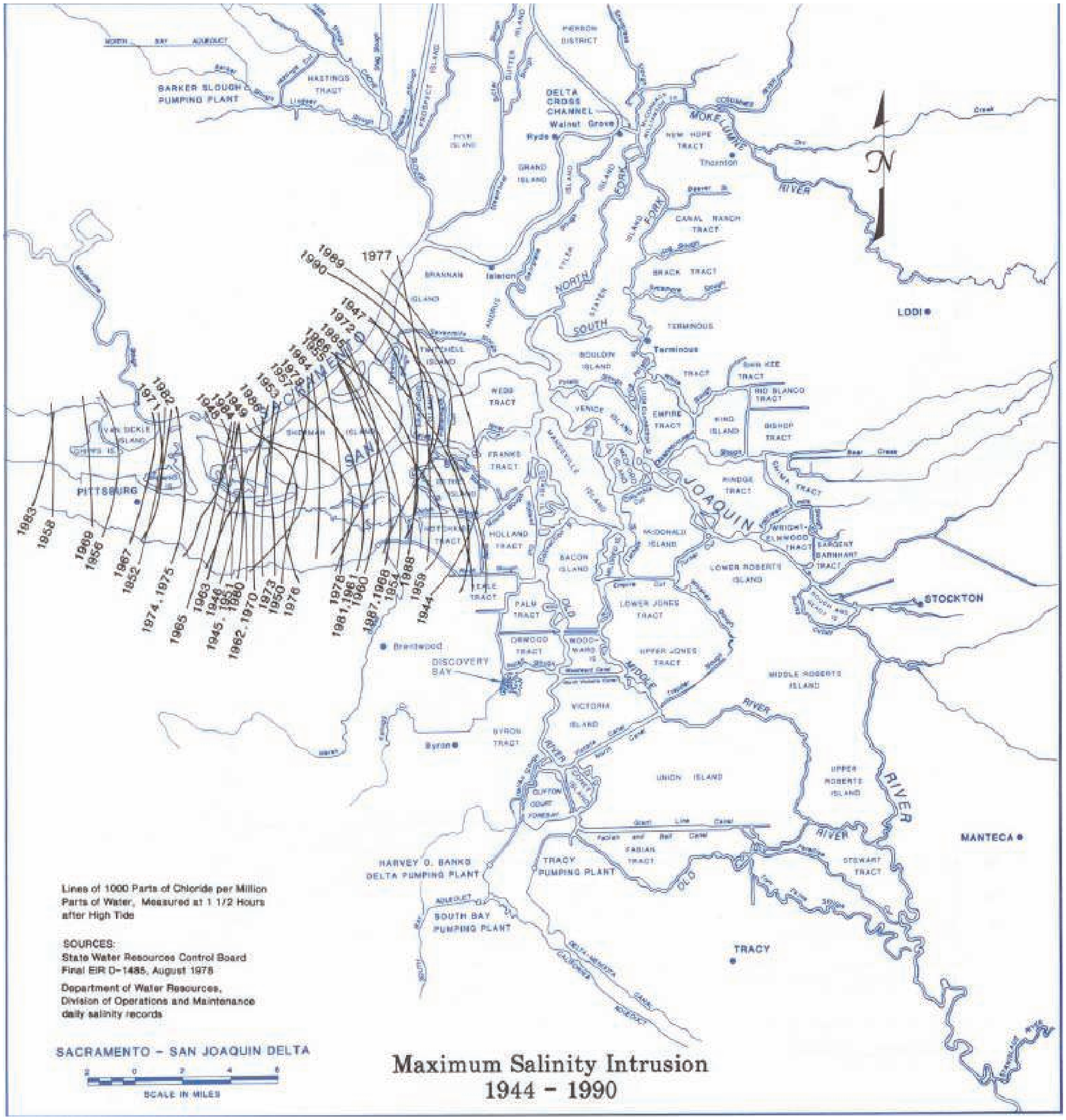


Figure D-10 – Salinity intrusion during pre-CVP period, 1921-1943 (DWR, 1995)



Lines of 1000 Parts of Chloride per Million Parts of Water, Measured at 1 1/2 Hours after High Tide

SOURCES:
State Water Resources Control Board
Final EIR D-1485, August 1978
Department of Water Resources,
Division of Operations and Maintenance
daily salinity records

SACRAMENTO – SAN JOAQUIN DELTA

2 0 2 4 6
SCALE IN MILES

Maximum Salinity Intrusion
1944 – 1990

Figure D-11 – Salinity intrusion during post-CVP period, 1944-1990 (DWR, 1995)

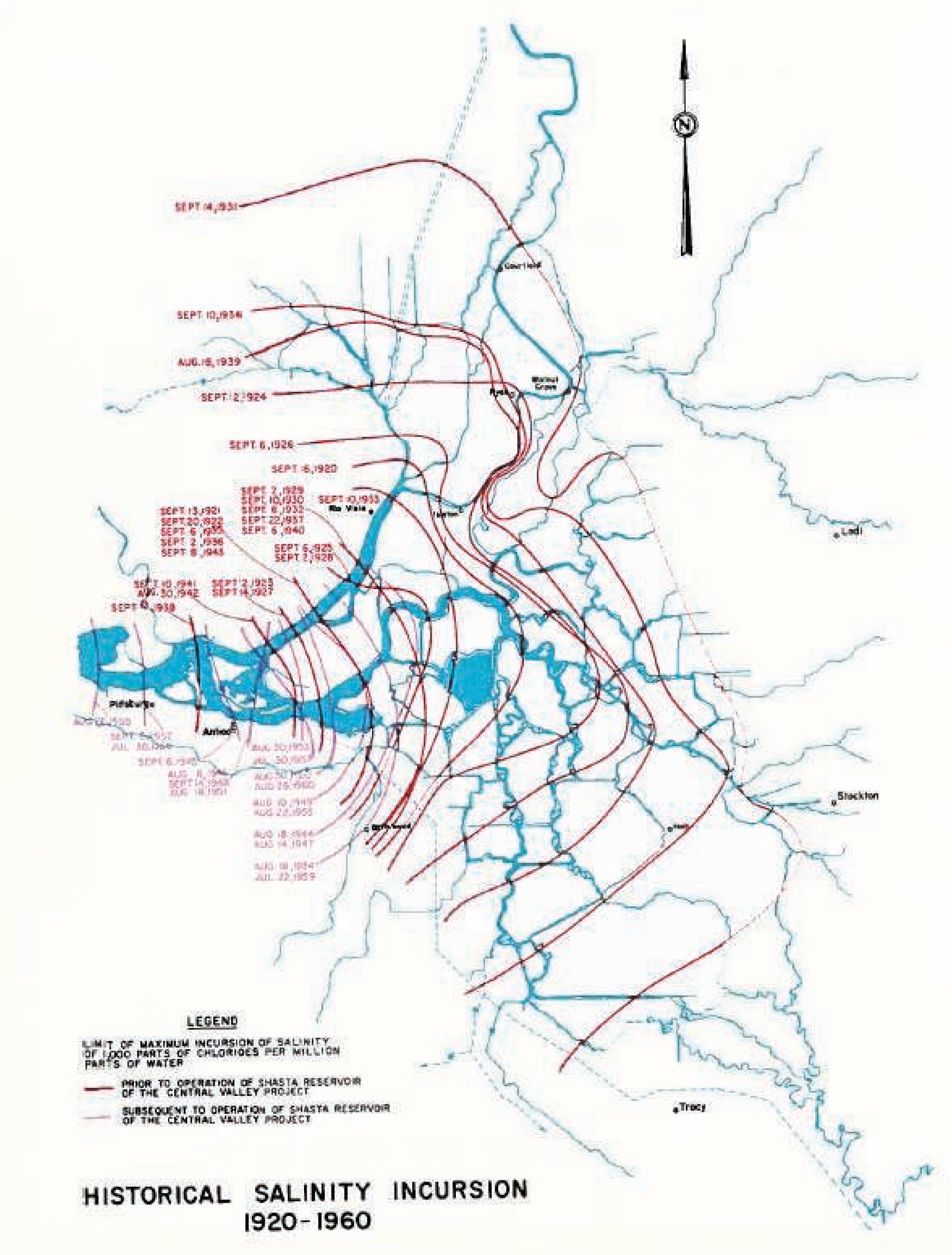
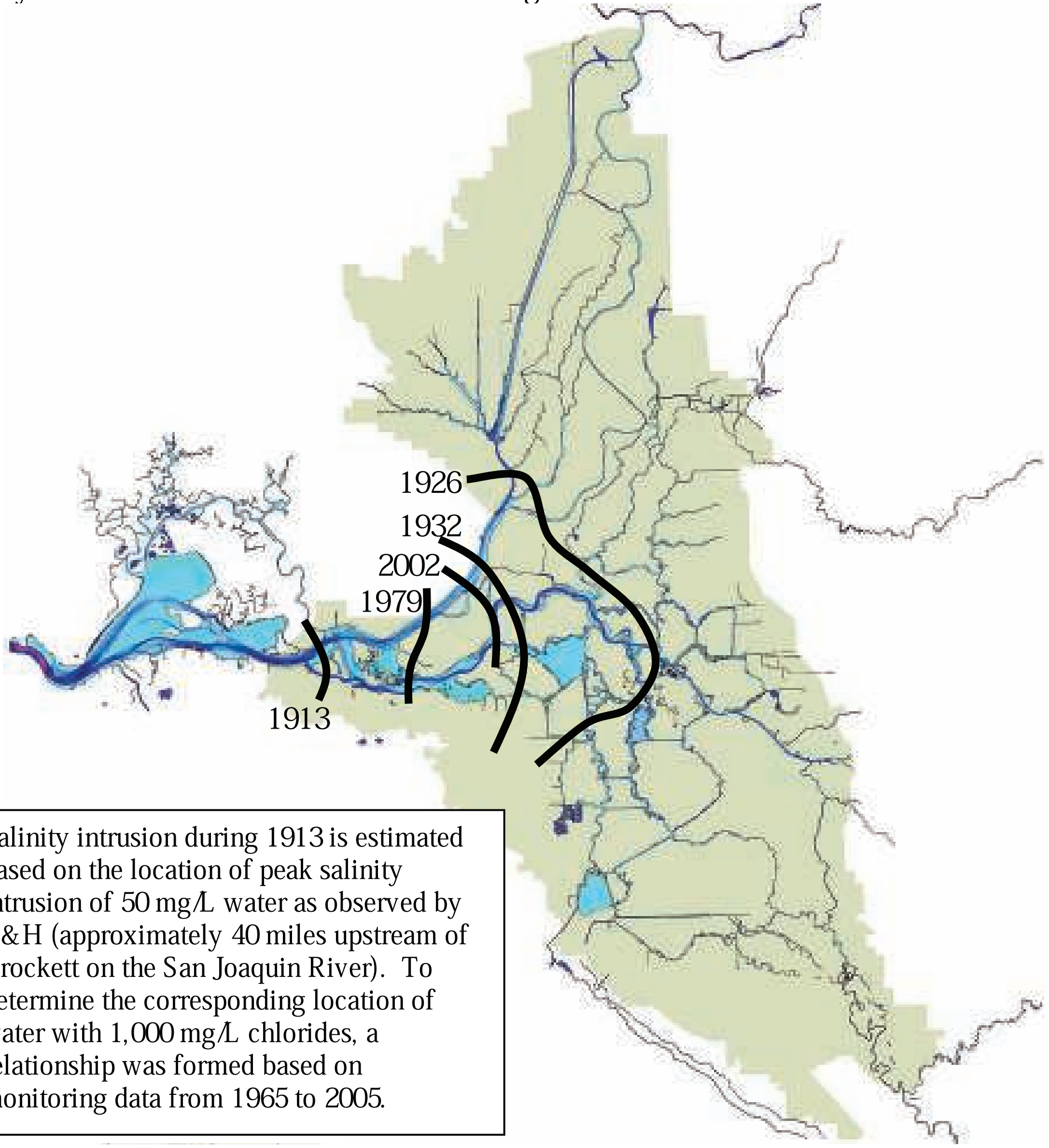


Figure D-12 – Salinity intrusion during 1920-1960 (DWR, 1960)

Figure D-13 illustrates the maximum annual salinity intrusion for comparable dry years[6]. Water year 1913 experienced the least extent of intrusion, most likely because upstream diversions were significantly less than in later years. Water years 1926 and 1932 were subject to extensive upstream agricultural diversions, while water years 1979 and 2002 had the benefit of the CVP and SWP to provide "salinity control". The CVP and SWP operations now regulate the amount of freshwater flowing through the Delta in order to prevent extreme salinity intrusions such as those observed during the 1920's and 1930's.



Salinity intrusion during 1913 is estimated based on the location of peak salinity intrusion of 50 mg/L water as observed by C&H (approximately 40 miles upstream of Crockett on the San Joaquin River). To determine the corresponding location of water with 1,000 mg/L chlorides, a relationship was formed based on monitoring data from 1965 to 2005.

Figure D-13 – Annual Maximum Salinity Intrusion for relatively dry years

Salinity intrusion for relatively dry water years with similar total annual unimpaired runoff, using 1,000 mg/L chloride concentration to distinguish the extent of intrusion.

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[6] Hydrological metrics from http://cdec.water.ca.gov/cgi-progs/iodir/wsihist for comparison: total unimpaired Sacramento River and San Joaquin River flow for water years 1913, 1926, 1932, 1979, and 2002 was 15.9 MAF, 15.3 MAF, 19.8 MAF, 18.4 MAF, and 18.7 MAF, respectively; Sacramento River water year type index for water years 1913, 1926, 1932, 1979, and 2002 was 6.24, 5.75, 5.48, 6.67, and 6.35, respectively; and San Joaquin River water year type index for water years 1913, 1979, and 2002 was 2.00, 2.30, 3.41, 3.67, and 2.34, respectively.

D.3. Temporal Variability of Salinity in the Western Delta

D.3.1. Seasonal Salinity at Collinsville

Collinsville, near the confluence of the Sacramento and San Joaquin Rivers, was one of the first long-term sampling locations implemented by the State of California. The Suisun Marsh Branch[7] of the DWR estimated monthly average salinity at Collinsville for the period 1920-2002, using a combination of 4-day TDS (total dissolved solids) grab samples from 1920-1971 and EC measurements from 1966-2002. Data from the overlap period of 5 years between the TDS grab samples and EC measurements were used in a statistical regression model, and the monthly averaged 4-day TDS samples were converted to monthly average EC (Enright, 2004). The result of this regression analysis was a time series of monthly EC values at Collinsville for the period of 1920-2002.

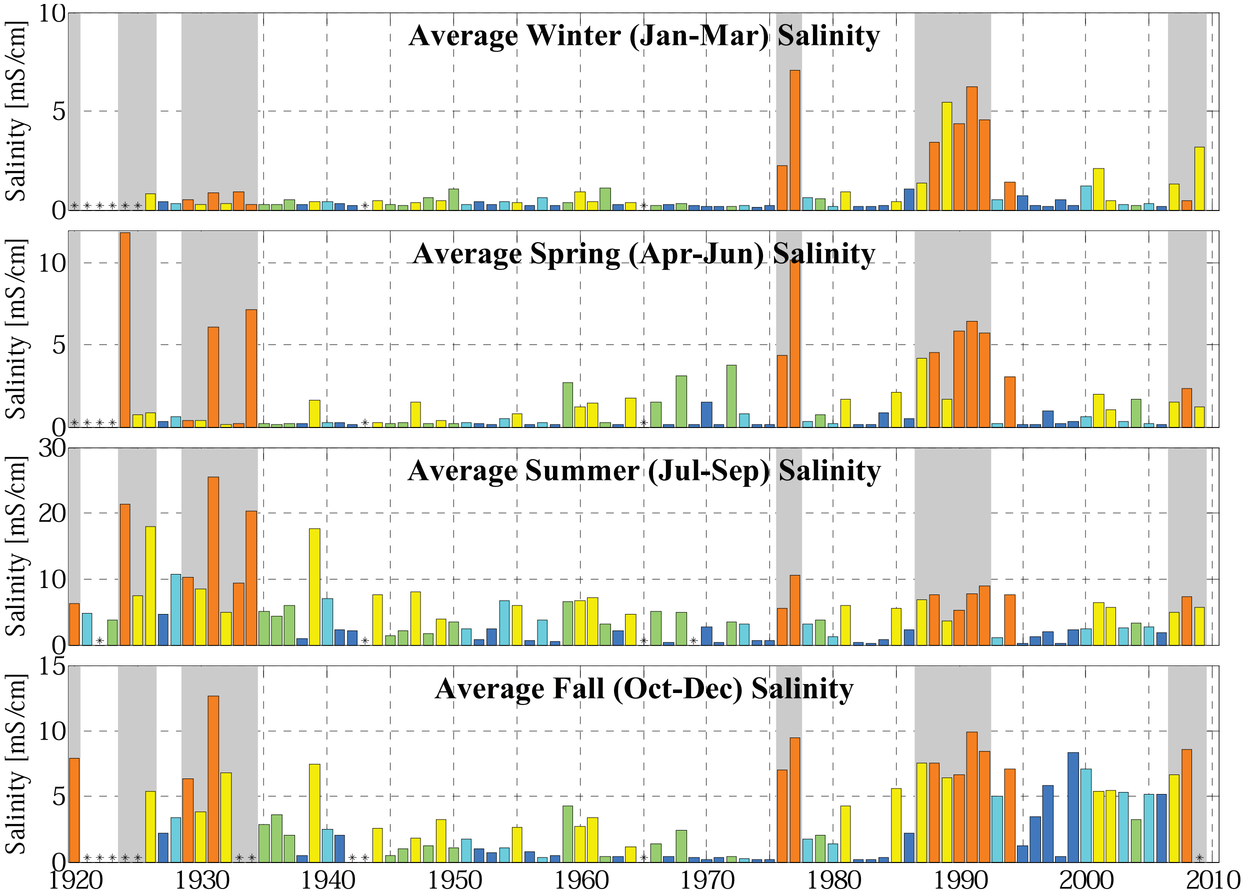

Figure D-14 – Average Seasonal Salinity at Collinsville

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[7] Data provided by Chris Enright (DWR), personal communication, 2007.

D.3.2. Effects of Water Management on Salinity at Collinsville

In order to compare the effects of water management on salinity at Collinsville, an empirical model of salinity transport (Denton (1993), Denton and Sullivan (1993)) was used in the following analyses. Contra Costa Water District's salinity-outflow model (also known as the G-model) estimates salinity in the western Delta as a function of NDO. Estimates of salinity at Collinsville were derived for both actual historical flow (1930-2008) and unimpaired flow (1922-2003) conditions.

Figure D-15 shows the estimated monthly-averaged salinity at Collinsville under unimpaired and actual historical flow conditions. The predicted seasonal and annual variations of EC at Collinsville are dependent on corresponding variations of NDO under both unimpaired and actual flow conditions. Water management practices have a significant effect on the seasonal variability of salinity at Collinsville, particularly during dry years (1930's, 1976-1977 and 1987-1993), when Collinsville experiences a much greater range of monthly-averaged salinity under actual historical conditions than would be the case under unimpaired conditions.

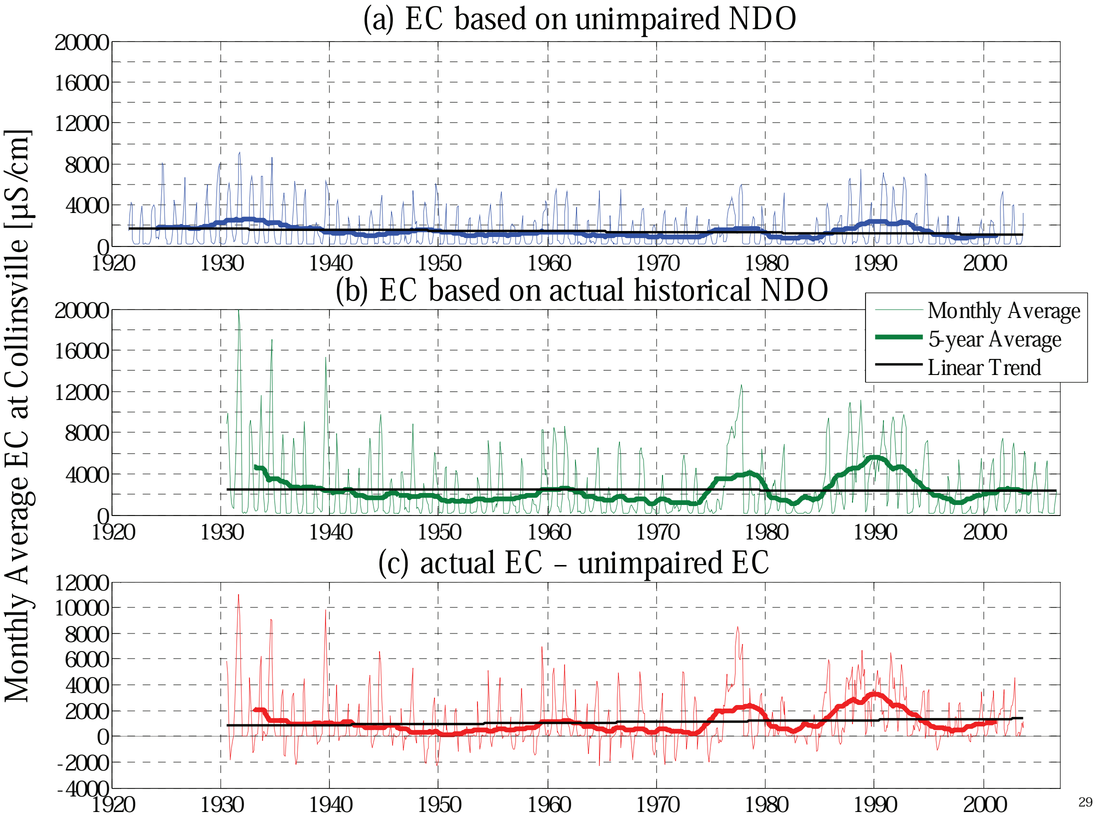

Figure D-15 – Estimates of Collinsville salinity using the G-model for unimpaired and actual historical flow conditions

Historical (actual) NDO during the 1930's was relatively low, sometimes averaging about -3,000 cfs for several months under actual conditions. The low values of NDO result in the high variability of estimated salinity in the 1930's under actual historical conditions.

The effects of water management on salinity at Collinsville are highlighted in Figure D-16, which shows the estimated salinity under actual historical conditions as a percent change from the unimpaired conditions. The data in Figure D-16 are the change in G-model estimates of salinity at Collinsville for the period of 1956-2003, computed as the difference between actual and unimpaired salinity as a percent change from the unimpaired salinity. Positive values indicate an increase in salinity under actual conditions and negative values indicate a decrease in salinity (freshening).

From April through August, estimated median salinity under actual historical conditions is substantially greater (more than a 100% increase) than median salinity under unimpaired conditions (Figure D-16). For the remainder of the year, there are no substantial differences between the estimates of median salinity under unimpaired and actual conditions. These distributions of estimated salinity indicate that water management practices result in significant increase in salinity throughout the year at Collinsville.

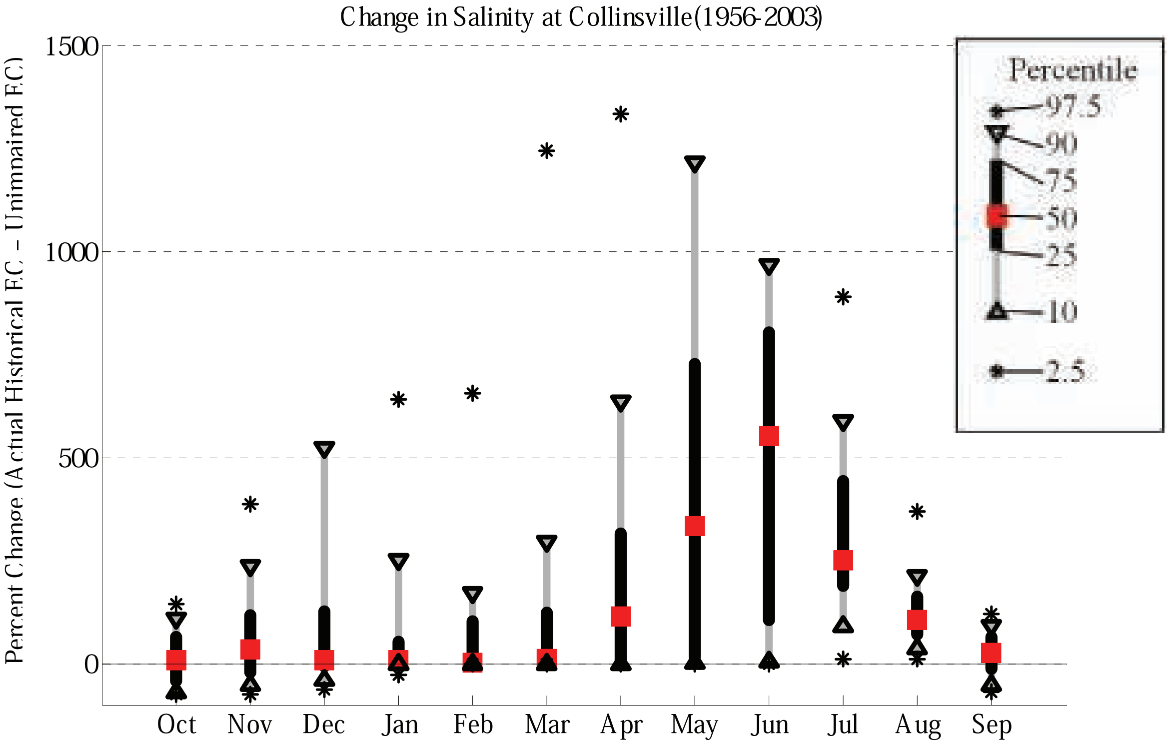

Figure D-16 – Estimated change in salinity at Collinsville under actual historical conditions, as a percent change from unimpaired conditions, 1956-2003

Figure D-17 shows the estimated salinities at Collinsville under actual historical and unimpaired conditions for just the more recent years (1994-2003). Positive values again indicate an increase in salinity under actual conditions and negative values indicate a decrease in salinity. The effects of water management on fall salinity are greater during this recent period 1994-2003 than during the longer period (1956-2003), but the effects during the recent period in the spring and early summer are smaller. This response reflects implementation of the X2 regulatory requirements agreed upon in the 1994 Bay-Delta Accord and regulated by the subsequent 1995 Water Quality Control Plan.

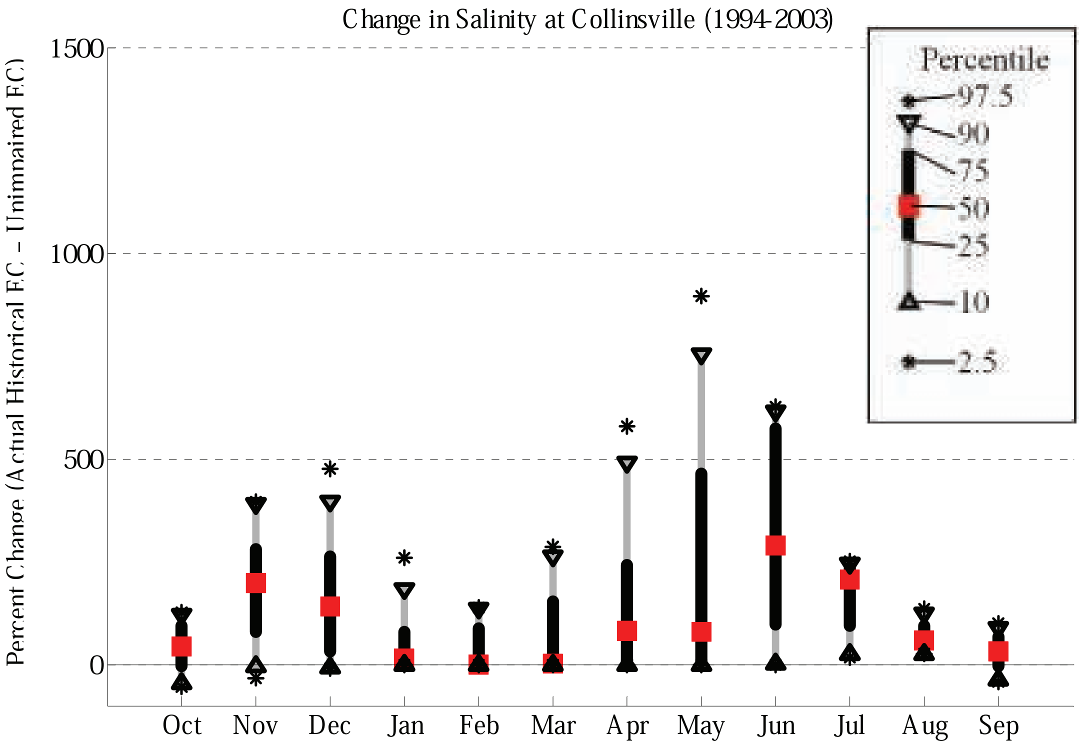

Figure D-17 – Estimated change in salinity at Collinsville under actual historical conditions, as a percent change from unimpaired conditions, 1994-2003

D.3.3. Fall Salinity in the Western Delta

Figure D-18 shows the average fall salinity (October-December) at three stations in Suisun Bay and the western Delta (Chipps Island, Collinsville, and Jersey Point). The fall salinity data categorized according to the pre-Endangered Species Act (ESA) period of 1964-1992 and the post-ESA period (1993-2006)[8]. Figure D-18 illustrates that there has been a noticeable increase in fall salinity since the release of the ESA biological opinions for winter-run salmon and Delta smelt in 1993. These increases occur during normal water years, when total annual runoff ranges from 15 to 30 MAF. During very wet years, there are large Delta outflows and the ESA limits do not affect water operations. Similarly, during very dry years, the biological opinions do not have a large effect on water operations because upstream reservoir storage is low and exports from the south Delta are already small.

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[8] In 1993, delta smelt and winter-run salmon were listed under the California ESA, triggering new water management regulations.

Antioch-216

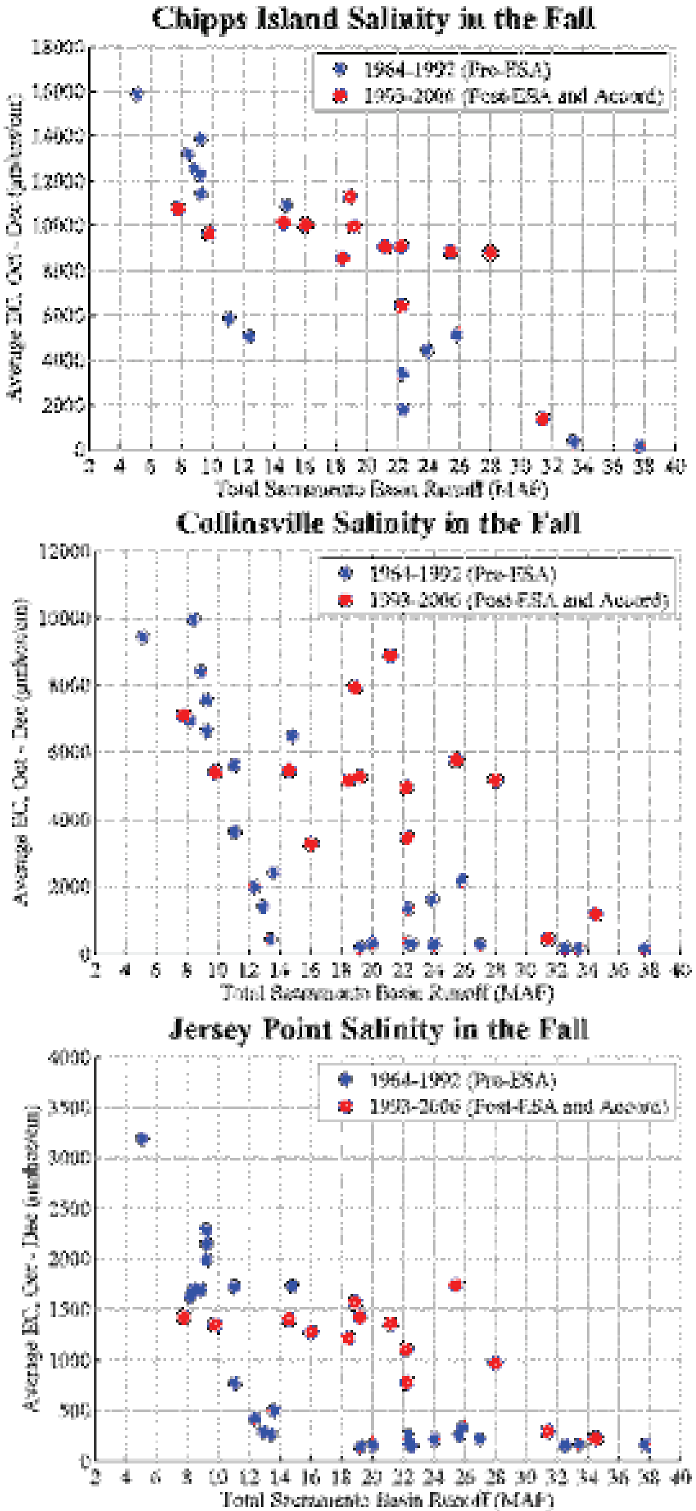

Figure D-18 – Post-ESA salinity in the Suisun Bay and western Delta

Figure D-19 shows the observed salinity at Chipps Island during the fall (October-December) for the period of 1976-1992 (pre-ESA) and 1993-2005 (post-ESA). Fall salinity at Chipps

Island during normal years is now comparable to fall salinity during dry and critical years prior to 1994.

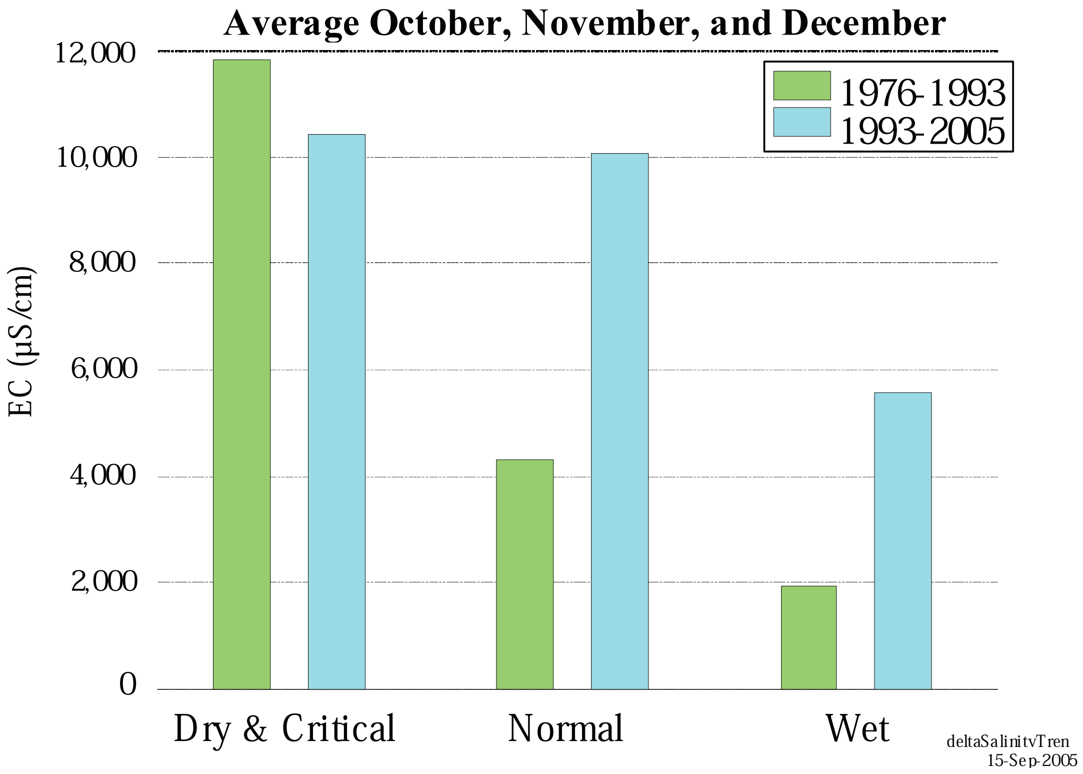

Figure D-19 – Increase in Fall Salinity at Chipps Island

D.4. General conceptual overview of salinity changes

Observed changes in seasonal salinity with time

The salinity regime in the western Delta has changed as the level of development has increased and water project operations have changed due to regulatory requirements. The comparison of three decades with similar hydrology in Figure D-20 presents a conceptual illustration of the changing salinity regime in Suisun Bay and the western Delta.

Monthly-averaged salinity in the spring and summer was substantially greater from 1966 through 1975 than during the early 1900's. However, fall and early winter salinity was lower than the early 1900's. This reduction in salinity in the fall and early winter was likely due in part to CVP and SWP reservoir releases for flood control purposes in the fall, which freshened the Delta. Flood control releases during this period were large because CVP and SWP diversions and exports were not fully developed and upstream reservoirs were often above flood control maximum storage levels in the fall, entering the wet season.

Salinity during 1995 through 2004, however, exceeded the salinities in the early 1900's during all months, for years with similar hydrologic conditions. The dramatic increase in fall salinity relative to observed levels from 1966 to 1975 is accompanied by a slight decrease in spring and summer salinity. This is likely due to minimum flow and X2 requirements imposed by the State Water Resources Board in 1995. However, spring and summer salinities remain much greater relative to salinity in the early 1900's.

The range of seasonal variability during 1966-1975 was greatly reduced because the Delta did not get as fresh as it did in the early 1900's. During the last decade, seasonal variability has increased such that the range of salinity observed in the Delta over the course of a year is similar to that in the early 1900's. However, salinity intrusion has moved inland relative to the early 1900's, resulting in saltier conditions in the Suisun Bay and western Delta and a reduction in the period when fresher water is available.

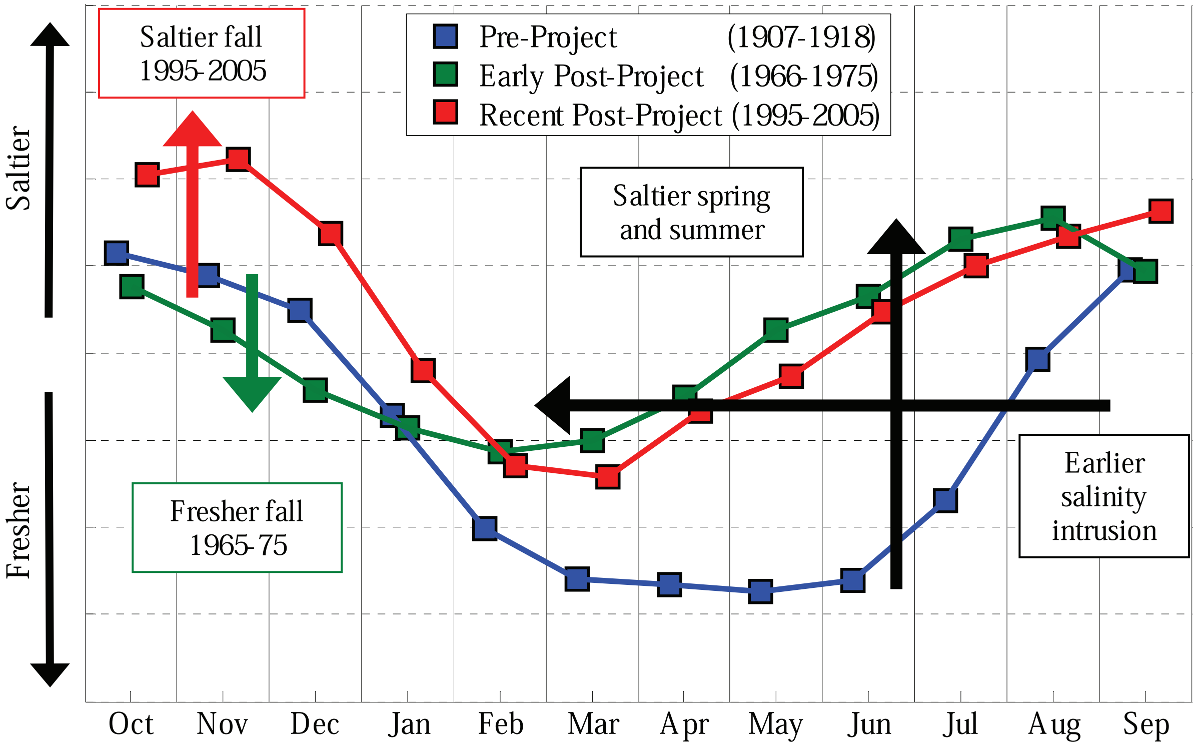

Figure D-20 – Conceptual plot of seasonal variability of salinity in Suisun Bay and the western Delta during different water management eras

The effect of water management for wet and dry years

Water management has the largest effect during dry years when the Delta stays relatively salty throughout the year with limited seasonal variability compared to unimpaired conditions. As shown conceptually in Figure D-21, during wet years the Delta freshens as much as it would under unimpaired conditions, but the Delta does not stay fresh for as long.

Antioch-216

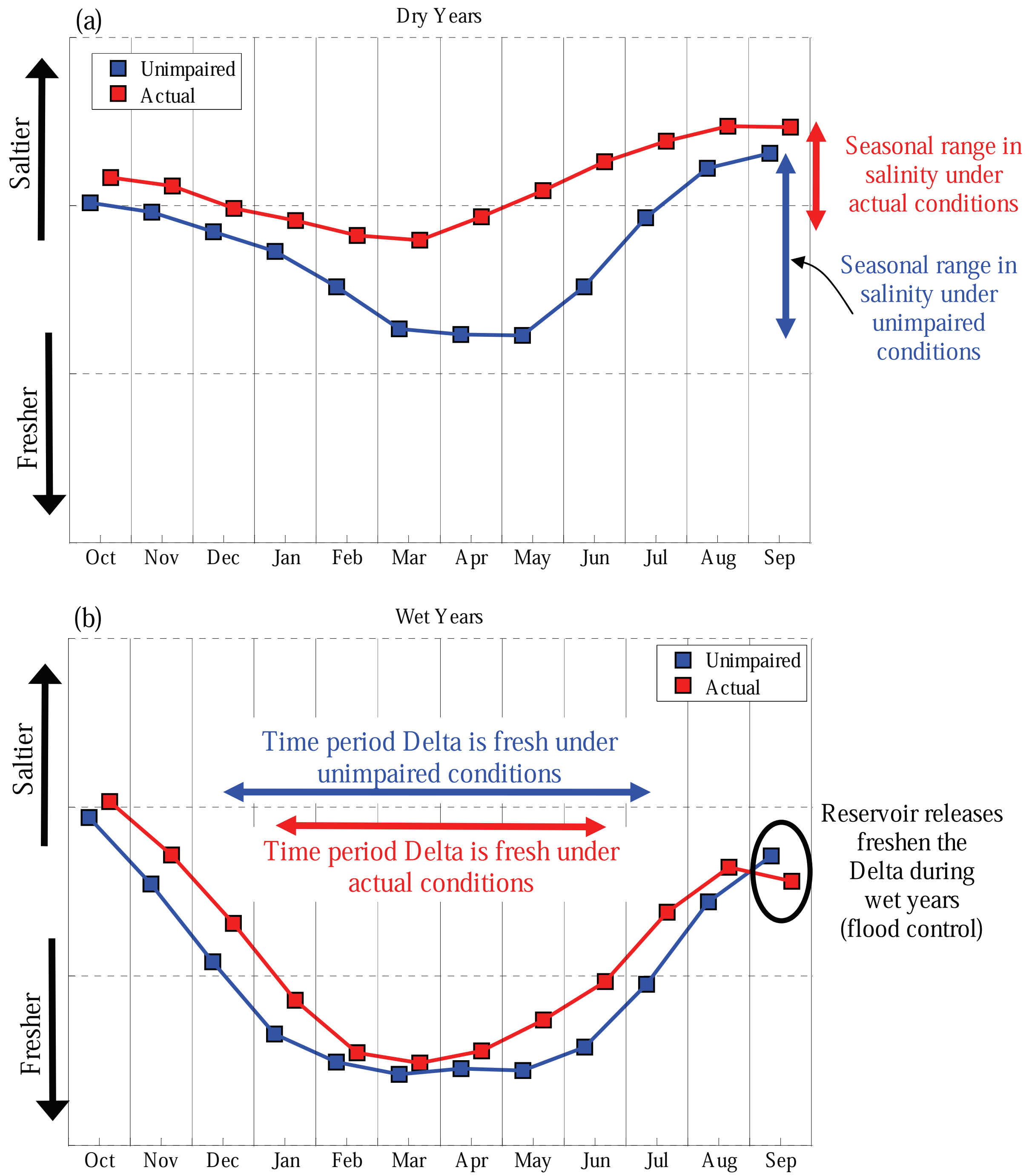

Figure D-21 – Conceptual plot of seasonal salinity variations in the Delta under actual historical conditions compared to unimpaired conditions in (a) dry years and (b) wet years

Appendix E. Qualitative Salinity Observations

The earliest written accounts of explorers were often concerned with adequate drinking water, and salinity was generally described in qualitative terms, such as "brackish," "fresh," or "sweet." For the purposes of comparing the present-day water quality with the historical conditions, these qualitative observations need to be quantified.

Testimony from Antioch Case (Town of Antioch v. Williams Irrigation District, 188 Cal. 451) indicated early settlers required water with less than 100 mg/L of chloride (approximately 525 μS/cm EC) for municipal use.[9] Similarly, DPW (1931) indicated that a "noticeable" level of salinity was 100 mg/L chloride. The current secondary water quality standard for municipal and industrial use is 250 mg/L chloride (1,000 μS/cm EC) (SWRCB 2006; US EPA 2003). This report assumes a value of 250 mg/L chloride (equivalent to 1000 μS/cm EC) to be the demarcation between "fresh" (or "sweet") water and "brackish" water.

E.1. Observations from Early Explorers

Table E-1 summarizes some reported observations of water quality made by early explorers and settlers. These observations were qualitative and were most likely only a glimpse of the ambient conditions and may not completely represent true historical water quality conditions. Moreover, these observations were from a time period when anthropogenic effects on this region were minimal and this region was close to natural conditions.

Table E-1 also lists the reconstructed Sacramento River annual flow (MAF) from Meko *et al.* (2001b) for the year of observation and for the previous year. For reference, the average Sacramento River flow from Meko *et al.* (2001b) for the period 1860-1977 is 18 MAF/yr.

Table E-1 – Qualitative salinity observations from early explorers

Date	Location	Description	Year / Reconstructed Flow [MAF]	Observer	Reference
1775 August	near the Sacramento-San Joaquin confluence	sweet, the same as in a lake	1774 / 25 1775 / 19	Canizares	Britton, 1987 in Fox, 1987b
1776 April	near Antioch (San Joaquin River)	very clear, fresh, sweet, and good	1775 / 19 1776 / 9	Font	Britton, 1987 in Fox, 1987b
1776 September	near the Sacramento-San Joaquin confluence	sweet	1775 / 19 1776 / 9	Canizares	Britton, 1987 in Fox, 1987b

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[9] Supplement to Respondent's Answering Brief, p. 10.

Date	Location	Description	Year / Reconstructed Flow [MAF]	Observer	Reference
1796	unknown	salinity "far upstream" at high tide	1795 / 6 1796 / 10	Hermengildo Sal	Cook, 1960 in TBI, 1998
1811 October	near the Sacramento-San Joaquin confluence	sweet	1810 / 19 1811 / 23	Abella	Britton, 1987 in Fox, 1987b
1841 August	Three Mile Slough north of Emmaton	brackish (undrinkable)	1840 / 16 1841 / 6	Wilkes	Britton, 1987 in Fox 1987b

E.1.1. Fresh Conditions

Table E-1 indicates that some early explorers observed "sweet" water near the confluence of the Sacramento and San Joaquin Rivers both in relatively wet years (August of 1775 and October of 1811, reconstructed runoff about 19 MAF/yr) and in relatively dry years (September of 1776, reconstructed runoff about 9 MAF/yr). Except as noted, it is unknown whether these observations were made at high tide or low tide.

In order to provide a context for these anecdotal observations, present-day observed monthly salinity (EC) conditions at Collinsville (located near the confluence of Sacramento and San Joaquin Rivers) are plotted against unimpaired annual Sacramento River flow in Figure E-1. The observed data are monthly-averaged salinity (μS/cm) during August-October for the period 1965-2005. The data for the post-ESA years (1994-2005) are shown as shaded circles. Note that the anecdotal observations in Table E-1 are likely "one-time" observations, while those shown in Figure E-1 are average monthly values.

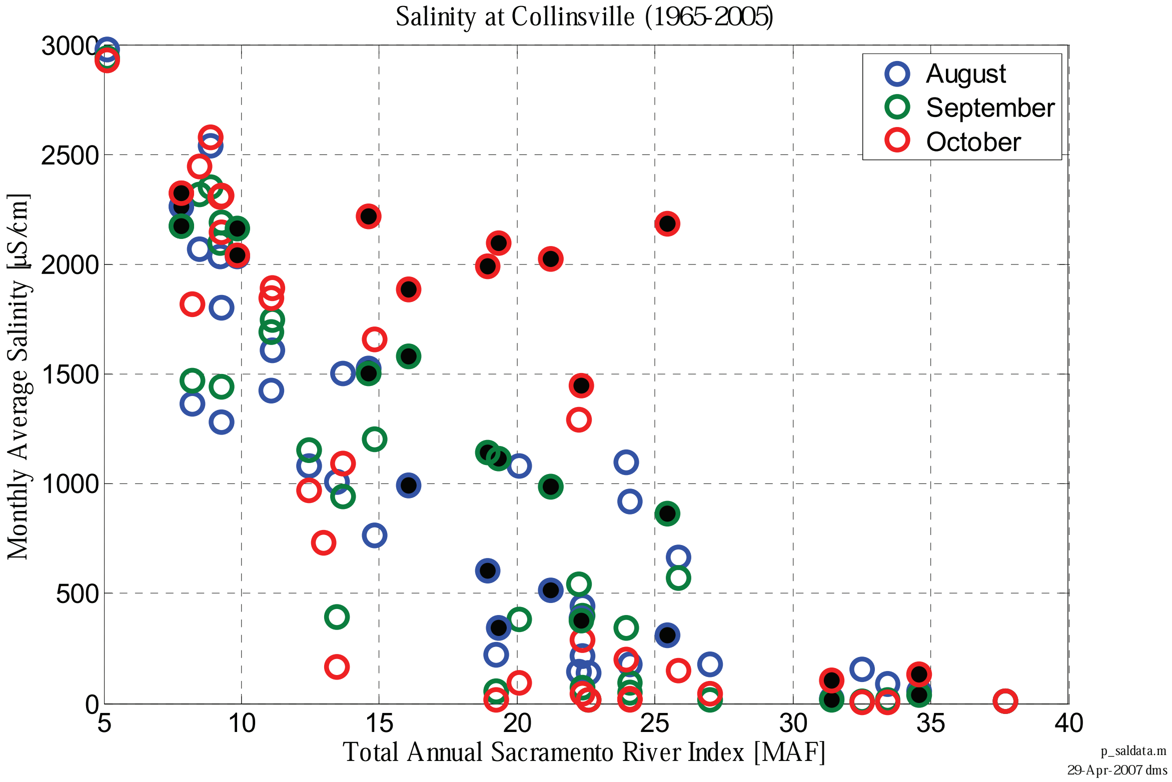

Figure E-1 – Observed salinity at Collinsville, 1965-2005

Under current management conditions, the monthly average salinity at Collinsville from August through October is only less than 1,000 µS/cm EC (the interpretation of the "sweet" threshold for drinking water) when the unimpaired runoff is greater than about 20 to 25 MAF/yr (Figure E-1). This suggests either the "sweet" threshold used in this report is too small, or salinity at Collinsville is higher today than it was in the late 18th and early 19th centuries.

If the definition of the "sweet" threshold is changed to 1,300 µS/cm EC and the post-ESA years (1994-2005) are excluded, then the monthly-averaged salinity at Collinsville during August-October is "fresh" (less than 1,300 µS/cm EC) when runoff is greater than 16 MAF/yr. This corresponds better to the anecdotal observations, discussed above, but suggests a recent increase in salinity at Collinsville during moderately wet years (with runoff between 14 and 26 MAF/yr). In 5 of the 12 post-ESA years (1997, 1999, 2000, 2003 and 2004), the water at Collinsville in October would not be considered "sweet" even under the relaxed criterion of 1,300 µS/cm EC, suggesting that October salinity under present conditions could be greater than it was in 1811.

E.1.2. Brackish Conditions

The qualitative observations of high salinity intrusion in Table E-1 are less specific about location. However, some of these observations have been interpreted by others (Cook, 1960, in TBI, 1998; Fox, 1987b) to indicate intrusion as far upstream as Rio Vista. The drought periods of 1976-1977 and 1987-1992 are similar to these periods when these qualitative observations were made. During 1976-1977, daily average salinity at Rio Vista exceeded 1,000 μS/cm for approximately six months of the year. During 1987-1992, salinity at Rio Vista at high tide often exceeded 2,000 μS/cm, particularly during the fall. This is consistent with the anecdotal observations made in 1796 and 1841, which report salt water extending into the western Delta.

Summary: Interpretation of the above observations in the context of the reconstructed Sacramento River flows shows that the Delta is generally saltier than the historical levels for equivalent runoff conditions and does not support the hypothesis that the present-day Delta is managed as a freshwater system in comparison with its historical salinity regime. Moreover, this analysis indicates that salinity in the western Delta has increased during September and October in the recent years (post-1994 period).

E.2. Observations from early settlers in the Western Delta

Observations from early settlers in the western Delta provide a more complete description of salinity in the late 1800's and early 1900's than the observations from early explorers discussed earlier. Assuming the early settlers inhabited a particular region for longer time periods than the early explorers, observations from the early settlers capture the temporal variability better than those from the early explorers.

E.2.1. Town of Antioch Injunction on Upstream Diverters

In 1920, the Town of Antioch filed a lawsuit against upstream irrigation districts alleging that the upstream diversions were causing increased salinity intrusion at Antioch. The court decision, legal briefings, and petitions provide salinity observations from a variety of witnesses. Although anecdotal testimony summarized in these legal briefs is far from scientific evidence, it provides a perspective of the salinity conditions prevailing in the early 1900's. Because the proceedings were adversarial in nature, this report focuses on the testimony of the upstream interests, who were trying to demonstrate that salinity intrusion was common near Antioch prior to their diverting water (prior to 1920). Consequently, the testimony may be biased in support of this "more saline" argument. Nonetheless, these anecdotal testimonies indicate that the western Delta was less salty in the past than it is today. Analyses of some of the testimonies are presented below.

Case History

On July 2, 1920, the Town of Antioch filed suit in the Superior Court of the State of California (hereinafter referred to as the "Antioch Case") against upstream diverters on the Sacramento River and Yuba River. A hearing for a temporary injunction began on July 26, 1920, and lasted approximately three months. On January 7, 1921, Judge A. F. St. Sure granted a temporary injunction, restraining the defendants "from diverting so much water from the said Sacramento River and its tributaries, to non-riparian lands, that the amount of water flowing past the City of Sacramento, in the County of Sacramento, State of California, shall be less than 3500 cubic feet per second" (Town of Antioch v. Williams Irrigation District, Supplement to Appellants' Opening Brief, p. 13).

The defendants appealed to the Supreme Court of the State of California, which issued its opinion on March 23, 1922. The Supreme Court reversed the lower court and withdrew the injunction, declaring "[i]t is evident from all these considerations that to allow an appropriator of fresh water near the outlet of these two rivers to stop diversions above so as to maintain sufficient volume in the stream to hold the tide water below his place of diversion and secure him fresh water from the stream at that point, under the circumstances existing in this state, would be extremely unreasonable and unjust to the inhabitants of the valleys above and highly detrimental to the public interests besides."

The Supreme Court did not make any comment whatsoever on the evidence of salinity intrusion prior to the upstream diversions in question. The Court indicated that their decision was based on a "policy of our law, which undoubtedly favors in every possible manner the use of the waters of the streams for the purpose of irrigating the lands of the state to render them fertile and productive, and discourages and forbids every kind of unnecessary waste thereof." (Town of Antioch v. Williams Irrigation District (1922) 188 Cal. 451). The Court concluded that allowing 3,500 cubic feet per second (cfs) to "waste" into the Bay to provide less than 1 cfs of adequate quality water for the Town of Antioch would constitute unreasonable use of California's limited supply of water.

The court did not base their decision on historical salinity observations at Antioch, which indicate that Antioch was able to divert freshwater at low tide at all times from 1866 to 1918, except possibly for some fall months during some dry years (Section 3.1).

E.2.2. Salinity at Antioch – then and now

In the present day, the City of Antioch maintains a municipal water intake on the San Joaquin River at Antioch. As a general operating rule, the City of Antioch pumps water from the river when salinity at the intake is less than 1,000 µS/cm EC. Salinity varies substantially with the tide; generally the greatest salinity is observed near high tide and the lowest salinity is observed at low tide. Figure E-2 shows that salinity in the San Joaquin River at Antioch is highly variable and is dependent on tidal conditions and season. Figure E-2 indicates that for water year 2000 (an above-normal water year) the City of Antioch could pump water all day for about four and half months (early February through mid-June) and could pump for a portion of the day at low tide for another three and half months (mid-June through September). For the remaining four months (October-January), water at Antioch's intakes exceeded 1,000 µS/cm EC for the entire day, regardless of tidal phase.

Testimony from multiple witnesses in the Antioch Case indicates that fresh water was always available in the San Joaquin River at Antioch at low tide until just prior to 1920. Antioch's legal position was that fresh water was always available before upstream development. In cross-examination of Antioch's witnesses, the upstream irrigators demonstrated that brackish conditions did occasionally exist at high tide.

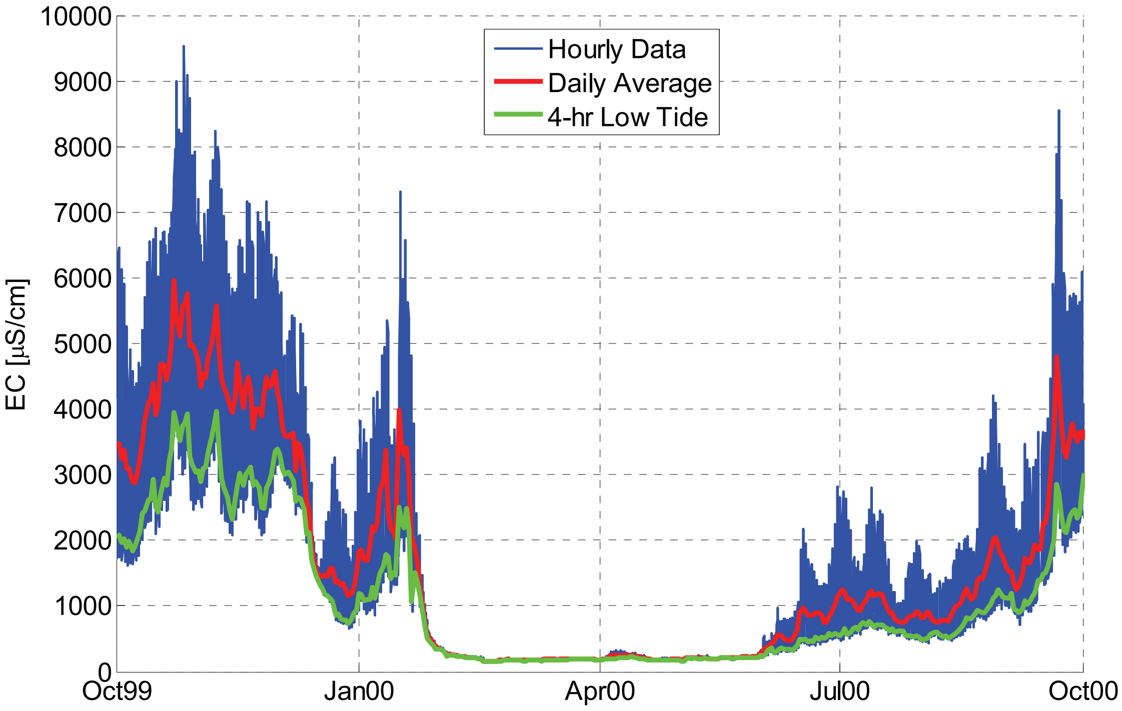

Figure E-2 – Salinity variations in the San Joaquin River at Antioch, water year 2000

Figure E-3 shows the distribution of low tide salinity (salinity during the freshest 4 hours of each day) for the period of May 1, 1983 through September 30, 2002.[10] These data indicate that, on average (in 50% of the water years), low tide salinity exceeds 1,000 µS/cm EC from late-August through December. The data in Figure E-3 provide context for the qualitative observations from the Antioch Case. During the driest 25% of the years (5 out of 20 years), low tide salinity exceeds 1,000 µS/cm EC from June through January, leaving the Antioch intake with no fresh water for eight months of the year.

Under average conditions corresponding to the period 1983-2002, Antioch would have to stop pumping from late August to late December in 10 of the 20 years; i.e., they would have an average of eight months of low-tide pumping per year, compared to the pre-1915 average of twelve months per year (based on the anecdotal information filed by the Appellants (upstream diverters) in the Antioch Case).

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[10] Data Source: Interagency Ecological Program, HEC-DSS Time-Series Databases. Station RSAN007. Agency: DWR-ESO-D1485C. Measurement: 1-hour EC. Time Range: May 1, 1983 through September 30, 2002

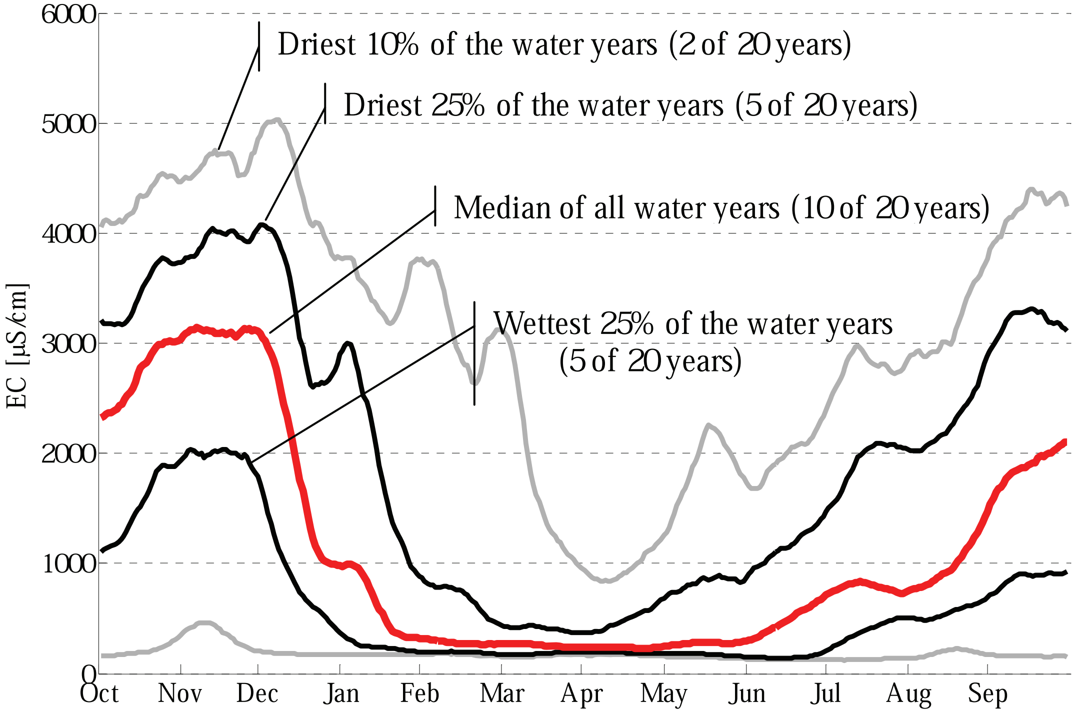

Figure E-3 – Seasonal Distribution of low-tide salinity at Antioch, 1983-2002

Conclusions

- The window, when Antioch is able to pump water with salinity less than 1,000 µS/cm EC, has substantially narrowed in the last 125 years.
- Antioch was apparently able to pump fresh water at low tide year-round in the late 1800's, with the possible exception of the fall season during one or two dry years.
- During 10 of the 20 years between 1983 and 2002, salinity was less than 1,000 µS/cm EC at low tide for only about eight months of the year.
- During the driest 5 years between 1983 and 2002, salinity was less than 1,000 µS/cm for only about four months per year; i.e., no fresh water was available at any time of the day for about eight months of the year.

E.2.3. Salinity at Kentucky Point on Twitchell Island – then and now

The appellants in the Antioch Case, representing the upstream diverters, identified one resident of Twitchell Island who reported the water at Kentucky Landing was brackish on "one or two occasions" between 1870 and 1875 during August and September. During this time, he had to travel up the San Joaquin River to Seven Mile Slough (the eastern boundary of Twitchell Island) and sailed as far as the mouth of the Mokelumne River (approximately 2 miles further up the San Joaquin River than the Seven Mile Slough junction) to obtain fresh drinking water.

For comparison, we look at salinity monitoring data in that region for 1981 and 2002 to see the location of potable water.[11] The source document (Town of Antioch v. Williams Irrigation District, 188 Cal. 451) for the 1870's drought uses up to 100 mg/L chloride concentration as the threshold for a potable water supply. Monitoring data from 1981 shows similar salinity intrusion as described by the Twitchell Island resident; salinity along the San Joaquin River at Bradford Island (about 1.5 miles upstream of Three Mile Slough) exceeded 1,000 µS/cm EC (about 250 mg/L Cl) during August and September. During the same time period, salinity was around 400 µS/cm EC (about 64 mg/L Cl) approximately 5 miles upstream on the San Joaquin River between Seven Mile Slough and the Mokelumne River. This comparison indicates that the extent of salinity intrusion in 1981 is similar to that which occurred in 1870 and 1871.

Similarly, in September 2002, the salinity in the San Joaquin River at San Andreas landing (less than 2 miles downstream of the Mokelumne River mouth) peaked at 977 µS/cm EC, which corresponds to approximately 225 mg/L chloride concentration. Therefore, if the observer was to travel upriver for potable water in 2002, they would have likely traveled up to the mouth of the Mokelumne River as they did in 1870. Salinity intrusion in critically dry years is even farther into the Delta than was found in 2002.

In conclusion, salinity intrusion up the San Joaquin River during the dry years of 1870 and 1871 as described by a Twitchell Island resident is consistent with salinity intrusion in 1981 and 2002 under similar hydrological conditions. There is no evidence that salinity intrusion during the drought of 1870-71 was more extensive than salinity intrusion during similar water years in the current salinity regime.

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[11] 1981 and 2002 were both dry water years in the Sacramento River basin as defined in D-1641 with similar annual unimpaired Sacramento River flow to the years 1870 and 1871. Annual unimpaired Sacramento River flow in 1870, 1871, 1981, and 2002 was 11 MAF, 10 MAF, 11 MAF, and 14 MAF, respectively.

SAN FRANCISCO BAY:

THE FRESHWATER-STARVED ESTUARY

HOW WATER FLOWING TO THE OCEAN SUSTAINS CALIFORNIA'S GREATEST AQUATIC ECOSYSTEM

The Bay Institute

SAN FRANCISCO BAY:

THE FRESHWATER-STARVED ESTUARY

HOW WATER FLOWING TO THE OCEAN SUSTAINS CALIFORNIA'S GREATEST AQUATIC ECOSYSTEM

PREPARED FOR:
SAN FRANCISCO ESTUARY PARTNERSHIP

BY:
The Bay Institute

SEPTEMBER 2016

The Bay Institute

bay.org

The Bay Institute is the research, policy and advocacy arm of bay.org, a nonprofit organization dedicated to protecting, restoring and inspiring conservation of San Francisco Bay and its watershed, from the Sierra to the sea. Since 1981, the Bay Institute's scientists and policy experts have worked to secure stronger protections for endangered species, water quality, and estuarine habitats; reform how California manages its water resources; and design and promote comprehensive ecological restoration projects and programs in San Francisco Bay, the Sacramento-San Joaquin Delta, the Central Valley watershed, and the Gulf of the Farallones.

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The report was researched and written by staff of the Bay Institute's Rivers and Delta Program: Alison Weber-Stover (Staff Scientist), Greg Reis (Staff Scientist), and Jonathan Rosenfield, Ph.D. (Conservation Biologist and Lead Scientist), with assistance from Peter Vorster (Hydrogeographer), under the direction of Gary Bobker (Program Director), who also co-authored and edited the report. Report design and production was overseen by Ashley Spiker (http://www.thespikerexperience.com).

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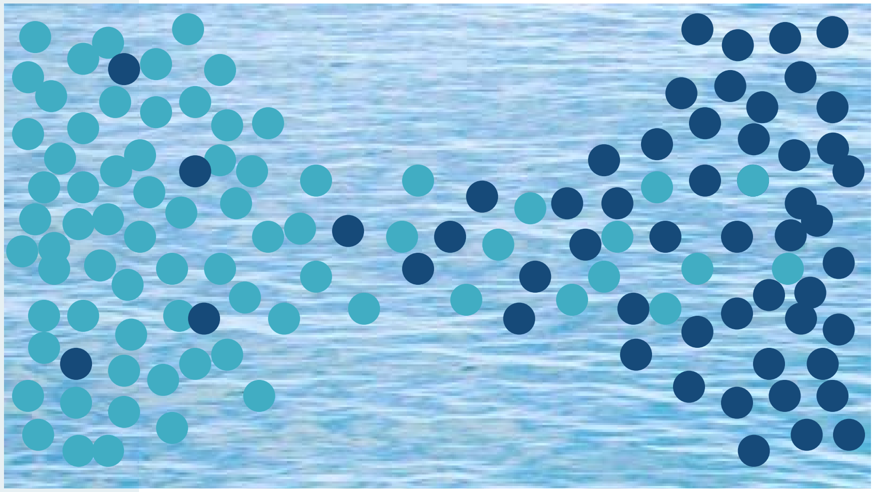
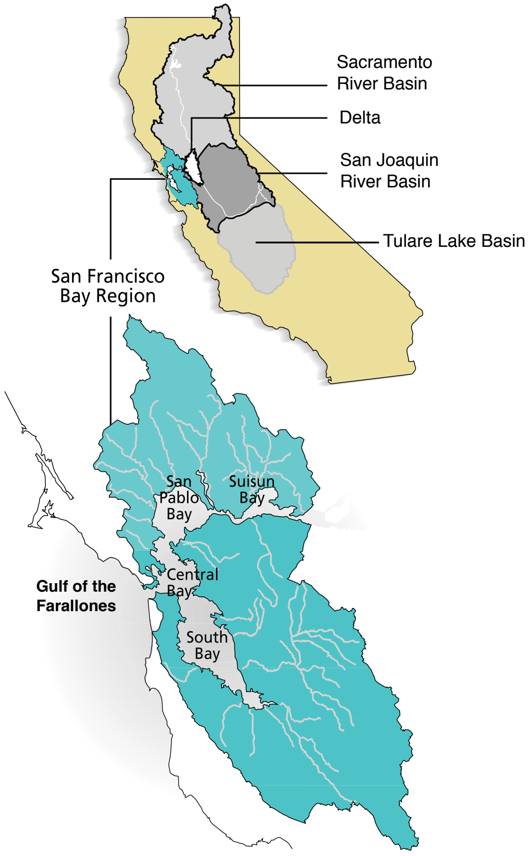
INTRODUCTION

THE INFLOW OF FRESH WATER DRIVES THE HEALTH OF THE SAN FRANCISCO BAY ESTUARY AND ITS WATERSHED, FROM MOUNTAIN RIVERS TO THE PACIFIC OCEAN OUTSIDE THE GOLDEN GATE

San Francisco Bay is an estuary, where salt water and fresh water mix to form a rich and unique ecosystem that benefits fish, wildlife and people. Fresh water sustains the Bay ecosystem. Drastic changes to Bay inflow place the ecosystem, and the services it provides to all of us, at risk.





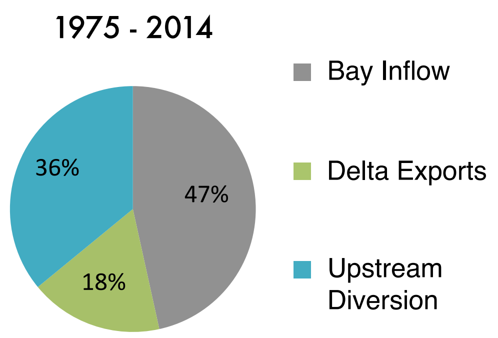
WHERE HAS ALL THE FRESH WATER GONE?

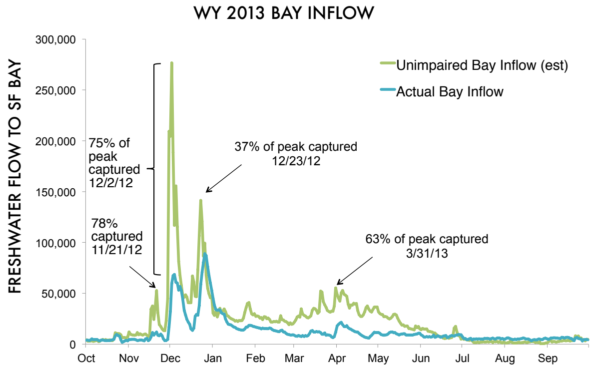
FRESH WATER NATURALLY FLOWED TO THE BAY – UNTIL WE STARTED CAPTURING AND REDIRECTING MOST OF IT, ESPECIALLY DURING ECOLOGICALLY CRITICAL PERIODS

Historically, most Bay *inflow* came from winter rains and spring snowmelt, which kept the upper estuary fresh most of the year and created increasingly brackish and saline habitats moving downstream to the Golden Gate. The Bay's fish and wildlife *evolved to take advantage* of these patterns of flow and habitat.

But, after building thousands of dams, over 600 large reservoirs, and 1,300 miles of diversion canals throughout the Bay's watershed, the flow that now reaches San Francisco Bay is **on average less than 50%, and in some years less than 35%**, of what it would be without those impairments. Ecologically critical winter and spring flows have been cut even more, with **about a third** of the seasonal unimpaired runoff and, just **one-fourth** of the runoff from some storms reaching the Bay.

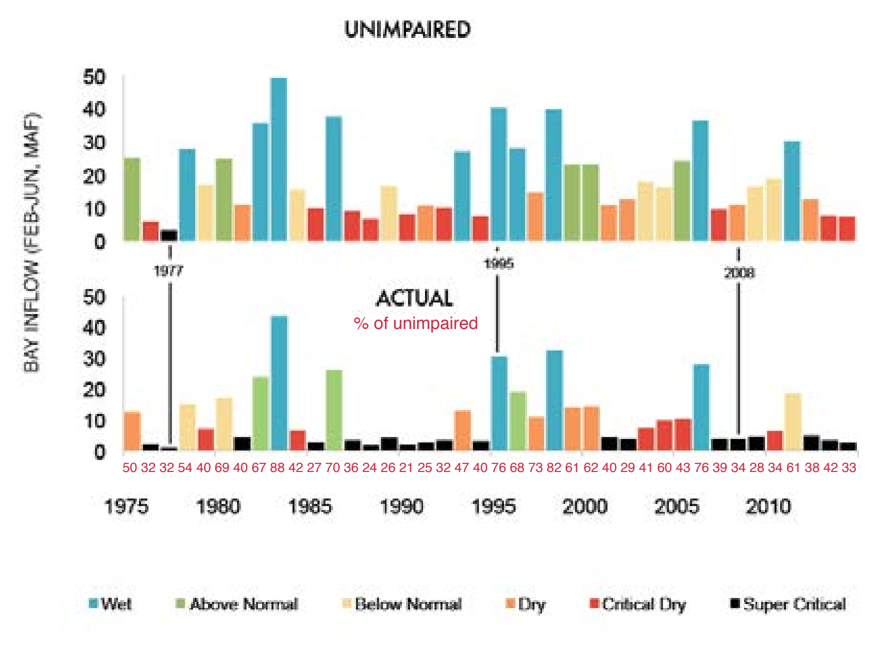
California's *water wars* – the fight over how much water cities, agriculture and the environment will get – are fought *upstream*, in the Bay's watershed and in areas that take water out of it. But *downstream*, in the Bay estuary and nearby coastal waters, is where the *outcomes of radically altering and reducing flows* can be seen most clearly. These outcomes include fish and wildlife species at serious risk of extinction, degraded water quality, shrinking beaches and marshes, and so much more.





THE CHANGE IS SO EXTREME THAT THE SAN FRANCISCO BAY ECOSYSTEM NOW EXPERIENCES A DEVASTATING, PERMANENT DROUGHT

Between 1975 and 2014, the unimpaired runoff in the watershed was only low enough to create a “supercritically dry’” year **once**, in 1977. But upstream diversions captured so much runoff during those four decades that the Bay experienced “supercritically dry” conditions – the amount of inflow typical in extreme drought – in **19 years** instead of only one. The resulting collapse of the Bay’s ecosystem is no surprise.



STARVING THE BAY

EXTREME FLOW REDUCTIONS DAMAGE THE BAY’S ECOSYSTEM

How much fresh water makes it to the estuary, *when*, and for *how long*, shapes the Bay’s ecosystem. Reducing Bay inflows so dramatically shifts the size and location of the ecologically important *salinity mixing zone*, reduces the inflow of *nutrients, food*, and *sediment* from the watershed that are vital components of fish and wildlife habitat; allows *pollutants* to accumulate; and facilitates *invasions* by undesirable non-native species.

SALINITY

The transition from fresh water to the ocean forms a gradient of increasingly saline habitats that are critically important for the estuary’s fish and wildlife. The amount and timing of inflow determines *where* and *how extensive* these productive low salinity habitats are. Winter and spring inflows move the critically important low salinity zone downstream in the upper reaches of San Francisco Bay. The *abundance* and *distribution* of many estuarine fish and invertebrate populations are *strongly* and *persistently associated* with the location of this zone; when it moves downstream, native species numbers increase.

Periods when the **average salinity was as high as in the past half-century previously occurred only three times in the last 1,600 years** – during recent droughts, January – July salinity was the highest it has been in 400 years. Reducing Bay inflow this drastically forces the low salinity zone to **move upstream**, exposing larval and juvenile fish to **poor water quality and habitat conditions** in the Delta, facilitating the **spread of**

invasive non-native species, and driving population **declines** of native species. Shifting the salinity field upstream also **brings salty water to fresh and brackish water marshes,** reducing the productivity of wetland habitats and number of plant and animal species in them, and slowing the formation of new soil.

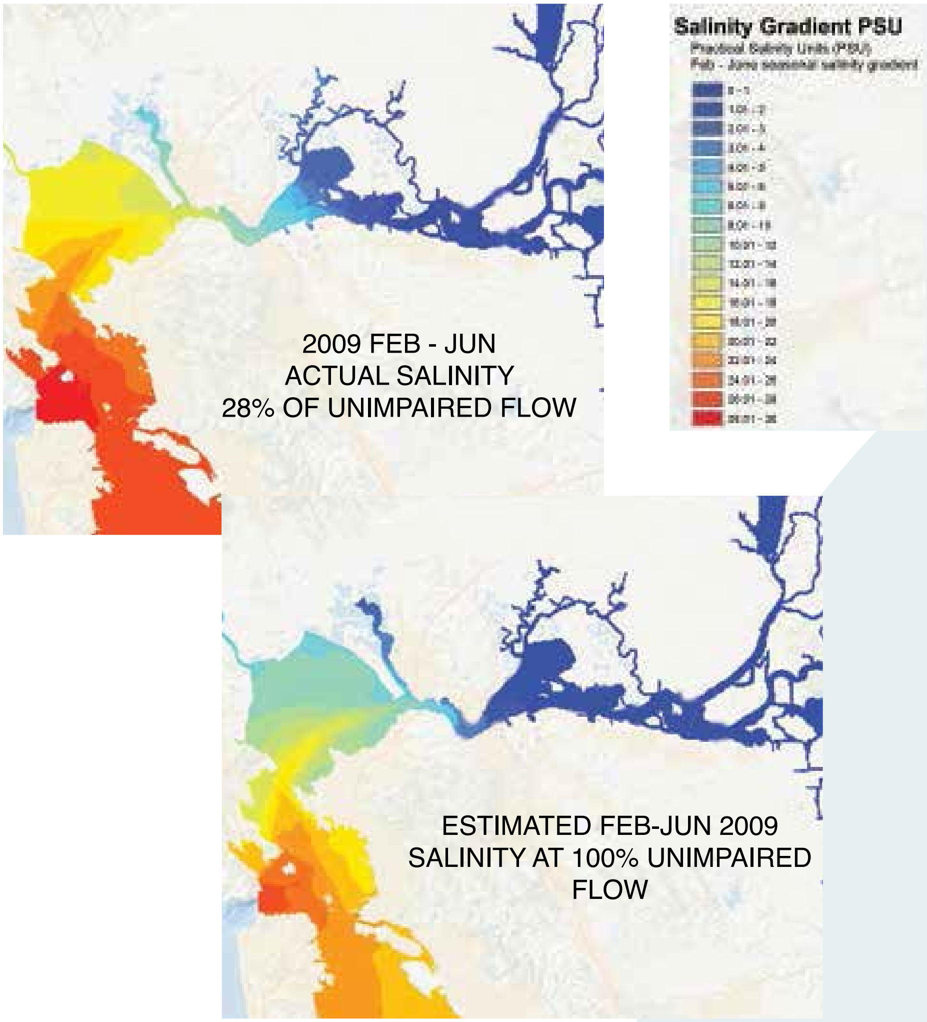


Photo Credit: David Sanger

Further downstream, **persistent increased salinities** from reduced inflow displace the native invertebrate community in the Central Bay, **allowing non-native sea squirts to dominate** the subtidal zone. In the South Bay, freshwater inflows riding on the surface over a deeper, saltier layer support *the base of the food web* with *large plankton blooms;* the effect is dampened when flows are reduced. Similarly, outside the Golden Gate, a *plume of brackish water* that forms when winter and spring flows to the Bay ride on the surface, *stimulates plankton growth* and facilitates the movement of *nutrient-rich bottom water* into the Bay. Because so much fresh water is captured upstream, salinity at the estuary's downstream boundary has increased and the brackish water plume has diminished. In combination with warming seas, reduced flows from the Bay to nearshore waters are likely to **lower productivity** and increase the risk of **starvation and reproductive failure** in seabirds, fish, and marine mammals.

SEDIMENT

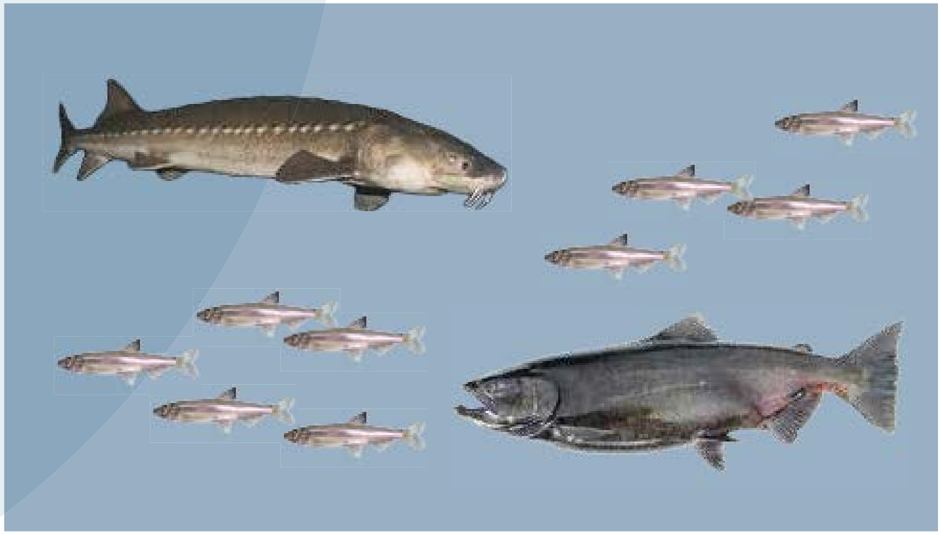
Higher Bay inflows carry more sediment (gravel, silt, and other particles), which helps *form and maintain wetlands and beaches*, and make the estuary's waters *more turbid*, or cloudy, protecting fish and invertebrates from predators. But dams and diversions capture sediment and reduce sediment-carrying flows. Sand makes up 70% of the Sacramento River's sediment load when flows are high; reducing flows helped **cut the sediment load in half** between 1957 and 2001. Flow reduction combined with other factors facilitated the shrinking of sandy beaches in the Bay by **two-thirds**, a **50%** increase in coastal erosion, and a decline of up to **40%** in turbidity in the upper estuary.

POLLUTION

When Bay inflows are low, concentrations of chemical and biological contaminants build up, sometimes to toxic levels, and increase the amount of time these pollutants spend in the estuary. Heavy metals and synthetic compounds like **copper, mercury, PCBs** and **silver** are more readily incorporated by aquatic organisms, at lower flows. The trace element **selenium**, which causes **birth defects** and **reproductive mortality** in many species, accumulates more rapidly in clams, and the fish and birds that prey on them, when flows are at the low levels seen in recent years. Low flows also encourage **toxic algae blooms,** which produce **neurotoxins** that build up in the environment and can kill animals and sicken people. These blooms are becoming **more frequent** in the upper estuary, and their toxins are detectable throughout the Bay.

FOOD WEB PRODUCTIVITY

San Francisco Bay is a *highly productive nursery* for fish, birds, mammals, and invertebrates like crabs and shrimp. Freshwater inflow stimulates the Bay estuary's food web by *increasing production of fish and large planktonic animals* that thrive in the muddy waters and wetlands that are created and sustained by sediment-laden peak flows. Flows also *transport* some of these organisms to other parts of the estuary, where they become prey for other species. **Altering flows alters the food web.** As flows decline, the **biomass of important invertebrate prey populations like Bay shrimp declines** correspondingly; water clarity increases, increasing the **rate of predation** on food prey species; and **non-native species colonize the estuary**, competing with or preying on native species. If the amount and timing of Bay inflows are allowed to more closely approximate natural patterns, these effects can be reversed.



WHO SUFFERS FROM THE BAY'S FRESH WATER STARVATION DIET?

The Bay ecosystem supports more than *750 plant and animal species*, including four unique runs of *Chinook salmon*, and millions of *waterbirds*. Seven million residents and more than twice as many visitors enjoy *seafood* produced locally in this estuary, *recreate* along its shores or in its waters, and draw satisfaction from its *wetlands* and *wildlife*. Reducing Bay inflows puts all of these values at risk.

VIABLE FISH AND WILDLIFE POPULATIONS NEED FRESH WATER

Conditions in the flow-starved estuary are very different from those in which native plants and animals evolved. As a result, some of the **most common species**, like Delta smelt, Chinook salmon, and sturgeon, are now among the **rarest**. What these and many other species – organisms that vary in their life histories, role in the food web, and location in the estuary – have in common is the *strong relationship between flow and healthy populations*.

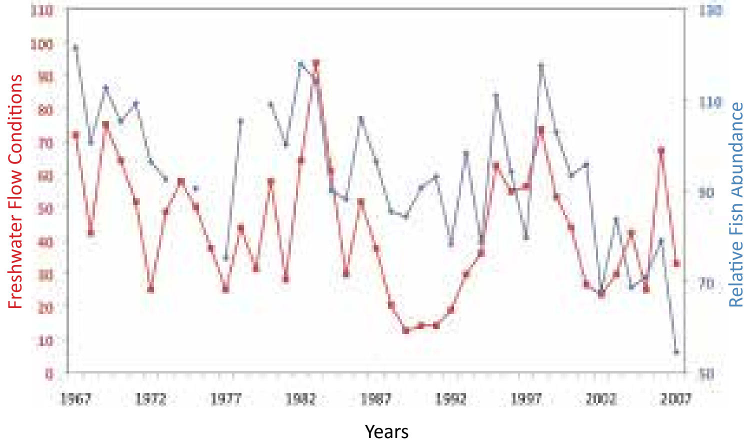
To be viable, the Bay's plants and animal populations need to be:

- abundant (higher populations ensure long-term survival through a range of different conditions)
- diverse (increased variation among individuals increases the odds that some will respond successfully to changing environmental stresses)
- productive (faster population growth rates allow species to exploit good conditions in a variable environment); and
- spatially distributed (exists in a large enough area reduces the risks posed by local catastrophes)

ABUNDANCE

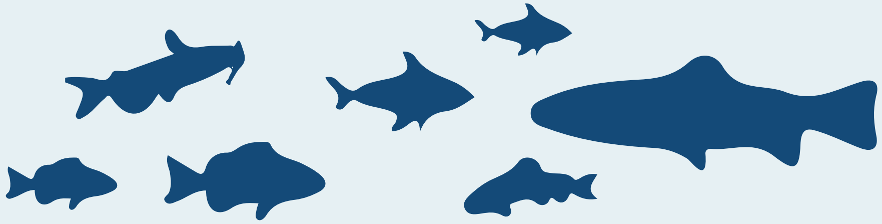
Reproduction, growth, and migration of many species, from invertebrates to forage fish to migrating salmon, are timed to occur during the critical winter and spring months when flows are higher. The *number of individuals* in these populations is strongly influenced by *how much Bay inflow* occurs during this period – this is one of the best-documented facts known about the Bay estuary. The dramatic decline in abundance of many populations closely tracks the dramatic decline in winter – spring Bay inflows; that is, **less flow has resulted in less fish** – for some species, populations are at **record or near record low levels.** In contrast, the abundance of many non-native species is inversely proportional to flow, increasing under low flow conditions. Flows in the fall also create brackish water habitat for Delta smelt and help returning adult salmon find their home spawning grounds.

MORE FRESHWATER = MORE FISH



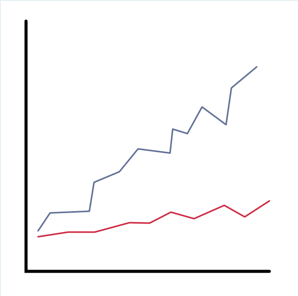
DIVERSITY

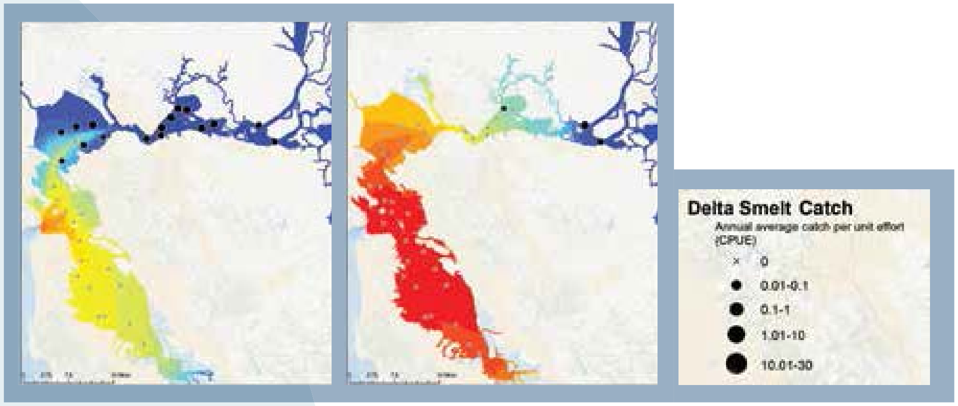
A population with more diverse individuals is *less vulnerable to extinction* because it has a *portfolio* of possible behavioral and ecological responses to changing or variable conditions. Restricting the amount and timing of flows year after year favors the survival of a **small subset of individuals** that are only able to prosper under a limited set of conditions. For instance, nearly **eliminating peak Bay inflows from the San Joaquin River and replacing them with small artificial pulses that occur during just one month** narrows the migration window for Chinook salmon, in essence gambling that these fish will reach the ocean exactly when food supplies and other conditions are good. The **collapse of California's salmon fisheries** shows that this gamble has not paid off.



PRODUCTIVITY

Fish and wildlife populations that can *grow quickly* can *rebound quickly* following times when conditions are poor. The Bay estuary's species evolved to rebound in wetter years after periods of drought. But the Bay's "permanent drought" means that wet years are infrequent and much less wet, and drier years are extremely dry and nearly continuous. As a result, the **higher flows that would allow populations to rebound rarely occur**, and the growth rate is limited or even negative.





SPATIAL DISTRIBUTION

When all individuals in a population are concentrated in a small area, the population is **more vulnerable to extinction** due to localized catastrophes. Lower Bay inflows significantly **reduce the size of the low salinity habitat** that many species depend on. Low inflows also shift this habitat– and the populations using it – upstream, exposing imperiled fish to the giant Delta pumps, where on average **9 million fish** are screened out of the exported water each year - **most do not survive** from the experience. In addition, to creating important habitat types, freshwater inflows to the Bay also help transport organisms between essential habitats. By **degrading water quality, eliminating signals that fish and wildlife use to orient themselves**, and **even drying up sections of rivers**, low Bay inflows can prevent populations from spreading out or migrating.

Photo Credit: Richard Eskite

DRIVING RECREATIONAL AND COMMERCIAL FISHERIES TO THE EDGE?

The flow and habitat conditions that once prevailed in San Francisco Bay made the area a *hub of commercial and recreational fishing activity on the West Coast*, with important fisheries for salmon, sturgeon, smelt, striped bass, and other species. The long-term trend of reducing Bay inflows has been a major factor in the **loss of thousands of fishing jobs** over the past few decades and the **historic closure of the ocean salmon fishery** in 2008-2010. While deteriorating ocean conditions, upstream habitat degradation, and poor hatchery management also played a role, scientists studying the closure have identified **better flow conditions as one of the few actions that can be taken to restore** the salmon fishery. **Starry flounder, sturgeon, and splittail** are other commercially valuable fisheries that depend on adequate flows and that are **also at risk.**

FLOW (AND FORAGE FISH) IS FOR THE BIRDS...

Forage fish (small fish and large invertebrates) that are *food items* for many larger fish, bird and mammal species perform a *crucial function* in the estuary's food web. For instance, fish-eating birds, such as pelicans, terns, and cormorants, rely on the existence of sufficient forage fish populations to feed them. Populations of many once common native forage fish species, like smelt, salmon, and shrimp, have **declined dramatically** in response to extreme reductions in Bay inflows and are now well below the levels needed to maintain viable populations of **other fish, pelagic seabirds and marine mammals,** so these other populations **are at risk of collapsing** too. Also, as reduced inflows reduce the area of brackish and freshwater wetlands or convert them to salt marsh, their **habitat value** for many bird populations is likely to **diminish.**

...AND THE WHALES

Marine mammals like seals and whales are a great tourist attraction in the Bay Area and the Northern California coast. By diminishing productivity and constricting the estuary's food web, reduced Bay inflows produce cascading effects that eventually create problems for these species. For example, **Orca whales** outside the Golden Gate prey on Chinook salmon, which were historically abundant and high in fat content; **dwindling salmon runs threaten** the local whale population.

… AND THE PEOPLE

Bay Area residents and tourists don't just benefit from Bay inflows by catching fish, buying local seafood, or going whale watching. They also *wade, swim, sail and kayak* its waters and play on its *beaches* and in its *wetlands*. But low flows **degrade water quality** in general and are now beginning to cause periodic **harmful algae blooms,** in particular. Some cyanobacteria blooms produce **neurotoxins powerful enough to make humans sick** and kill small mammals; although the blooms occur in the upper estuary, neurotoxins produced upstream have been detected in the Central Bay. Low Bay inflows also **threaten the continued existence** of beaches and wetlands throughout the region. As rising sea levels and other forces erode these popular areas, water diversions **limit the peak flows** that would normally resupply them with sediment.

Photo Credit: David Ferris

A Bay Area where it's hard to catch salmon, see pelicans or Orca whales, find today's local catch at the restaurant, hang out at the beach, or even be in contact with the water? This is a **high price to pay for ignoring the effect** of the radical alteration of Bay inflows on the many ecosystem services and economic benefits that the San Francisco Bay estuary provides.

TURNING THE FLOW BACK ON

Fortunately, there are actions that Californians can take to avoid that increasingly likely scenario.

ADOPT STRONGER WATER QUALITY STANDARDS FOR THE BAY ESTUARY NOW

Overwhelming evidence demonstrates that today's **21-year old Bay-Delta water quality standards do not require nearly enough flow** to protect the beneficial uses of the San Francisco Bay Estuary's waters as mandated by the Clean Water Act. That finding has been confirmed time and again by policy makers, regulatory agencies, and independent science review panels. Yet California is still years away from completing the update of its standards begun in 2009, despite the federal requirement to review standards every three years. It's **time to end the delays and adopt new standards** that require enough flow to restore estuarine productivity and viable fish and wildlife populations, discourage the establishment and spread of invasive non-native species, and use indicators of biological and ecosystem health to measure progress and increase effectiveness.

REQUIRE ALL WATER DIVERTERS TO CONTRIBUTE THEIR FAIR SHARE

The primary responsibility for meeting Bay estuary water quality standards falls on a small subset of water districts that get water from the federal and state water projects. These agencies represent **a quarter or less of total water use** in the Bay's watershed. Requiring all water users, including those with senior water rights, to contribute a **fair share** would spread the burden more equitably and generate **millions of acre-feet of additional water to restore the estuary.** It's also time to more broadly overhaul California's antiquated water rights system, which favors older water claims over the needs and public benefits generated by different water uses; this system has also awarded the right to use **five times more water in California than occurs naturally**, on average.

REDUCE RELIANCE ON THE DELTA AS A SOURCE OF WATER SUPPLY

In 2009, California adopted a landmark policy to reduce reliance on water supplies from the Delta region of the upper estuary and increase local self-reliance in areas that take water out of the Delta. California has only begun to tap the potential for local self-reliance; using water more efficiently, reusing and recycling water, cleaning up degraded water, capturing and reusing stormwater runoff, and storing water underground in aquifers **could save up to 14 million acre-feet of water** – over half the total amount of water used for human use throughout the Bay's watershed each year – each year. Implementing the new policy could also significantly **reduce California's carbon footprint;** for instance, transporting water via the State Water Project represents about 3% of the state's total energy consumption. Setting **targets for conserving water in the agricultural sector** – which uses about 80% of the state's developed water supplies – would generate additional water to restore a healthy Bay estuary and establish greater parity between agriculture and the urban sector, which is required to achieve a per-person conservation target of 20% by 2020.

Photo Credit:
Fernand Ivaldi
Getty Images

INTEGRATE FLOW AND HABITAT RESTORATION TO BATTLE CLIMATE CHANGE

Wetlands and beaches not only provide important habitat for fish and wildlife; they also act as natural flood barriers to protect shoreline communities in the Bay Area and Northern California. Loss of sediment supply and rising sea levels threaten to erode these benefits by literally eroding wetlands and beaches to nothing. **Freshwater flow regimes that help maintain wetlands and beaches** should be a part of efforts to design, evaluate, and permit restoration of these critical areas.

WE MUST ACT NOW

The science overwhelmingly indicates that more freshwater flow, following a more natural pattern, must reach the San Francisco Bay estuary to restore its fish, wildlife, water quality, food web, marshes, beaches, coastal fisheries, and other public benefits. The only barriers to action are the general lack of understanding about the severely degraded condition of this freshwater flow-starved estuary and the lack of political will to change the unsustainable way California manages its water resources. Can Californians be made aware of the pending collapse of the Bay estuary ecosystem – and the loss of all that ecosystem provides us – and motivated to demand action now? Can decision-makers at every level – federal, state, and local – be prevailed upon to take the steps necessary to prevent the destruction of California's greatest aquatic ecosystems before it is too late? The window of opportunity to protect this treasure is closing rapidly.


Butter Lupine Photo Credit: David Sanger

INTRODUCTION

THE FLOW OF FRESH WATER DRIVES THE HEALTH OF THE BAY AND ITS WATERSHED, FROM MOUNTAIN RIVERS TO THE PACIFIC OCEAN OUTSIDE THE GOLDEN GATE

The San Francisco Bay estuary is one of the world's great ecosystems – a natural treasure comparable in scale and importance to the Everglades, Chesapeake Bay or the Great Lakes. Like these other large ecosystems, the health of San Francisco Bay is at risk from many environmental insults. Contaminated agricultural runoff and legacy pollutants poison aquatic food webs. Invasive plants and animals compete with native species for food and habitat. Only a small fraction of its original wetlands remain. But perhaps the most serious and seemingly intractable threat comes from the large-scale and unsustainable diversion of the fresh water that should flow to the Bay from its vast watershed in California's Central Valley ("Bay inflow"). The radical alteration of Bay inflow is intimately connected to every other problem that threatens the Bay estuary's ecosystems. The inescapable facts are that the Bay estuary is being starved of the freshwater flow that makes it California's greatest aquatic ecosystem – and that people don't understand that fresh water flowing to the ocean is what keeps the Bay alive.

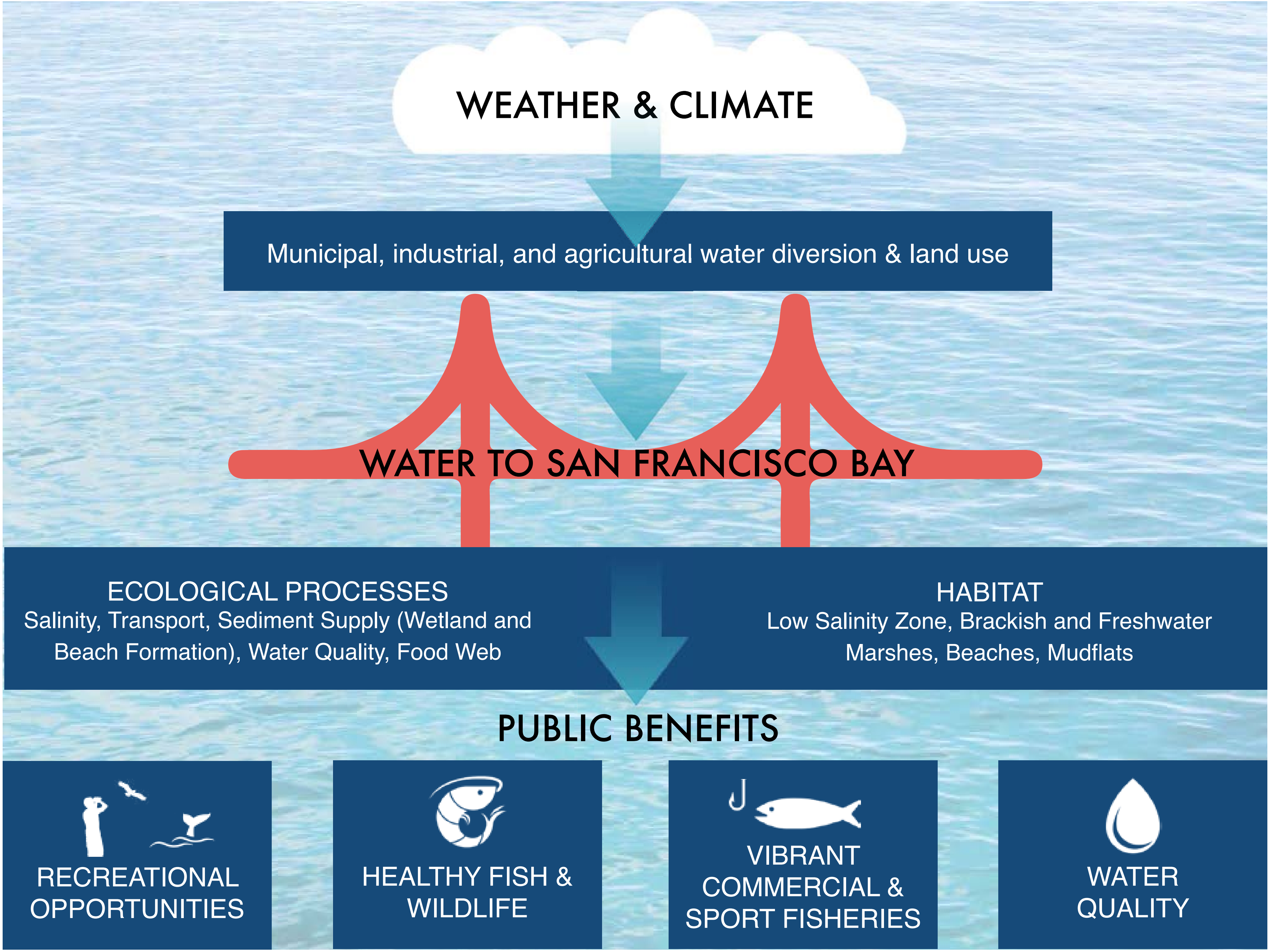
Freshwater flows define the San Francisco Bay estuary. As the place where fresh water and saltwater mix, the estuary provides a unique brackish water ecosystem for hundreds of plant and animal species – many found nowhere else on Earth. San Francisco Bay is the most famous and recognizable part of this estuary, an ecosystem formed by the mixture of fresh water from the rivers and streams of California's Central Valley and salt water from the ocean. When freshwater inflow to an estuary is drastically altered, as in it has been for San Francisco Bay, the very nature of the ecosystem is changed, with dramatic consequences for the fish and wildlife that depend on the estuary's unique habitats. Ultimately, people who enjoy the many benefits this ecosystem offers – from its fishable and swimmable waters to its beaches and rich wetland habitats – lose out when we deny the estuary the freshwater flow it needs.

THE BAY IS A MAJOR BUT UNAPPRECIATED CASUALTY IN CALIFORNIA'S "WATER WARS"

The long-standing conflicts over how much water should be diverted from the estuary and its watershed to provide water for irrigation, industry, and drinking water supplies are often depicted as occurring far upstream from San Francisco Bay. News stories describe battles over how much water should be held back in the thousands of reservoirs in the Bay's watershed, or diverted from Central Valley rivers, or exported by the giant pumps in the Sacramento-San Joaquin Delta, in order to be delivered to cities and farms. Government agencies and water districts fight over appropriate limits on water extractions in order to safeguard water quality, fish, and wildlife. People debate whether agribusiness should grow thirsty crops that depend on government subsidies and water from overdrafted groundwater basins and distant watersheds, and whether agricultural water use should be metered in our semi-arid environment.

What is rarely mentioned is that the outcomes of all battles in these water wars affect the Bay and the coastal ocean outside the Golden Gate. Most of the freshwater flow that shaped these environments historically is captured today in a massive system of reservoirs, siphons and pumps. The loss of freshwater flow is harming the Bay and the nearshore marine ecosystems, the fish and wildlife that depend on them, and the humans that benefit from and enjoy them (Figure 1).

Figure 1: The amount and timing of critical freshwater inputs to the estuary are a function of what nature provides and the amount of water humans divert and store upstream. Unsustainable water diversions lead to altered ecological processes and degraded habitats which produce cascading effects on many beneficial uses that people gain from a functioning estuary ecosystem. The amount of fresh water reaching San Francisco Bay generates myriad public benefits, including healthy fish and wildlife populations, improved water quality, viable commercial and recreational fisheries, and ample recreational opportunities such as enjoying beaches or viewing wildlife.



WEATHER & CLIMATE

Municipal, industrial, and agricultural water diversion & land use

WATER TO SAN FRANCISCO BAY

ECOLOGICAL PROCESSES
Salinity, Transport, Sediment Supply (Wetland and Beach Formation), Water Quality, Food Web

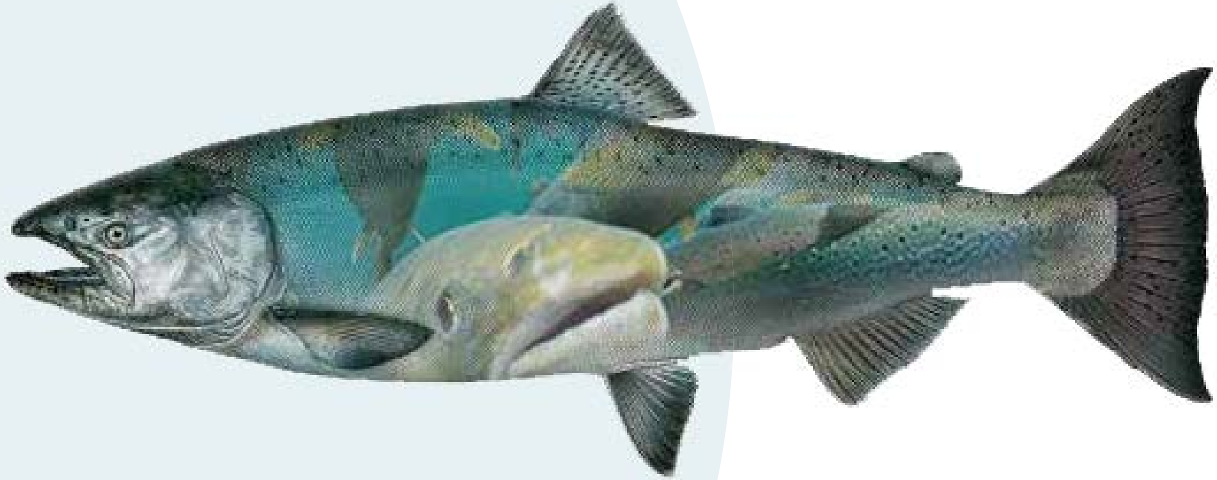
HABITAT
Low Salinity Zone, Brackish and Freshwater Marshes, Beaches, Mudflats

PUBLIC BENEFITS

- RECREATIONAL OPPORTUNITIES
- HEALTHY FISH & WILDLIFE
- VIBRANT COMMERCIAL & SPORT FISHERIES
- WATER QUALITY

CALIFORNIA'S PAST INVESTMENTS IN THE BAY ARE AT RISK

Californians have invested a half-century of effort and billions of dollars to control water pollution, restore wetlands and prevent exotic species from being introduced to the Bay estuary. But that enormous financial and social investment is at risk unless we let a larger share of the watershed's runoff flow downhill to the Bay. Californians can protect their investment in the Bay by changing the water use and water management practices that prevent us from protecting the freshwater flows that support this majestic ecosystem and the jobs that rely on its health.



This report describes how:

- The Bay's natural freshwater flow regime has been altered by the world's largest system for capturing and moving water;

- The estuary's vital ecological processes, including salinity distribution, transport of sediments, nutrients, and food, pollution control, habitat availability, and food web dynamics, are damaged by these alterations to the natural runoff pattern; and,

- The living beings that depend on the health of the Bay, from simple aquatic plants, to forage fish, to migrating salmon, to marine mammals, to humans, are at serious risk from the loss of services the Bay ecosystem provides.


Photo Credit: The Bay Institute

WHERE HAS ALL THE FRESH WATER GONE?

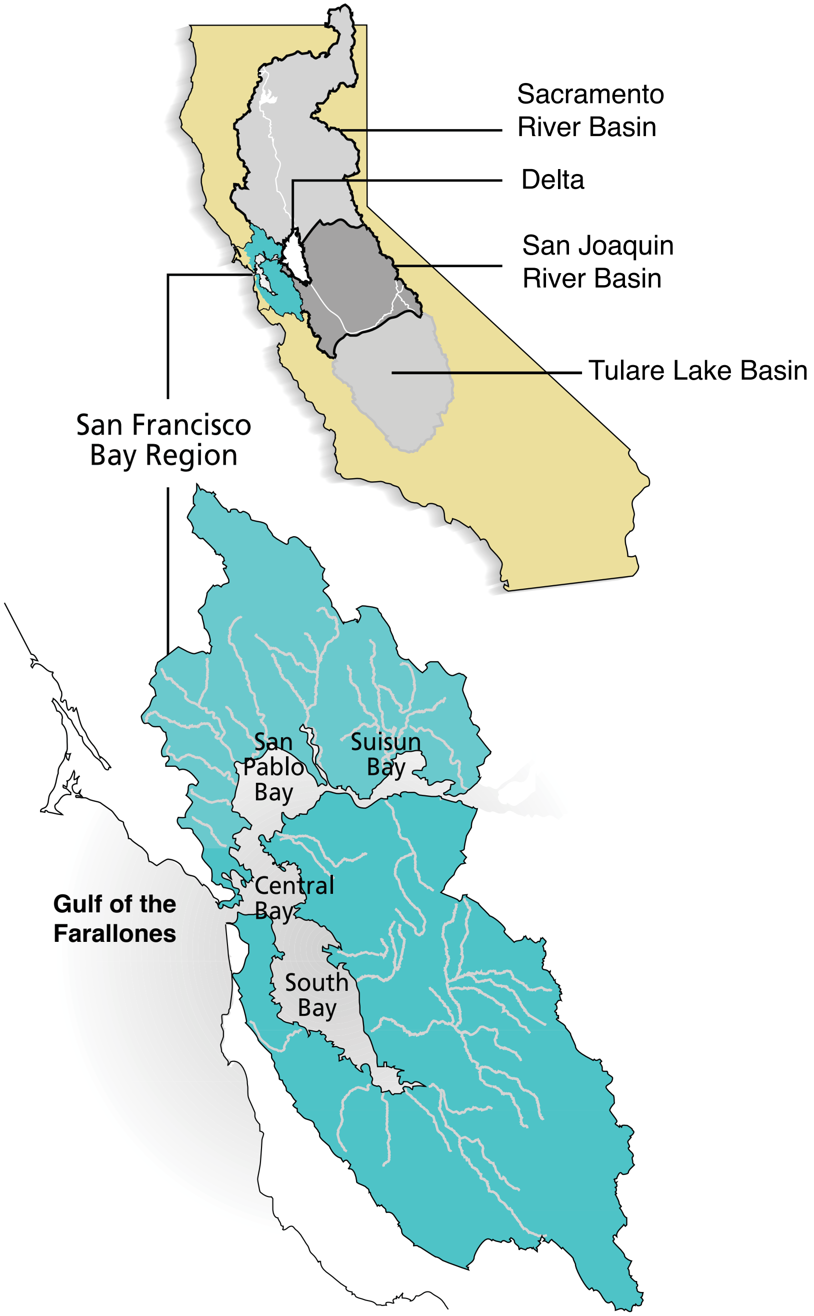
PATTERNS OF NATURAL AND ALTERED FLOW TO SAN FRANCISCO BAY

San Francisco Bay is part of the largest estuary on the west coast of the Americas. The estuary extends from the inland Delta where the Sacramento and San Joaquin Rivers of California's Central Valley converge, out to the nearshore coastal waters of the Gulf of the Farallones. The Bay itself encompasses four major embayments – Suisun Bay, San Pablo Bay, Central Bay, and the South Bay (Figure 2).

THE SAN FRANCISCO BAY ESTUARY AND ITS WATERSHED

Figure 2: From the peaks of the mountain ranges surrounding the Central Valley to the Golden Gate, the San Francisco Bay watershed historically drained up to 40% of California's land area. Most of the Bay's inflow comes from rivers and streams that flow into the Sacramento and San Joaquin Rivers and then is funneled through the Delta to the Bay. Locally important creeks and rivers that discharge directly into the Bay contribute about 10% of the Bay's freshwater inflow. The once vast Tulare Lake periodically overflowed into the San Joaquin River, but now the basin of this dry lakebed contributes water to the Bay only in the wettest years.

Sacramento - San Joaquin Delta
Photo Credit: David Sanger



Freshwater flow drives everything that happens here. The Bay's vast watershed now drains about a third of the land area of California, collecting surface and ground water from the Sacramento and San Joaquin River watersheds, and in exceptionally wet years, from the Tulare Lake Basin, south of Fresno (which contributed water to the Bay more frequently before the construction of the current water supply system). Smaller rivers and creeks that flow directly into the Bay such as the Napa River, Guadalupe River, Sonoma Creek, Coyote Creek, Alameda Creek, San Francisquito Creek and Walnut Creek contribute less than 10% of inflow[1].

FRESH WATER NATURALLY FLOWED TO THE BAY....

The natural pattern of freshwater inflow to the Bay is shaped by California's Mediterranean climate. About 80% of the annual precipitation in the Bay's watershed occurs from November through March[2]. Winter storms can deposit large amounts of rain or snow in a matter of days, increasing runoff dramatically for short periods and periodically freshening the Bay. As temperatures warm in the spring, accumulated water held in the mountain snowpack – the state's largest "reservoir" – melts and flows into the Bay, with high runoff that freshens the Bay for a much longer period than the peak flows that follow winter rainstorms. The high volume of the spring flow establishes an ecologically important salinity gradient in the estuary, which creates freshwater habitats in the Delta and parts of northern San Francisco Bay and increasingly brackish water habitats closer to the Golden Gate. As freshwater flows to the Bay decline in late summer and early fall, the zone of brackish water moves upstream as far as the western part of the Delta. Except under drought conditions, the Delta remains a freshwater ecosystem throughout the year[3].

As discussed later in this report, the estuary's native species have adapted to this naturally variable pattern of inflow to the Bay. The first pulses of runoff from winter storms trigger the migratory journeys of juvenile salmon and cue fish that live in the Delta and northern San Francisco Bay to begin to move to spawning areas. The large winter floods and spring snowmelt shape habitat availability in the estuary and drive numerous essential ecological processes downstream.

High year-to year variability in precipitation and runoff is characteristic of a Mediterranean climate. Multi-year wet periods and dry periods (droughts) also are typical. Since the mid-1970s, the Bay's watershed has experienced three very dry periods (1976-1977, 1987-1992, and 2012-2015) and two extended wet periods (1978-1986; 1995-2000). Within the last millennium, the watershed has experienced even longer (decade- to century-long) droughts and wet periods[4]. The high variability between seasons and across years and the resulting shifts in the estuary's salinity were probably essential in limiting the establishment of invasive non-native species prior to the 20th century.

... UNTIL WE DISRUPTED THE PATTERN – AND RADICALLY REDUCED FLOWS TO THE BAY

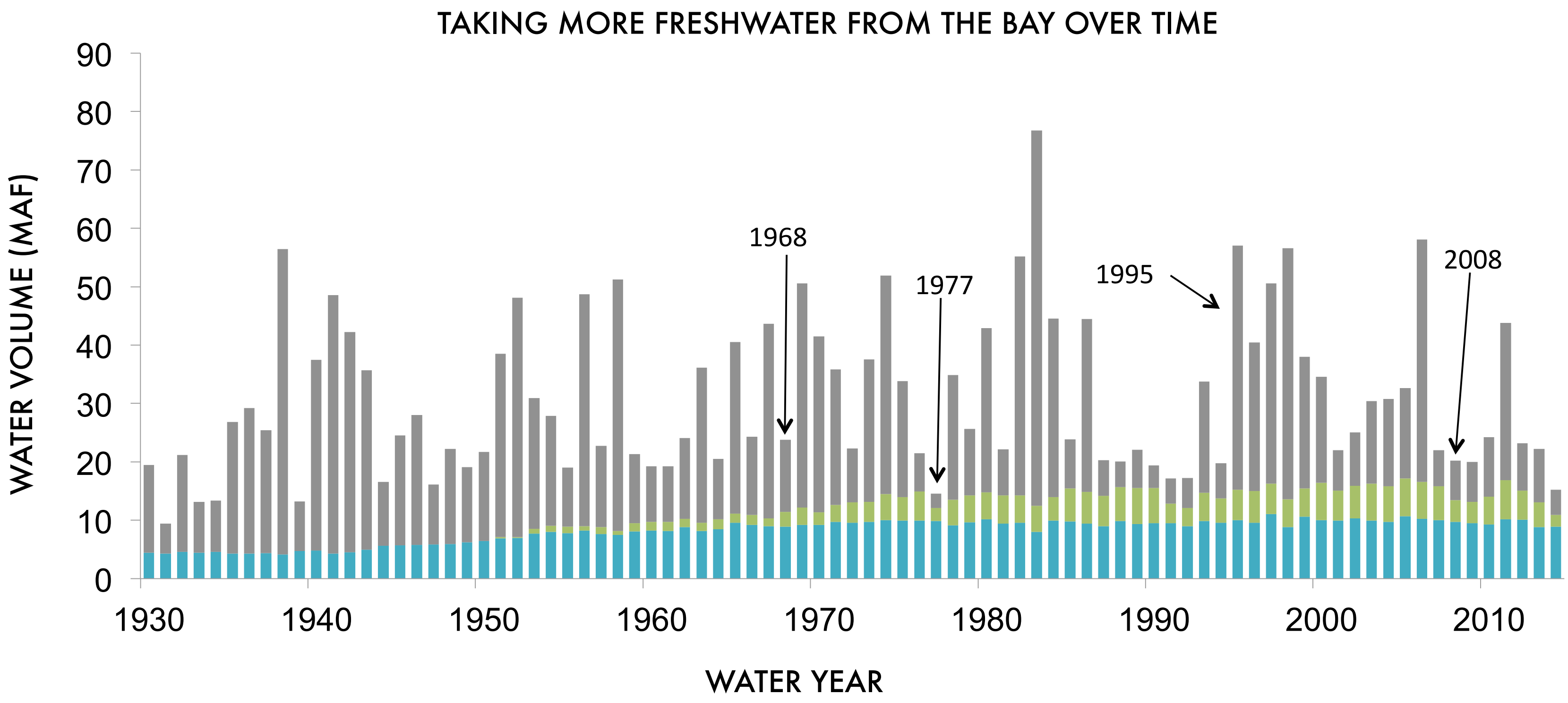
By draining and filling wetlands and floodplains for conversion to agriculture and denuding hillsides for mining and logging, Californians began to change the pattern of runoff from the Bay's watershed in the latter half of the 19th century. These actions reduced the watershed's capacity to absorb snowmelt and storm runoff and increased the sediment load in rivers and streams. Agricultural diversions upstream of the estuary also increasingly reduced the total amount of fresh water that made it to the estuary. The impact on Bay inflows throughout the watershed became more pronounced in the 1920s and 1930s as flood control projects were built in the Sacramento Valley, the construction of dams and use of motorized pumps for wells drove the tremendous expansion of irrigated agriculture, and growing Bay Area cities started importing water from rivers that drained to the Bay. Urban landscapes, with their impermeable surfaces, further decreased the watershed's ability to retain or slow runoff from periodic storms. Much larger inflow changes resulted from the construction and operation of the massive federal Central Valley Project (CVP) – including Shasta Dam on the Sacramento River, Friant Dam on the San Joaquin River, and the Tracy Pumping Plant in the Delta – in the 1940s and 1950s.

The final component in the radical alteration of the Bay's hydrology came in the 1960s and 1970s when the State Water Project (SWP) began operating the Banks Pumping Plant in the Delta that exports water to cities in the southern Bay Area and Southern California and agriculture in the San Joaquin Valley. Together, the state and federal Delta pumping facilities are part of the world's largest water storage and conveyance system; they have become the single largest extractor of the Bay watershed's fresh water. Since 1985 the combined CVP/SWP exports from the Delta have averaged over 5 million acre-feet per year, and over 6 million acre-feet per year in the period from 2000 to 2007 (Figure 3).

Since the SWP began exporting water from the Delta, a variety of state, federal, and local water agencies have constructed many more large dams and canals throughout the Sierra Nevada and Central Valley to capture, store and transport watershed runoff. Thousands of dams, over 600 large reservoirs, and 1300 miles of aqueducts now store and re-distribute over 30 million acre-feet of water, roughly equivalent to the surface water runoff from the entire watershed in an average year[5].

This massive transformation of the watershed has dramatically altered every component of the natural Bay inflow pattern, including the magnitude and timing of flows, the frequency and duration of high flow events, and the variability between high and low flows. The magnitude of the reduction in freshwater flow inputs is revealed by comparing the amount of water that actually reaches the Bay to the amount that would have reached the Bay if there were no dams, diversions, or exports of water ("unimpaired flow" or "unimpaired runoff"). The percentage of annual unimpaired flow that actually reached the Bay prior to the completion of Shasta Dam (1945) was much greater than it has been since the SWP began withdrawing major amounts of flow from the Bay's watershed, in 1968. Since 1975, total annual flow is on average less than 50% of what it would be without storage in dams, diversions, and direct exports from the Delta (Figure 3). In some years, it is less than 35% (Figure 5, left panel). Worse yet, even greater reductions in flow during the ecologically important winter and spring seasons occur frequently.

TAKING MORE FRESHWATER FROM THE BAY OVER TIME



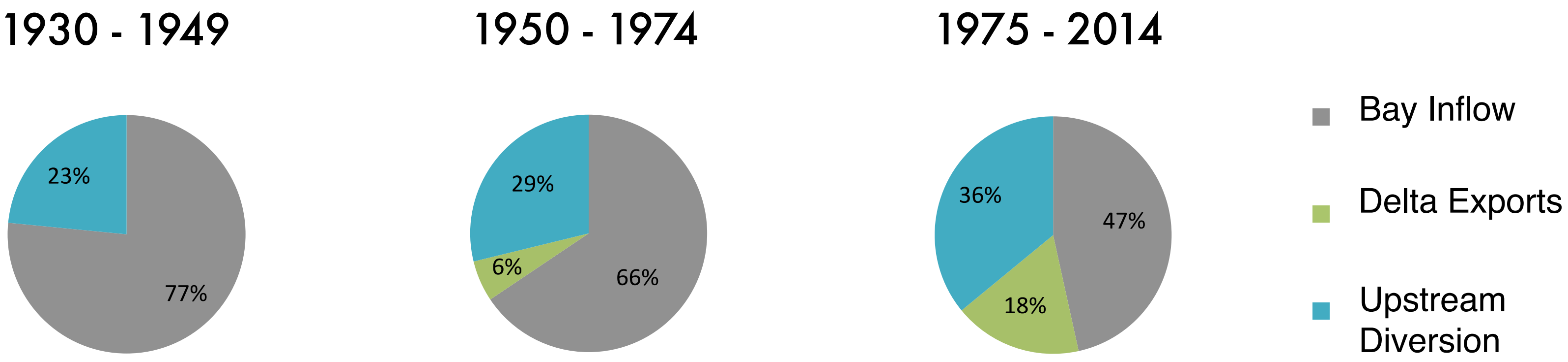


Figure 3: The amount of fresh water that would flow to San Francisco Bay from California's Central Valley (bars, top panel) varies tremendously from one year to the next. By contrast, the amount of available Central Valley runoff that is diverted or stored upstream (aqua bars) or exported from the estuary (green bars) for agricultural, industrial and municipal uses has increased steadily over the last half century. As a result, the proportion of water diverted or exported from the estuary has also dramatically increased over the same time period (pie charts, bottom panel), leaving less water to flow into the Bay (grey). Recently, diversions and exports of water have averaged approximately half of the amount available – in dry years, much less than half the runoff reaches the Bay. Important years identified in the figure, include 1968, when the State Water Project began exporting water from the Delta; 1977, a record drought year; 1995, when water quality standards for the estuary were last updated; and 2008, when new federal protections for imperiled Delta smelt, Chinook salmon, steelhead, and green sturgeon were issued.

About 80% of the water diverted from the Bay's watershed is used for agricultural irrigation. Photo credit: Fernand Ivaldi, Getty Images

SAN FRANCISCO BAY'S DEVASTATING, PERMANENT DROUGHT

Because Bay inflows have been drastically reduced and flow patterns radically altered, the estuary has experienced extreme drought conditions for much of the past four decades. The amount of runoff associated with the very driest years was once the exception. It is now the new normal. The overall change in Bay inflows from human water use has been so severe that the Bay ecosystem is experiencing a nearly permanent drought (Figure 4). The driest winter – spring period in the last 95 years occurred in 1977. But because so much runoff is now captured (especially during the winter and spring months), the estuary experienced 1977-like, "super-critically dry" conditions in 19 years, or almost half the years between 1975 and 2014. In contrast, wet year conditions (in which native species have the best chance to recover from persistently low Bay inflows) occurred in the Bay's watershed in 25% of the past 40 years. But actual flows to the Bay resembled those of wet years in just four years during the 1975-2014 period. During six of the past 10 years less than 40% of the unimpaired runoff available in the winter and spring made it to the estuary.

PERMANENT DROUGHT: HOW MUCH OF THE WATER IN THE

UNIMPAIRED

WINTER-SPRING RUNOFF CONDITIONS IN THE BAY'S CENTRAL VALLEY WATERSHED 1975-2014

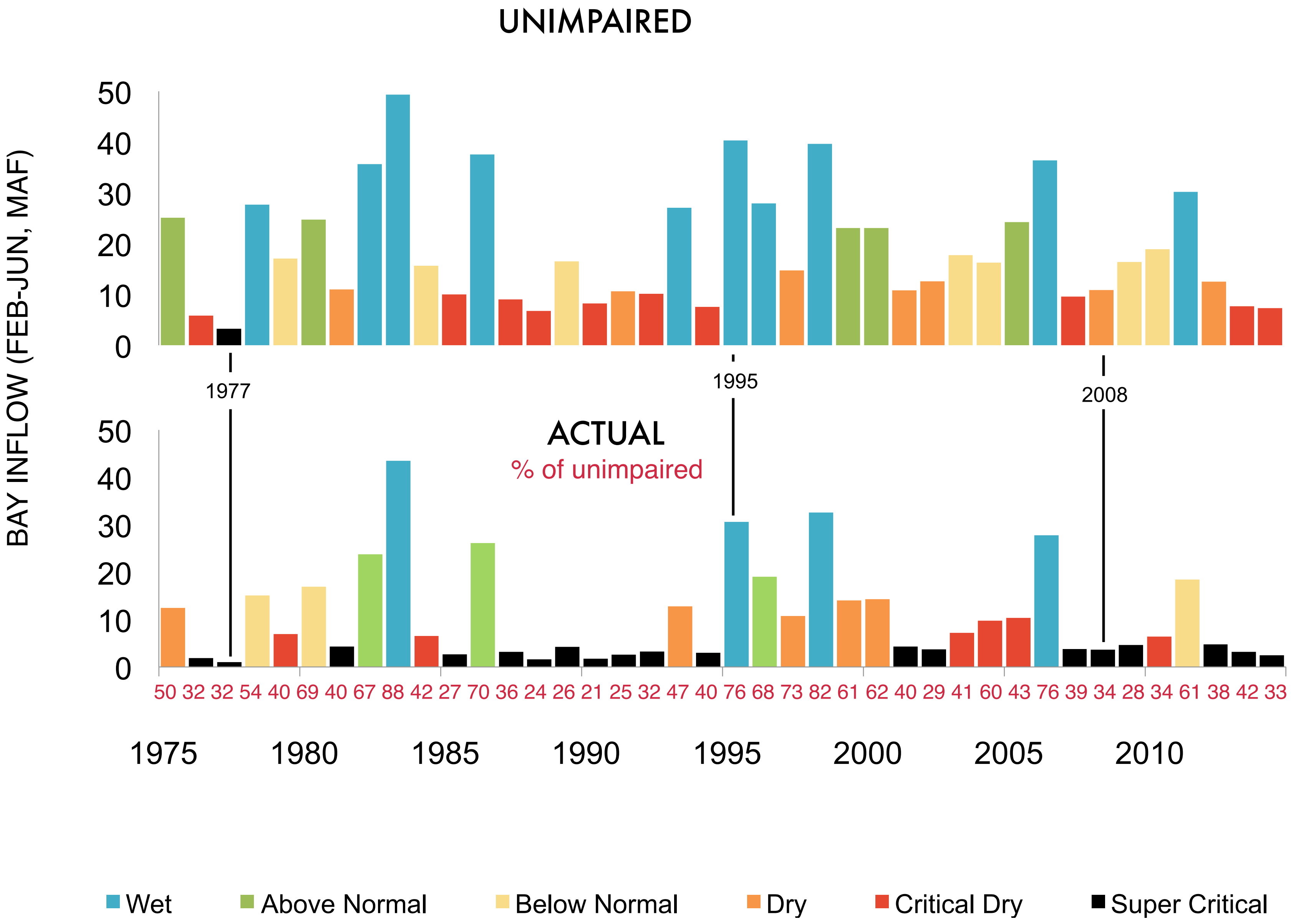
ACTUAL

WINTER-SPRING INFLOW CONDITIONS IN THE BAY 1975-2014

Figure 4: The Bay's vast watershed receives massive volumes of snow and rain in some years and very little in other years. Most of this water becomes runoff during the winter and spring months and many native species have evolved to capitalize on this pulse of water. The percentage of available runoff that reaches the Bay decreases as the combined total of watershed diversions and Delta exports increase. By dividing winter-spring runoff conditions into categories, the bar charts to the right show when Wet (blue), Normal (green), Below Normal (yellow), Dry (orange), Critically Dry (red), and Super Critically Dry (black) years occurred in the Bay's watershed (upper bar graph; "unimpaired") and the corresponding conditions that actually occurred in the Bay (lower bar graph, "actual"). Each of these categories represent one-fifth of the years as measured by their unimpaired runoff, except for the Super Critically Dry category, which represents the driest single year (~2.5%) of the 40 years represented here.

The pie charts show the relative frequency of these different hydrological conditions as they occurred in the Bay's watershed (upper pie chart, "unimpaired") and what the Bay's ecosystem actually experienced (lower pie chart, "actual"). As a result of intensive water diversion and exports, the estuary and its unique and valuable fish and wildlife species have experienced extremely dry conditions throughout most of the past four decades. For example, Super Critically Dry conditions, which occurred naturally only in 1977, are by far the most common conditions experienced in the estuary these days. Wet conditions occurred in the Bay less than half as frequently as they did in the watershed that feeds it. Years 1995 and 2008, marked on the bar graphs, correspond to state and federal actions that reserved relatively minor amounts of water for fish, and have failed to modify or mitigate the trend of intensive and growing diversion of Bay inflows.

BAY'S WATERSHED ACTUALLY REACHES THE BAY?



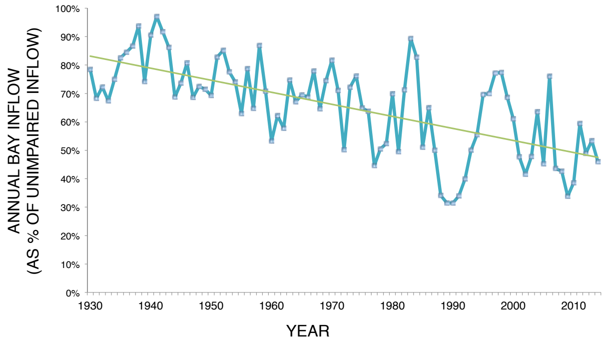
DRYING UP ECOLOGICALLY CRITICAL PERIODS

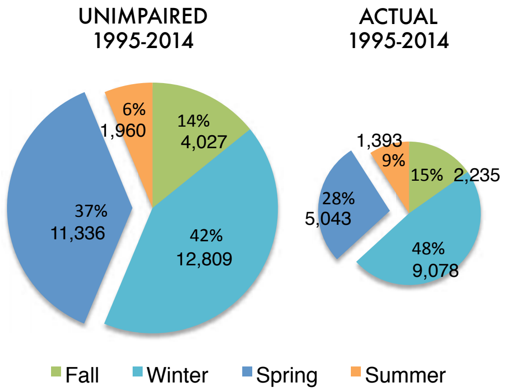
The change in total annual flow to the estuary is only one indicator of the massive changes in inflow to the Bay as a result of how California uses its limited water supply. The natural seasonal timing of flow has been modified as well (Figure 5, middle panel). For example, although over three quarters of the Bay's unimpaired inflow arrives as winter storms and spring snowmelt, the percentage of available runoff that actually made it to the Bay between February and June reached as low of 28% in 2009. During the last decade, only an average of 35% of unimpaired runoff made it to the Bay during May, making this the most impaired month of the year. In contrast, state water quality regulators report that 75% of unimpaired Bay inflow during the winter-spring period is necessary to fully protect the estuary ecosystem[6]; and in fact, scientific studies from around the world indicate that ecosystem function is severely impaired if less than 80% of freshwater flows remain in rivers[7]. When instead just one-third or less of these ecologically vital flows are allowed to make it to the Bay, there is absolutely no reason to expect any other outcome except ecological collapse.

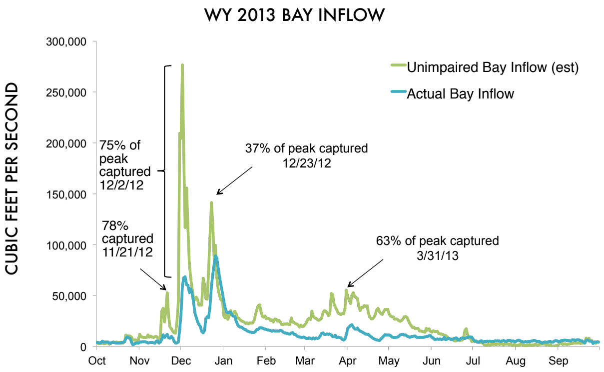
Even seasonal and monthly averages don't reveal the full impact of the change to Bay inflows – short-duration peak flows have been severely reduced, and nearly eliminated in many cases (Figure 5, right panel). In all but the wettest years, the brief pulses of flow that follow rainstorms and snowmelt events – and which are so important to migrating fish like salmon – have been virtually eliminated, as reservoirs, river diversions, and exports from the Delta capture these critical flow spikes. The biggest winter floods have been severely curtailed[8]. For example, in late November and December of 2013, 75-78% of the peak flows were captured in reservoirs, diverted upstream, or exported directly from the Delta. The precious runoff that does still make it to the Bay—from below dams and the few remaining undammed watersheds—could be further curtailed if one or more new and expanded dam and diversion projects, most of which would be very expensive, produce low yields, and be partly subsidized by taxpayer funding, are built and operated.

Upstream dams and diversions capture the majority of runoff in the Bay's watershed. Photo Credit: California Department of Water Resources

A BAY CHANGED: ALTERATIONS TO FRESHWATER FLOW







ANNUAL

Compared to the amount of runoff in the Bay's Central Valley watershed each year, the amount of water that actually reaches the Bay has been declining steadily over time. A greater proportion of available runoff (the "percentage of unimpaired flow") reaches the estuary in wetter years; during dry years the Bay receives proportionately less of the water available. This occurs because the total amount of water that humans divert and store in reservoirs does not vary much in response to annual hydrology.

Data source: CDEC and DWR Dayflow

SEASONAL

The fraction of water that would arrive in the estuary during different seasons without storage and diversions (unimpaired conditions; left pie chart) and what actually arrives after the effect of human water management (right chart, numbers are volume in thousands of acre feet). Not only is the volume of freshwater flow reduced, but the distribution of this flow across seasons is altered as well. For example, under unimpaired conditions, 37% of the Central Valley's runoff would flow to the estuary during the spring, but only 28% of the (much smaller) volume that actually makes it downstream arrives during the spring. This disproportionate reduction in fresh water flowing into the estuary during the spring occurs during the very season when native fish and wildlife population are most responsive to freshwater flow.

PEAK FLOWS

Estimated flow to San Francisco Bay during a year in the absence of storage or diversions (green line) compared with the estimated flow that actually reached the estuary (blue line). The difference between unimpaired and actual inflow on key dates shows that natural early season peaks in flow are largely eliminated by storage and diversion operations. Native species rely on pulses of water (which result from periodic rainfall and snowmelt events) to orient during migration and to cue important life cycle transitions. California's water management practices eliminate this important natural signal. The loss of short duration peak flows puts native species at a disadvantage and facilitates invasion by non-native species.

Figure 5: Water storage, diversion, and export changes the natural pattern of freshwater flow in multiple ways. The total amount of water diverted from the estuary and its watershed for human use increased steadily over time, resulting in less and less fresh water making it downstream annually (left panel). The timing of the freshwater flow that remains is also radically altered by human water management practices. For example, the seasonal timing of flow has been changed such that proportionately less water arrives during the ecologically critical spring months (center panel). Also, diversions have a disproportionate effect on short-term peak flows, which native species rely on to orient their migrations or to spawn (right panel).

American avocet Photo Credit: Judy Irving

STARVING THE BAY

HOW FLOW REDUCTIONS DAMAGE KEY COMPONENTS OF THE BAY'S ECOSYSTEM

As rivers approach the sea, salty and fresh water mix to form an estuary. In addition to diluting what would otherwise be seawater, the freshwater flowing into an estuary creates unique and productive ecosystems. Estuaries contain special fresh water and brackish (low salinity) habitats that shift position dynamically in response to the tides and seasonal or annual variations in fresh water flow. The balance between fresh and salt water determines the size and shape of these estuarine environments and their capacity to support the fish and wildlife species that have evolved to specialize in them.

How much freshwater flow makes it as far as the estuary, when it arrives during the year, and the extent to which the amount and timing of arriving flow change from year to year, all determine what kind of benefits fish, wildlife, and humans receive from the estuarine environment. When the flow of fresh water is reduced dramatically for a prolonged period of time, the transport of nutrients, food (from simple photosynthetic organisms to fish), and sediment from the watershed into the estuarine environment is reduced as well. In the absence of periodic flushing, pollutants accumulate in the system. In addition, reduced freshwater flow facilitates invasion by undesirable, non-native species and proliferation of harmful organisms that generate toxic water pollution. Alone and in combination, the effects of reduced freshwater flow into the Bay estuary undermine its water quality, its ability to support fish and wildlife populations, and the formation and maintenance of surrounding beach and wetland habitats.

This chapter describes how changing freshwater inflows to the Bay directly affects many fundamental ecological processes, including salinity distribution, transport of sediment and biological materials, pollution control, habitat formation and maintenance, and food web dynamics. In many cases the specific mechanisms through which freshwater flow into the Bay acts on these processes and habitats are understood incompletely. Flow acts as a master variable, and its interactions with different ecosystem elements are complex and difficult, if not impossible, to untangle. Yet the size and diversity of freshwater flow's effects on the Bay's ecosystem are clear. The next chapter will explain how all these flow-related changes to the Bay impact the fish, wildlife, and people who rely on it for many critical services.

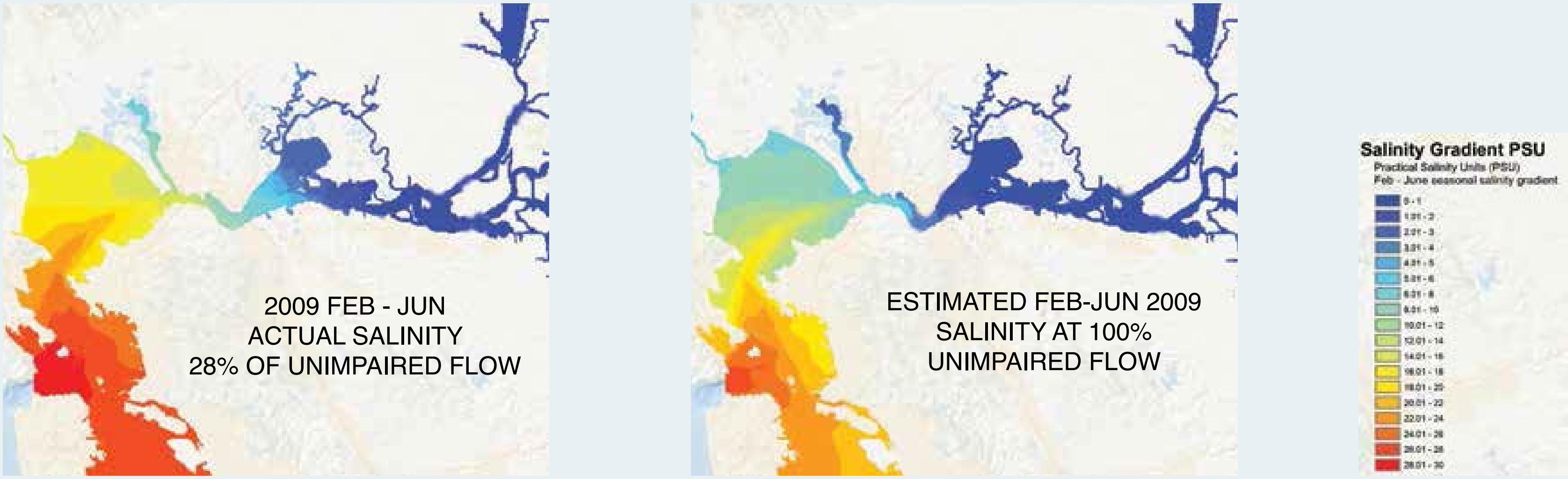
SALINITY

The transition from fresh water to salt water in the estuary is a dynamic gradient that moves daily, seasonally and annually. Where this transition occurs is influenced in large part by how much fresh water flows into the estuary. The amount of water at different salinity levels determines the quantity and quality of habitat for plants and animals that live in the estuary. Habitat condition and location can be altered by salinity in many ways, including:

- Extent – how much habitat is there?
- Distribution – where in the estuary is the habitat available?
- Quality – how suitable is the habitat for the species that use it?
- Connectivity – can species access and move among habitats?
- Timing – is the habitat available during key life stages for species?
- Persistence – is the habitat available for multiple generations?

Reductions in freshwater flow to the Bay shift the timing and location and restrict the extent of the salinity gradient, altering estuarine habitats in ways that can translate to population level effects on species that utilize those habitats. Periods when the average salinity was as high as in the past half-century previously occurred only three times in the last 1,600 years – during recent droughts, January – July salinity was the highest it has been in 400 years. The timing of peak inflow has been changed from May to February, changing the position of the estuary's salinity field throughout the spring and summer months[9] (Figure 6). How the salinity field is affected depends on what part of the estuary is being considered.

THE EFFECT OF WATER DIVERSION ON SALINITY IN THE BAY



In 2009, a Dry year in the Bay's watershed, only 28% of available runoff from the Central Valley made it to the Bay; the rest was diverted, stored, or exported. Because there was so little fresh water, Central Bay, San Pablo Bay, and even parts of Suisun Bay became very salty.

Had no water been stored, diverted, or exported, the salinity distribution in 2009 would have looked more like this (the actual salinity distribution in 1980). Fish and wildlife that use freshwater and brackish habitats would have been able to use all of Suisun Bay and most of San Pablo Bay.

Figure 6: Water diversions and exports affect the distribution of salinity throughout the Bay. Most aquatic organisms are sensitive to the salinity of their habitat; thus, changes in salinity distribution reflect changes in habitat availability for many of the Bay's species. These maps show the actual distribution of salinity in one Dry year (2009; left panel) and what the salinity distribution would have looked like without diversion or export of fresh water (right panel).

Data sources: U.S. Environmental Protection Agency. Salinity Gradient - Coarse-grid version of UnTRIM San Francisco Bay-Delta Model, Delta Modeling Associates. Basemap - ESRI, DeLorme, BEBCO, NAANGDC, & other contributors

GROUND ZERO: THE SALINITY TRANSFORMATION OF NORTHERN SAN FRANCISCO BAY AND THE DELTA

Bay fish and their prey benefit from lower salinities at critical times: A unique and ecologically critical area known as the low salinity zone (LSZ) occurs in the upper, northern part of the estuary. This zone is especially important for juvenile fish and invertebrates[10]. Historically, as freshwater flows naturally increased in the winter and spring, the LSZ was located in the broad, shallow reaches of Suisun and San Pablo Bays, and shifted gradually upstream in the summer and fall. Numerous scientific studies over many decades have documented the powerful and persistent correlations between the abundance of many of the Bay's fish populations, including longfin smelt, starry flounder, and striped bass, with the position of the LSZ in the ecologically sensitive winter and spring period[11]. That is, the number of fish of many estuarine populations increases as the LSZ moves downstream in response to increasing flows. How fish and invertebrate populations are distributed is also correlated with the location of the LSZ, with benefits decreasing as the zone shifts upstream with less inflow. For example, the position of the LSZ during the winter and spring affects the exposure of larval and juvenile fish to diversion into the large export pumps in the southern Delta[12]. The abundance and distribution of Delta smelt are also correlated with the location of the LSZ in the fall[13].

Several types of zooplankton (small invertebrate animals) are also strongly affected by the position of the LSZ, including mysid shrimp, Bay shrimp, and seasonal populations of other small zooplankton[14]. These organisms are essential food for the Bay's fish and wildlife populations. The historic zooplankton community in the LSZ has been devastated over the past three decades by a combination of reduced freshwater inflows to the Bay, increased water exports from the Delta, and the introduction of non-native invasive species[15]. Allowing more of the Central Valley's natural flow of fresh water to reach the estuary during the spring is one of the few tools available to improve the distribution and increase the abundance of important zooplankton species in the open waters of San Francisco Bay.

Exotic species invade when salinities are less variable: Reducing inflows not only constrains the downstream movement of the LSZ but also generally keeps the salinity field more uniform and less dynamic from season to season and year to year in the upper reaches of the estuary. This reduced salinity variation is a primary factor in the establishment and success of undesirable non-native plant and animal species. For example, establishment of nuisance species such as the overbite clam appears to have reduced phytoplankton abundance in the upper estuary[16]. There is evidence that exotic zooplankton invasions are facilitated by consistently low inflow to San Francisco Bay[17]. Some introduced species, like inland silverside – a voracious predator – increase in abundance during periods when flows are low[18]. Once established, these invaders contribute to deteriorating habitat conditions for native species by competing for food, space and other important habitat needs.

Wetlands change as salinity changes: The freshwater and tidal marshes and riparian areas that occur on the margins of the upper estuary buffer the land from tides and storm surges and support over 500 fish and wildlife species, including a large number of rare species such as Suisun song sparrow, San Francisco common yellowthroat, California black rail, and giant garter snake[19]. Restoring wetland habitat is a high priority for current management efforts; currently, less than one tenth of historic wetland remains around the Bay and only 4% in the Delta[20].

Pollen records indicate that extended periods with higher than average salinity have previously occurred only three times in the last 1,600 years[21]. Since 1950, primarily as a result of flow reductions and flow pattern alterations throughout the Bay's watershed, we are now experiencing the fourth such period[22]. Tidal marshes with higher salinity have lower numbers of plant species and are less productive[23]. Even short-term changes in freshwater inflows can convert freshwater marsh to brackish marsh, and brackish marsh to salt marsh; as temperatures, atmospheric CO2, and salinities all rise, the longer-term impact of wetland conversion could have large consequences on ecosystem function[24].

Ridgway's Rail (formerly, Clapper Rail) is one of many species native to the San Francisco Bay area that are endangered. These secretive birds, which rarely fly, forage in tidal mudflats and make their homes in the upper vegetated zone of the marshes that once dominated the Bay's margin. Photo Credit: David Sanger

Small shifts in salinities can affect how seeds germinate, grow, and are distributed; which species occur; and how much food the marsh provides for fish and wildlife[25]. For instance, during the short but severe 1976-77 drought, a marsh at the east end of the Carquinez Strait became much more saline and plant composition shifted, with bulrush decreasing and salt-tolerant pickleweed invading. These changes can be long lasting; according to one study, when salts accumulate in tidal marsh soils, "larger pulses of fresh water of greater duration will be required to reduce soil salinities in the marsh and promote germination and recruitment"[26].

Marsh formation is critical as a tool for adapting to climate change. Salinity plays a key role in the rate at which marshes can rise in response to changing sea levels. Organic matter accumulates faster in freshwater marshes, and the rate of soil formation decreases with increasing salinity[27]. Absent sufficient freshwater inflow, sea level rise will push the salinity field further inland, reducing the area available for brackish and freshwater habitats in the upper reaches of the estuary. The resulting conversion of brackish and freshwater wetlands to salt marsh will reduce the amount of marsh area that can buffer the impact of rising seas. As marshes erode, so too do the benefits of flood regulation and water quality control that they provide to communities along the estuary's shores. Also, reductions in the area of less saline marsh habitat will affect species like black rails that depend on vegetation not found in salt marshes.

LOOKING DOWNSTREAM: SALINITY CHANGES IN CENTRAL AND SOUTH SAN FRANCISCO BAY ARE ALSO A PROBLEM

Farther downstream, the saltier Central and South Bays also experience major salinity changes when freshwater runoff into the Bay is high. In the winter and spring— the time of year when human activity alters flows the most – reducing Bay inflow can change salinity distribution in the Central and South Bay even more than in the upper estuary[28]. During the 1987-1992 drought, for example, when inland water diversions and exports reached (then) record high levels, the winter – spring salinity at Fort Point, under the Golden Gate Bridge, was the highest experienced in 400 years[29].

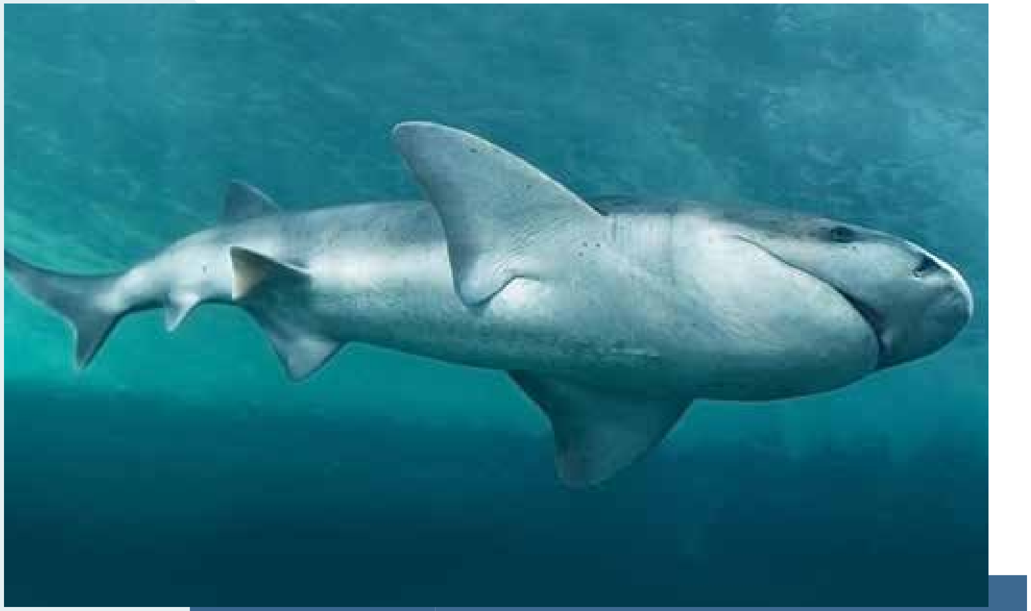
Species in Central Bay shift in response to flow-related salinity changes: What kinds of species are present in the Bay near San Francisco, and how they interact, are influenced by freshwater inflow and the salinity field. For instance, rates of growth, reproduction and migration for invertebrates in the Bay like oysters, barnacles, and sea squirts (sessile marine invertebrates) are highly affected by freshwater inflows. When winter inflows are reduced, large non-native sea squirt species dominate the invertebrate community, competing for space and limiting populations of other species, such as oysters. Although prolonged exposure to fresh water during very high flood flows may kill oysters, new oyster populations readily establish at lower salinities, probably in response to the limiting effects of higher flows on their invasive competitors[30].

Seasonal salinity stratification dominates the South Bay: During the summer and fall, the lagoon-like South Bay is about as salty as the ocean, with circulation driven by the tides and winds. But, in winter, high freshwater inflow from the upper estuary can cause strong density-driven currents to form, with fresher water on top and saltier water on the bottom—a phenomenon known as stratification. As Bay inflow diminishes through the spring, and as more saline water outside the Golden Gate is drawn into the Bay by tides, the Central Bay becomes saltier and a density-driven current of more saline water flows into the South Bay along the bottom. The South Bay is usually stratified in the spring, and unstratified in summer and fall. This seasonal pattern causes a spring peak in phytoplankton productivity[31], and many fish species respond positively to the changes in South Bay salinity associated with the variation in Bay inflow[32].

BEYOND THE BAY: FLOW EFFECTS ARE FELT IN THE GULF OF THE FARALLONES

Salinity changes in the saltiest part of the estuary – the Gulf of the Farallones, just west of the Golden Gate – are also most influenced by the seasonality and magnitude of freshwater flows. During winter and spring, outflows from the Bay create a plume of brackish water (as low as 20 parts per thousand [ppt] salinity and up to 5 meters deep), stimulating phytoplankton growth and contributing to overall foodweb productivity in the Gulf of the Farallones, a protected marine sanctuary[33]. At times, this plume briefly extends as far offshore as the Farallon Islands and Cordell Bank. The plume tends to turn to the north in winter, extending as far as Ft. Bragg, CA. During the summer when flows are lower, the plume is smaller but still extends outside the Golden Gate, turning to the south[34].

Plankton and larger organisms such as salmon, sharks, and marine mammals all converge at the plume front. Birds that nest on the Farallon Islands also feed at the plume front. But this highly productive, flow-driven habitat is being diminished. Bay inflow accounts for 86% of the variability in salinity at the Golden Gate[35]. Salinity at the ocean boundary has increased by 12 parts per million per year since 1920[36], showing that the brackish water plume has become substantially reduced over time[37].



Sevengill shark Credit: Aquarium of the Bay

The Bay – ocean connection is a two way street: Increased inflow to the Bay and subsequent outflow to the ocean during the spring increases the exchange of water, nutrients, and organisms in both directions. Wind-driven coastal upwelling brings denser, cooler, nutrient-rich, saltwater closer to the ocean surface. As this marine water flows into the Bay, it benefits bottom-feeding organisms[38]. When spring inflows to and outflows from the Bay are reduced, not only are the ecological benefits of the brackish water plume at the surface affected, but the importation of saltier water along the bottom is also cut back, reducing nutrient inputs to the Bay's benthic habitats[39].

These two phenomena – upwelling of nutrient-rich water and the brackish plume – interact to form the rich marine ecosystem of the Gulf of the Farallones. Reducing inflows to the Bay not only limits the benefits the Bay receives from both of these ecologically important processes, but may also affect the productivity of coastal environments. Indeed, the state of our scientific understanding indicates that freshwater flows into the estuary have multiple effects that reach far downstream into marine environments. According to a recent study:

> “The effects of [freshwater flow from the watershed] propagated further down the estuary salinity gradient than [effects from the Pacific Ocean] that propagated up the estuary salinity gradient, exemplifying the role of variable freshwater outflow as an important driver of biotic communities in river-dominated estuaries.”[40]

In plain English, freshwater flow impacts downstream areas more than the more saline habitats downstream impact the fresher upstream areas. As the effects of climate change become more acute, the benefits of freshwater flow for coastal waters will become even more critical. Warming ocean conditions, weaker upwelling, and shifts in the Pacific Decadal and North Pacific Gyre Oscillation are reducing marine productivity along the California coast with cascading effects on the food web[41]. As productivity declines, birds, fish and marine mammals are more likely to starve and less likely to reproduce successfully. For these creatures, improving freshwater flows would help grow the food items, such as juvenile salmon, that are an important part of the offshore food web, and would also restore seasonal brackish surface water habitats in the Gulf of the Farallones, supplying fuel for the marine ecosystem outside the Golden Gate and potentially helping to offset oceanic climate change effects.

SEDIMENT

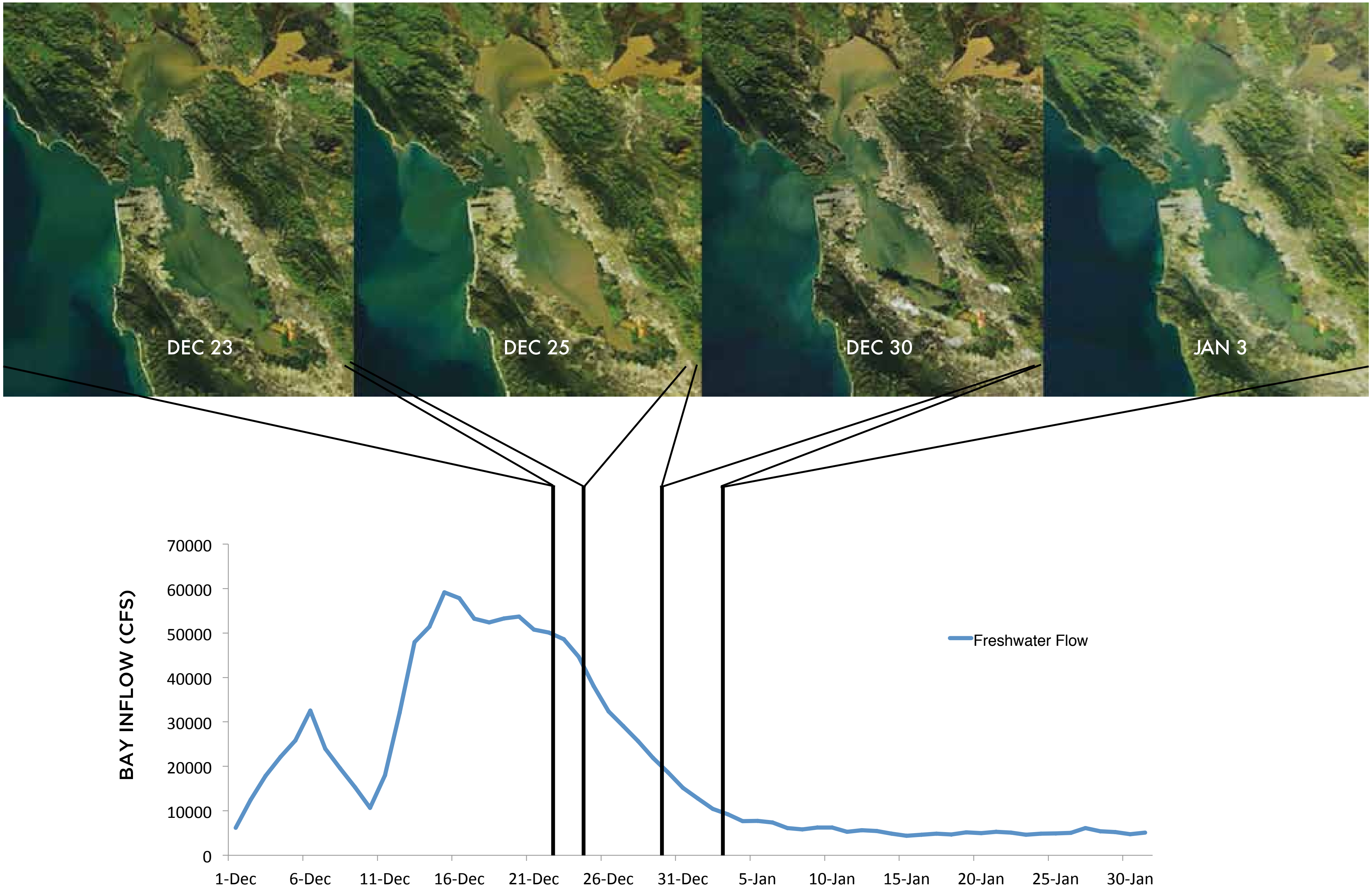
Moving water transports particles of varying sizes, from large gravel to silt to tiny bits of organic matter, collectively termed “sediment.” In the Bay, the transport of sediment plays a vital role in the formation of habitats like marshes and beaches. In addition sediment-laden high flows contribute to the occurrence of cloudy, “turbid” water in the estuary’s upper reaches, an important habitat attribute for many fish.

Water moves more sediment when it flows faster. In the Bay’s watershed, most sediment is transported during high flow periods (Figure 7). Eventually the water slows down as it reaches the tidal parts of the estuary, with the heaviest particles settling out first. Sediment is deposited on the bottom of the Bay and in marshes along its edges. Sediment passing out the Golden Gate may remain suspended, settle to the ocean floor, or be deposited on nearby beaches.

LESS SEDIMENT REACHES THE BAY TODAY

Over time, humans have dramatically altered the amount of sediment delivered to the estuary, with significant ecological and human costs. In the 19th century, the amount of sediment reaching the Bay actually increased because of erosion from ranching, farming and hydraulic mining in the Sierra Nevada[42]. In recent times, however, far less sediment has flowed downstream – with major consequences for the Bay. Thousands of dams constructed over the past century and a half throughout the watershed now trap the flow of gravel, clay, sand and silt. Meanwhile, hundreds of miles of stream bank were engineered to limit erosion in the watershed. Submerged islands trap sediment in the Delta[43] and dredging of navigation channels removes sediment directly from the system[44].

FRESHWATER FLOW MOVES SEDIMENT INTO AND THROUGH THE BAY



Images from NASA

Figure 7: Peak flows of fresh water into the estuary carry sediment through San Francisco Bay and beyond. The graph above shows flow during a brief pulse of freshwater flow in the days following a December 2014 storm. When Bay inflows increase, a plume of suspended sediment is transported downstream, as seen in the satellite photos of San Francisco Bay from December 23, 2014 to January 3, 2015. Sediment suspended in the Bay's waters from these infrequent, but critically important, peak flow events is important for restoring tidal marshes and maintaining habitat for native fishes. Sediment supplies to the Bay and nearshore ocean have been limited by physical changes to the landscape (e.g., they are trapped behind dams and removed by dredging) and by elimination of the higher peak flows that could mobilize the sediments that remain. New projects to store or divert large amounts of water upstream of the Bay could siphon off more of the declining suspended sediment supply and further truncate the peak flows that carry that sediment downstream.

IT'S CLEAR – AND THAT'S THE PROBLEM

Capturing more water upstream and regulating downstream releases traps large volumes of sediment in reservoirs, limits erosion and overbank flooding along Central Valley rivers and tributaries, and reduces the frequency of flood events that would otherwise allow more sediment to reach the Bay[45]. Peak flows that can mobilize significant amounts of sediment occur much less often, and when they do, they carry much less sediment than previously[46]. Sediment input from the largest source in the Bay's watershed, the Sacramento River, declined by half between 1957 and 2001[47].

Many estuarine fish species respond to water turbidity – reduced visibility due to suspended sediments – in order to evade predators, find food, and move between habitat areas. Because the amount of sediments available for resuspension in the Bay has declined, turbidity has been dramatically decreased – by 36% in 1999[48] and by as much as 40% in the Delta[49]. The occurrence of clearer water is believed to expose highly endangered fish species like salmon and Delta smelt, and other organisms to increased risk from predators[50] and lost feeding opportunities[51].

FEEDING HUNGRY MARSHES AND BEACHES

A healthy sediment supply is crucial to the persistence of marsh and beach habitats throughout the estuary. As they become saltier due to reduced inflows, the brackish and freshwater marshes of the upper estuary require even larger amounts of sediment to maintain their physical form and elevation[52]. The problem is magnified by accelerating sea level rise, which will drown the Bay's existing wetlands unless they gain elevation. Maintaining low Bay inflows – or further reducing them – at the same time that sea levels rise, will ensure continued loss of this unique estuarine habitat. Reducing sediment inputs to wetlands undermines California's large-scale investment of time, money and energy to restore them.[53]. These and all types of wetlands are not just habitats for fish and wildlife; they also function as barriers against the effects of sea level rise on at-risk human communities and valuable infrastructure around the Bay; insufficient sediment inputs will make it more difficult to provide and maintain these barriers[54].

Bay inflows also transport sediments that feed and maintain local beaches, and these areas shrink or are lost as sediment inputs decrease. Twenty-three miles of sandy beaches in the Bay have been reduced to 7 miles, and most of the remaining beaches are in different locations than historical beaches[55]. Outside the Golden Gate, the coastline is the most rapidly eroding section in the state, with erosion accelerating 50% since the 1980s[56].

Baker Beach, Photo Credit: Christian Mehlführer

Although Bay inflow reductions aren't the only cause, they are an important contributor to the beach erosion problem. High Bay inflows can carry a lot of sand: at low flows, sand is a small percentage of the total sediment load in the Sacramento River, but it represents up to 70% of the total at high flows[57]. The loss of high flows into the Bay cuts off sand resupply to chronically eroding beaches throughout the Bay Area and along the open coast south to Pacifica (where most sediments have a Sierran origin, transported on flows from the Bay's watershed)[58]. Beach erosion in these areas removes habitat for many bird and invertebrate species, such as breeding populations of snowy plovers that require undisturbed beach area for nesting[59]. And, of course, people enjoy beaches too.

POLLUTION

Preventing pollution before it happens by eliminating or reducing toxic inputs to air, land, and water is always the best policy. In conjunction with that approach, maintaining adequate freshwater flow into the Bay helps to dilute the concentration of chemical and biological contaminants before they reach levels that are toxic and decreases the amount of time these substances spend in the Bay where the dilution factor is much lower than in ocean waters. Conversely, when freshwater flows are reduced for long periods, both naturally occurring and synthetic contaminants can increase to toxic levels.

TOXIC POLLUTANTS DO MORE HARM WHEN FLOWS ARE LOW

The amount of Bay inflow is known to significantly affect how readily available some heavy metals are to aquatic organisms like shellfish[60]. Silver and copper concentrations in benthic organisms in the South Bay typically decrease after winter inflows lower salinities, especially in years with higher flows. Reducing Bay inflows from the Central Valley could also reduce the effectiveness of processes that assimilate and neutralize waste in the South Bay[61].

Significant amounts of "legacy" contaminants from past mining and industrial practices are embedded in the Bay's sediments, where they can be taken up by benthic organisms and then bioaccumulate in the foodweb. Over the past 20 years, for instance, mercury and PCB (Polychlorinated Biphenyl) concentrations in fish have persisted at high levels, limiting consumption of popular fish species[62], even long after being phased out from human use. Low flows can exacerbate the transfer of contaminants from the sediment to the food web; in Suisun Bay, for instance, the concentration of mercury in suspended sediment is higher at low Bay inflows (because waves resuspend bottom sediment) and lower at higher inflows[63].

Selenium is a naturally occurring element, essential, in trace amounts, for animal cell function. But it is highly toxic at even slightly higher doses, causing birth defects, reproductive failure, or death. The primary sources of selenium in the Bay's watershed include discharges into the Bay from oil refineries and irrigation runoff from selenium-laden soils on the west side of the San Joaquin Valley.

Low flows promote uptake and integration of selenium into the food web[64]. Low flows are specifically correlated with higher selenium concentrations in clams[65]. As a result, diving ducks, sturgeon, and Sacramento splittail, which eat clams, can develop deformities and reproductive problems because of the elevated selenium levels associated with low flows[66]. Selenium concentrations in clams rise to a level of concern when Bay inflows are less than 7,000 cfs[67]; these extremely low Bay inflow levels occurred in 2014 and 2015 when the State of California relaxed minimum water quality and flow requirements in order to increase deliveries for agricultural irrigation in the Central Valley.

TOXIC ALGAL BLOOMS – CAN REDUCING FLOWS GENERATE NEUROTOXINS?

When freshwater flows are reduced to low levels, the estuary can become a good environment for harmful organisms that generate dangerous toxins.

Cyanobacteria (also known as “blue green algae”) are ancient photosynthetic ancestors of modern plants and algae. Some of the chemicals produced by cyanobacteria are extremely toxic to humans and wildlife. Periodic proliferation of certain cyanobacteria (such as Microcystis aeruginosa) are called “harmful algal blooms” or HABs. These blooms produce neurotoxins that can kill fish, aquatic mammals, waterfowl, and even dogs[68]. When these toxins get into drinking water supplies they are a real risk to human health.

Blooms of toxic cyanobacteria are occurring with increasing frequency in the upper estuary[69]. Toxins produced by HABs have been detected in invertebrates and fish throughout the entire estuary[70]. Organisms that are not killed outright by these toxins can transfer the poisons to their predators; the toxins become more concentrated as they move up the food chain (in a process known as “biomagnification”).

A recent review prepared for the California Environmental Protection Agency concluded that HABs in the Bay estuary are more frequent when water moves more slowly (increased residence time) and water clarity is high[71]; both of these conditions occur when inflows are low. The fact is that low flows not only fail to dilute or flush pollutants but also actually provide the very conditions that support the growth of organisms that generate powerful toxins. In this case, maintaining adequate inflows is a crucial element in preventing the creation of powerful toxins that threaten people and the environment.

Cyanobacteria bloom, Photo Credit: US Geological Survey

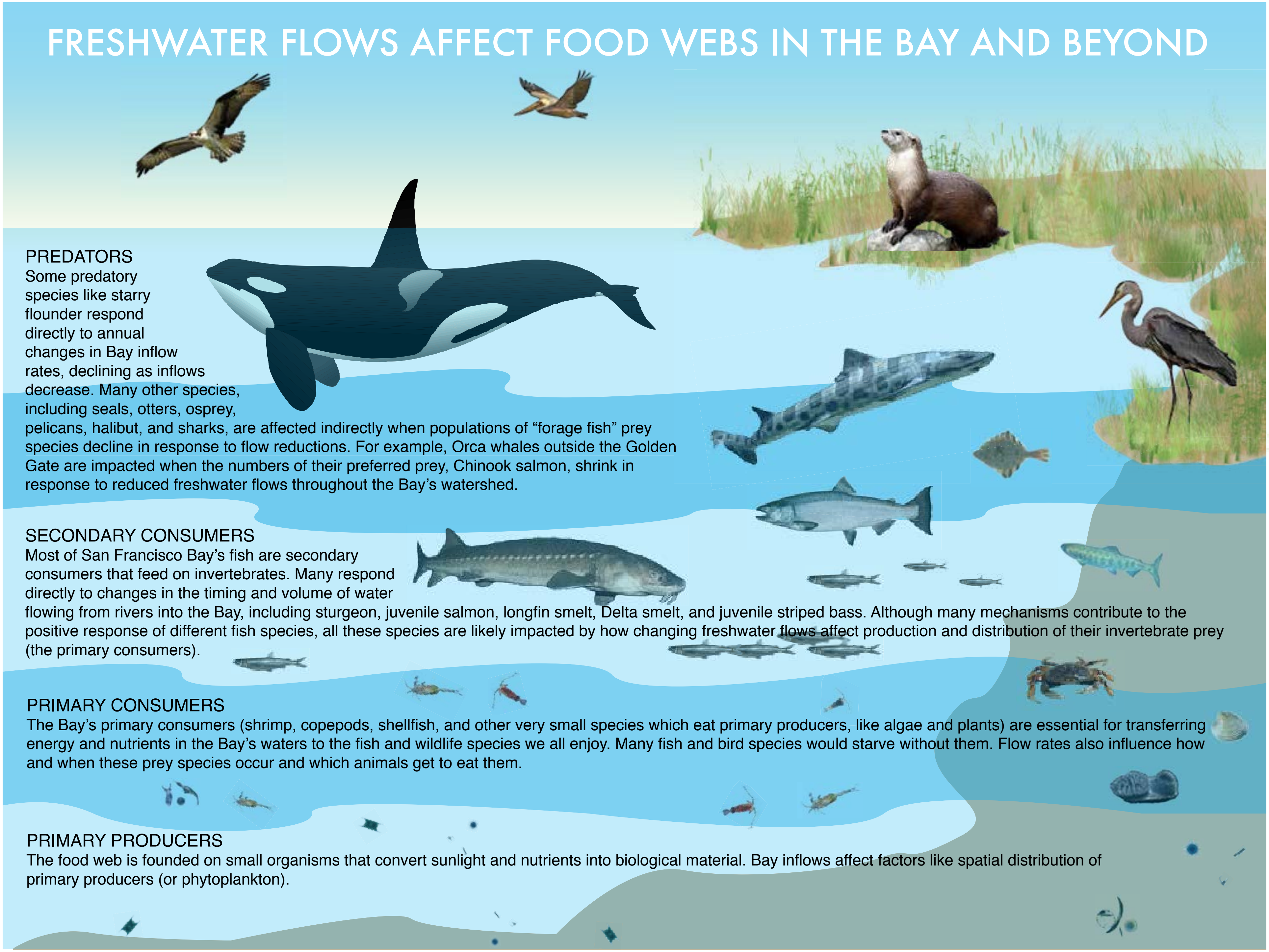
FOOD WEB PRODUCTIVITY

Estuaries are highly productive nursery habitats for fish, birds, mammals, and invertebrates like crabs and shrimp. The San Francisco Bay estuary is no exception. Beginning in the 19th century, San Francisco was the center of major commercial and recreational fisheries for salmon, sturgeon, herring, smelt, rockfish, halibut, flounder, and crab. The Bay’s bounty played a large role in feeding the growing population of central and northern California and even Oregon.

Not surprisingly, this natural productivity depends on the many environmental processes that are driven or influenced by how much fresh water makes it to the estuary. As river flows reach the upper estuary, they slow down and spread out into a mosaic of shallow waters, mudflats and brackish and freshwater marshes; all of the critical inputs of nutrients, sediments and food the flow brings supports the growth of phytoplankton (tiny aquatic plants) and zooplankton (very small invertebrate animals), and a host of larger creatures that feed on them, in the water column and along the wetland margins. These freshwater and brackish habitats are more productive than the saltier ones downstream[72] and a large number of rare species are only found there[73]. Even though there are many factors that affect productivity, the science is clear that productivity of the food web in estuaries is closely tied to freshwater inflow[74], and that flow's stimulation of the food web has an important impact on survival and growth rates of many species[75].

One way to focus on how the estuary's food web works is to take a closer look at the production of juvenile Chinook salmon from the Bay's Central Valley watershed. Production of juvenile salmon emigrating from the Central Valley's rivers is strongly correlated with the amount and timing of freshwater flow[76]. River flows carry these young fish downstream to the estuary, along with the nutrients, sediments, and food that stimulate productivity. The estuary's muddy waters and wetlands (a result of sediments transported from upstream) provide cover and abundant food that allow the young salmon to survive and grow, along with other small fish and invertebrates. Some of the young salmon become prey for larger species, including birds and mammals. The survivors migrate on currents driven by inflows and the tides, and some become food in distant parts of the estuary, even outside the Golden Gate. The juvenile Chinook salmon produced in the Bay's watershed eventually become one of the primary food items in the diet of the Orca whales that reside in the Gulf of the Farallones[77]. This means that even creatures that rarely enter the Bay rely on the productivity of the food web driven by the amount and seasonal timing of Bay inflow (Figure 8).

FRESHWATER FLOWS AFFECT FOOD WEBS IN THE BAY AND BEYOND



PREDATORS

Some predatory species like starry flounder respond directly to annual changes in Bay inflow rates, declining as inflows decrease. Many other species, including seals, otters, osprey, pelicans, halibut, and sharks, are affected indirectly when populations of "forage fish" prey species decline in response to flow reductions. For example, Orca whales outside the Golden Gate are impacted when the numbers of their preferred prey, Chinook salmon, shrink in response to reduced freshwater flows throughout the Bay's watershed.

SECONDARY CONSUMERS

Most of San Francisco Bay's fish are secondary consumers that feed on invertebrates. Many respond directly to changes in the timing and volume of water flowing from rivers into the Bay, including sturgeon, juvenile salmon, longfin smelt, Delta smelt, and juvenile striped bass. Although many mechanisms contribute to the positive response of different fish species, all these species are likely impacted by how changing freshwater flows affect production and distribution of their invertebrate prey (the primary consumers).

PRIMARY CONSUMERS

The Bay's primary consumers (shrimp, copepods, shellfish, and other very small species which eat primary producers, like algae and plants) are essential for transferring energy and nutrients in the Bay's waters to the fish and wildlife species we all enjoy. Many fish and bird species would starve without them. Flow rates also influence how and when these prey species occur and which animals get to eat them.

PRIMARY PRODUCERS

The food web is founded on small organisms that convert sunlight and nutrients into biological material. Bay inflows affect factors like spatial distribution of primary producers (or phytoplankton).

HARD TIMES FOR THE UPPER ESTUARY FOOD WEB

Freshwater flows into the estuary are an extremely powerful driver of productivity in northern San Francisco Bay and the Delta. Over many decades, scientists have documented strong and persistent statistical relationships between winter – spring inflows and the abundance of major invertebrate prey populations like Bay shrimp[78]. In years with low inflows, Bay shrimp biomass correspondingly declines[79]. Under natural runoff patterns, inflows are high enough in most years to support a productive ecosystem. The human-made "permanent drought" experienced in the Bay, however, in combination with other factors, has had catastrophic effects on the food web. Primary production in the Delta declined 43% between 1975 and 1995[80]. One flow-related factor is the long-term decline in suspended solids entering the estuary on peak inflows, and the resulting increase in water clarity, which increases predation risk for many species. Another factor driving the decline in food web productivity is the almost complete loss of fresh water inflow from the San Joaquin River basin portion of the Bay's watershed[81] (most of which is either diverted upstream or exported by the giant Delta pumps).

Figure 8: San Francisco Bay and the nearshore ocean support an incredible array of fish, bird, mammal, and invertebrate species that are linked together in a complex food web. Freshwater flows into the estuary have direct effects on the productivity of this food web – major decreases in fresh water flows and/or changes in the timing of that flow lead to smaller populations of many key organisms. The creatures that feed on these "flow-dependent" species, including birds and mammals that live in the nearshore ocean, are indirectly impacted by declines in their food supply. Human water diversions in the Bay's watershed have had measurable (and often dramatic) negative effects on the food web of San Francisco Bay and the nearshore ocean.

Overbite clam

Photo Credit: Luis A. Solórzano

An additional alteration to the Bay's food web is invasion by exotic (non-native) species, which can displace native fish and wildlife populations[82]. Reduced inflows favor the spread of invasive species[83], probably because flow reductions undermine the ability of native species to dominate their historical habitats. The extent of change varies by location, with the biggest changes in the historically fresh and brackish portions of the upper estuary, which are increasingly dominated by invasive species over time[84]. The most dramatic example of food web alteration by an exotic species is the colonization of this region in the 1980s by the overbite clam; this one species filters large amounts of phytoplankton from the water column, leaving less energy available for all the other species that feed on plankton or its consumers. The overbite clam invasion coincided with a dry period when reservoir operations and water diversions prevented more than three-quarters of the Central Valley's winter-spring unimpaired runoff from reaching the Bay[85]. The conjunction of these stressors has been implicated in multiple changes in the structure and functions of the upper estuary's low salinity zone[86].

Despite these major changes, many fish and zooplankton of the upper estuary continue to respond positively when estuary inflows increase because the flow-related mechanisms that drive their productivity have not changed[87]. In addition, the effect of the overbite clam may be ameliorated at higher flow levels as their abundance fluctuates in response to salinity changes[88], with the population responding to shifts in the extent and location of the low salinity zone[89]. Indeed, increases in freshwater flow may help control a wide range of nuisance species in the estuary, such as Brazilian waterweed (*Egeria densa*), toxic algae, jellyfish, clams, and inland silverside[90].

To make matters even worse in the post-invasion world, declining inflows in recent years have facilitated the occurrence of harmful algal blooms of cyanobacteria in the Delta and upper estuary. When such blooms occur, they can change phytoplankton community composition and toxin levels[91]. The new fact on the ground is that the loss of inflows has not only been undermining the ability of the food web to support native species in the upper estuary, but now it is actually helping create a new food web that is toxic to fish, wildlife and humans.

THE FAR SIDE: PLANKTON IN THE SOUTH BAY AND OUTSIDE THE GOLDEN GATE

Because fresh water is less dense than saltier water, freshwater inflow from the upper estuary rides on the surface of the water column as it enters the South Bay in the spring. This sets up strong density-driven currents in the South Bay[92], which in turn provide the right conditions for a spring plankton bloom[93]. When South Bay waters become stratified during and after these spring inflows, sun penetrates the fresher surface waters allowing algal cells to grow[94], unchecked by the large population of grazing organisms that live on the bottom of the Bay[95]. How large these plankton blooms are "is directly related to the intensity and duration of river-driven density stratification"[96], and when Bay inflows are very high exceptionally large blooms occur as a result[97].

As mentioned earlier, the surface plume of brackish water that flows out the Golden Gate in winter and spring creates a highly productive environment that makes an important contribution to the richness of the marine ecosystem in the Gulf of the Farallones National Marine Sanctuary[98]. The plume front creates a food-rich habitat where invertebrates, fish, birds, and marine mammals all converge to eat and be eaten. Flows into the Bay and then onward to coastal waters also directly facilitate the transport of nutrients and organisms and cue stages in the outmigration of juvenile Chinook salmon and other fish which are important food sources for marine mammals like Orca whales.

Orcas near Golden Gate Bridge
Photo Credit: Jennifer Hagerty

Chinook salmon Photo Credit: Bay.org

WHO SUFFERS FROM THE BAY'S STARVATION DIET?

HOW FISH, WILDLIFE, AND PEOPLE ARE HARMED BY A FRESHWATER-STARVED BAY

Every day, the seven million of us who live in the Bay Area can enjoy San Francisco Bay by walking along its shores, gazing at it from our cars, homes, or offices, or by swimming in or boating on its waters. Each year, more than twice that many people visit the region to enjoy this spectacular estuary, its waters, and its natural bounty. The benefits that people derive from vibrant fish and wildlife populations, good water quality, and diverse natural settings are all tied to making sure enough fresh water makes it into the Bay. In other words, Bay inflow isn't just good for the Bay ecosystem but is one of the foundations for the quality of life and the strength of the economy in the Bay Area.

The San Francisco Bay estuary supports some 750 species of plants and animals, and many more are found throughout its vast watershed. Nowhere else on Earth do so many distinct types of Chinook salmon use one place as a migratory corridor and juvenile rearing area. The Bay's wetlands are home to over a million waterbirds, including many unique native species, and an important food source and resting place for millions of migrating birds. These species all evolved in response to predictable natural patterns of inflow to the Bay.

Cold freshwater flows in rivers throughout the Bay's watershed provide excellent conditions for spawning of a wide range of fish species, like Chinook salmon, Sacramento splittail, green and white sturgeon, and steelhead. The emerging year-class of juvenile fish then migrate into the Bay where they join a complex food web of resident and migratory species living in the open waters, wetlands, and nearby terrestrial habitats. Most species in the Bay are affected in some way by the freshwater pulses that flow through it and mix with its more saline marine waters (Figure 9). As explained in the previous chapter, all the critical processes that make the Bay estuary a productive place for fish and wildlife – from the transport of fish, food, nutrients and sediments in Bay inflow to the formation of low salinity zones, wetlands and beaches – are shaped by how much freshwater flow arrives, when it arrives, how frequently it occurs, and how long it lasts. There are many examples, unfortunately, of what happens when the flow is no longer big enough, doesn't last long enough, isn't frequent enough, or doesn't occur at the right time.

WHAT DO THESE SPECIES HAVE IN COMMON?

SPECIES	NATIVE?	LIFE SPAN (YEARS)	RESIDENT/ MIGRATORY/ NURSERY REARING	REPRODUCES WHERE?	ABUNDANCE CORRELATED WITH FLOW?
Chinook Salmon	Yes	3-5	Anadromous	River	**YES**
Striped Bass	No	4-10	Anadromous	River	**YES**
Green Sturgeon	Yes	Decades	Anadromous	River	**YES**
Delta Smelt	Yes	1	Resident	Delta	**YES**
Longfin Smelt	Yes	1-3	Resident/ Migratory	Delta/ Suisun	**YES**
Starry Flounder	Yes	7-8	Nursery Rearing	Ocean	**YES**
Sacramento Splittail	Yes	5-7	Resident	Shallow Freshwater	**YES**
American Shad	No	5-7	Migratory	River	**YES**
Staghorn Sculpin	Yes	1-3	Resident	Ocean/ Estuary	**YES**
Leopard Shark	Yes	Decades	Nursery Rearing	Ocean/ Bay/ Estuary	**YES**
Bay Shrimp	Yes	1.5-2.5	Nursery Rearing	Ocean	**YES**

Figure 9: The relationships between freshwater flow and species abundance are widespread. The specific mechanisms by which flow affects abundance, and the relative importance of mechanisms are likely to vary for different species (Kimmerer 2002b); however, the strong, significant correlations that persist across decades of monitoring provide powerful evidence of the benefits of freshwater flow to San Francisco Bay's fish and wildlife populations.

VIABLE POPULATIONS OF FISH AND WILDLIFE NEED FRESH WATER

The massive transformation of the Bay's watershed by tens of thousands of dams, canals, pumps, and wells has changed the patterns of flow to the Bay so much that the current conditions bear little resemblance to those in which the Bay's native fish and wildlife evolved. The result is a system where native species are in decline – some very close to extinction – while nuisance non-native species increasingly take advantage of the altered ecosystem.

Populations of many aquatic organisms at different levels of the food web have sharply declined, and six native fish species - Delta smelt, longfin smelt, steelhead, green sturgeon, and the winter and spring runs of Chinook salmon – that used to be among the most common in the estuary are now listed as in danger of extinction by the federal government and/or the State of California (Figure 10). To have viable populations, these species need to be:

- *abundant* (have enough individuals to ensure long-term survival through a range of different conditions)

- *diverse* (have enough variation among individuals to ensure that some will respond successfully to changing environmental stresses)

- *productive* (able to grow the population fast enough to exploit good conditions in a variable environment); and

- *spatially distributed* (exist in a large enough area to avoid catastrophic localized pressures).

American shad   Photo Credit: Brian Currier

COLLAPSE OF SPECIES ACROSS MULTIPLE TROPHIC LEVELS

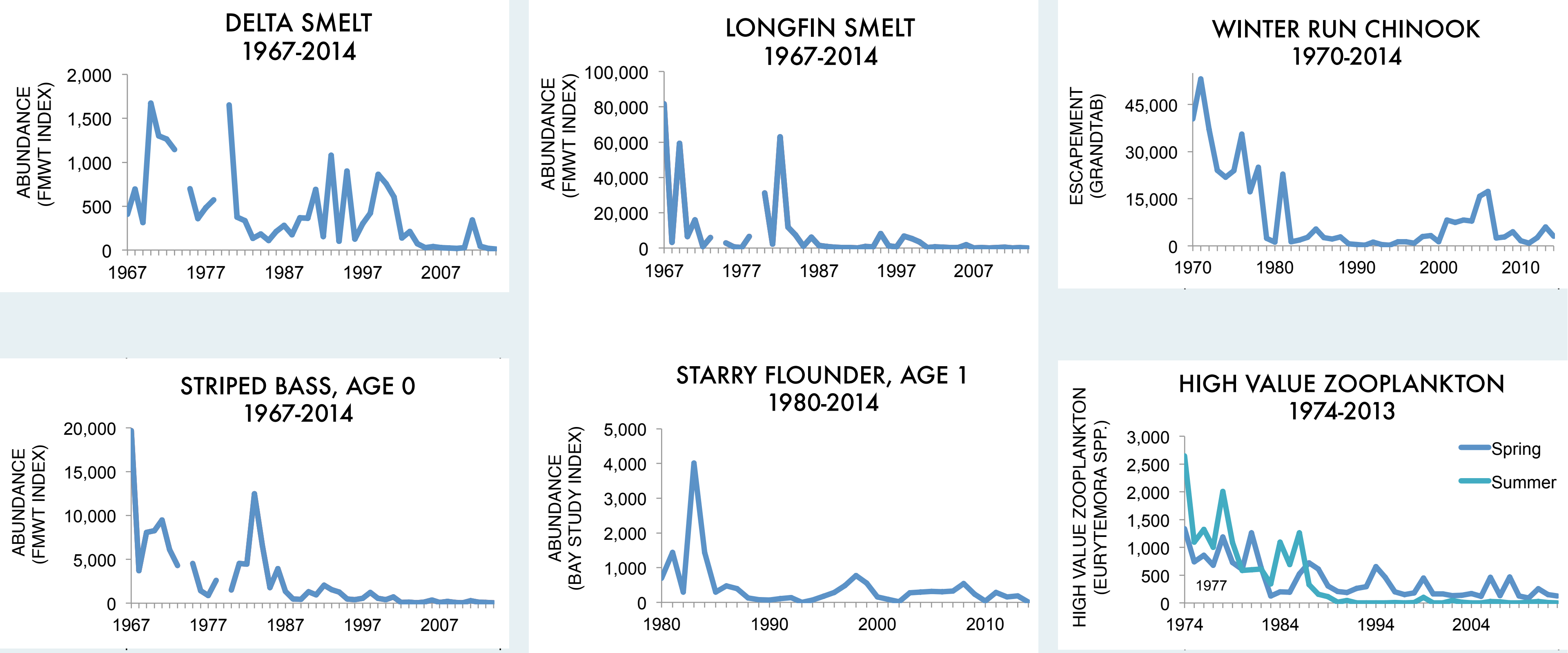


Figure 10: Abundance trends of several populations that serve as key indicators for the health of the San Francisco Bay estuary and its watershed. Data sets and length of data time series differ across species.

Many populations that use the San Francisco Bay estuary as a nursery or migration pathway are in severe decline. These declines pre-date, but have been exacerbated by, water management actions during the current drought.

Data provided by: California Department of Fish and Wildlife's Bay Study, Fall Midwater Trawl, Zooplankton Study, Anadromous Resources Assessment and the Interagency Ecological Program for the San Francisco Estuary

The outlook for these populations is grim in large part because Bay inflows are no longer adequate to maintain the services the Bay ecosystem once provided to support abundant, diverse, productive and spatially distributed populations.

One of the best-documented facts about the estuary is the strong, persistent relationship between freshwater flow and healthy populations of key species. Over the past few decades many scientific studies have documented the critical role freshwater flows play in maintaining viable populations of native fish and wildlife, and the productive habitats and food webs that support them, in estuaries in general and the San Francisco Bay estuary in particular[99]. This overwhelming body of evidence has led federal and state regulators and resource managers, as well as numerous scientific review panels, to conclude that current freshwater inflows to the Bay estuary are no longer adequate to sustain native fish and wildlife populations[100].

ABUNDANCE: LESS FLOW, LESS FISH

Obviously, the more individuals of a particular plant or animal species there are, the less vulnerable that species is to extinction risks from natural or human disturbances like habitat destruction or toxic pollution. Native fish species such as Delta smelt, longfin smelt, and Chinook salmon were among the most abundant species in the Bay ecosystem until the second half of the 20th century, but are now among the most rare species, and altering and reducing flows has been the main reason for their decline.

How much Bay inflow there is during critical times in fish life cycles strongly affects abundance: Critical parts of the life cycle of many fish species in the Bay estuary – such as reproduction, growth, and migration – are timed to occur during the winter and spring months because the inflow from rainfall and snowmelt during this period was naturally higher, creating beneficial habitat conditions. The amount of timing and flow in any winter – spring period has a large effect on how populations of these species respond during the months and years following[101] (Figure 11).

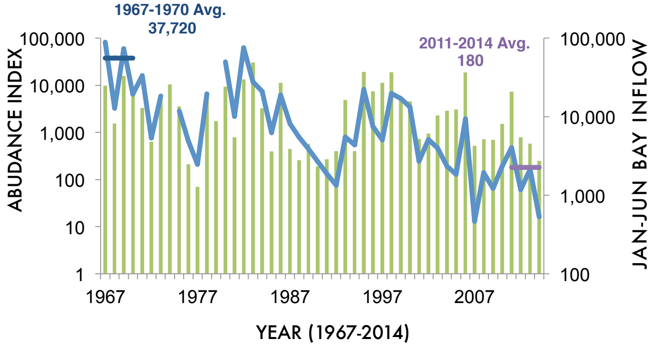
During the winter and spring, the migration of juveniles of fish species like Chinook salmon, steelhead, and sturgeon is cued by rising flow levels, and the young fish make their way along with the flow from their natal rivers through the estuary to the ocean. More Chinook salmon survive the journey when flows are higher[102].

At the same time, small forage fish like Delta smelt and longfin smelt, important parts of the estuary food web, respond to increasing flows by moving to spawning areas in the upper estuary and breeding. Longfin, once the most common native fish residing in the estuary and now one of the rarest, respond dramatically to flow changes – their abundance is tightly and positively correlated to winter – spring Bay inflows[103]. No other factors, including the impact of invasive species, appear to affect longfin population dynamics during the first few months of life[104].

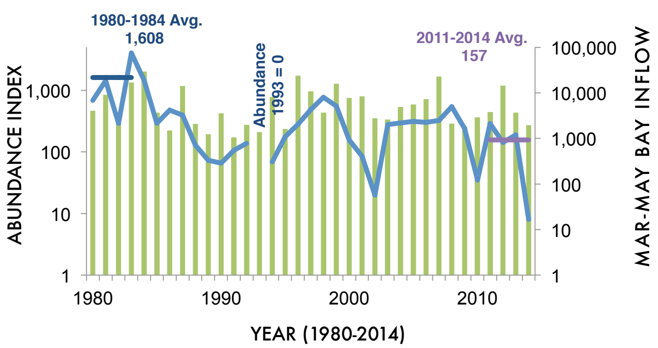
During the spring months young starry flounder (another species caught by recreational and commercial fishermen) migrate into the Bay estuary from the ocean to mature[105]. The number of one-year-old starry flounder rearing in the estuary in a given year is strongly correlated to the amount of freshwater inflow in the previous spring[106].

DECLINING BAY INFLOWS = DECLINING FISH POPULATIONS

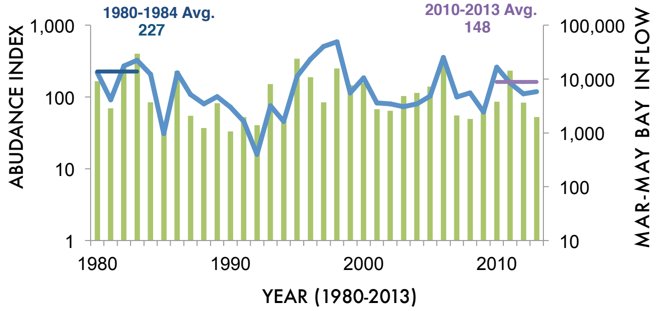
🟩 Bay Inflow
🟦 Abundance Index


LONGFIN SMELT

Longfin smelt - Recent average decline 99.5%

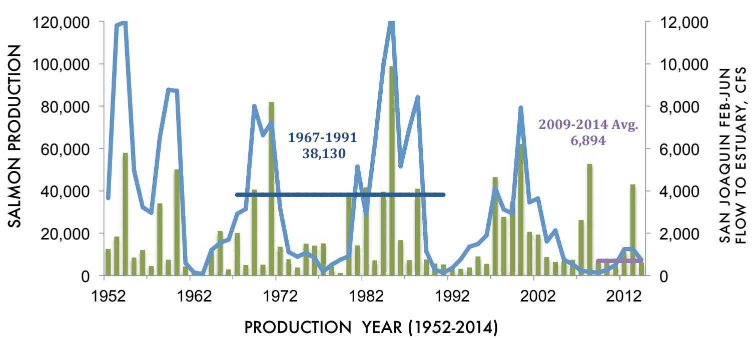

STARRY FLOUNDER

Starry flounder – Recent average decline 90%


BAY SHRIMP

Bay Shrimp - Recent average decline 35%

Figure 11: Strong correlations between abundance (blue lines, left vertical axis; abundance indices from biological sampling programs) and winter-spring inflow into San Francisco Bay (green bars, right vertical axis; "Bay Inflow") have persisted for many decades for fish species and their invertebrate prey. Longfin smelt were once the estuary's most common resident fish and a key component of a commercial smelt fishery; this population has declined by orders of magnitude and is strongly and significantly correlated with freshwater flow rates. Starry flounder, a predatory fish, generally increase in years following those with high freshwater flows into the estuary. Bay shrimp are prey for smelt, flounder, and a host of other fish and bird species; their population tracks closely with springtime Bay inflows.


SAN JOAQUIN RIVER CHINOOK SALMON PRODUCTION

🟩 San Joaquin River Flow during juvenile migration

🟦 San Joaquin River Chinook Production (measured in the ocean 2 years later)

Chinook salmon - Recent average decline 89%

Chinook salmon production (the estimated number of fish from a given watershed that reach age-2 in the ocean) is highly correlated with freshwater flow rates that occurred when juvenile salmon migrated to the ocean, two years earlier. The figure matches production of naturally spawned Chinook salmon from the San Joaquin River with the river's flow to the estuary two years earlier, during outmigration of that same cohort of fish.

Many other species produce a significant and persistent population response to winter – spring inflows, from the smaller organisms and other zooplankton that fish feed on, such as shrimp[107] to the popular non-native sportfish like striped bass and American shad that once thrived alongside native species[108], and from the estuary's brackish upper reaches to as far away as the South Bay[109].

While the population effects of inflow to the estuary are most noticeable in the winter and spring, the effects are not limited to these seasons. The endangered Delta smelt, a small native fish found nowhere else in the world which used to be one of the most common fish in the estuary, benefits from increased area of brackish habitat that forms when fresh water reaches the upper estuary in September and October[110]. The adult Chinook salmon that successfully survived their journey to and through the ocean rely on the same fall inflows to provide adequate water quality conditions for their return migration[111] and help orient them towards their native spawning grounds[112].

Exporting Bay inflows (and fish) into giant pumps also cuts down on abundance: In the Delta region of the upper estuary, giant pumps operated by the federal Central Valley Project and State Water Project export water for use by irrigators in the San Joaquin Valley and cities in Central and Southern California. These pumps are so powerful that much of the Bay inflow is drawn toward the interior Delta, and along with it fish and invertebrates, and their eggs and larva. More than 9,000,000 fish on average are screened out of water to be exported by the pumps each year; though this process is called *"salvage,"* most of these fish will die before or shortly after they are released back into the Delta[113] (Figure 12). The real impact of salvage is actually much larger because larval fish are not counted and most small fish die (typically in the mouths of predators) before they reach the salvage facilities. In drier years, these export impacts can have a devastating impact on fish abundance, taking up to 40% of the annual population of Delta smelt (which live only one year) and up to 15% of outmigrating juvenile Chinook salmon[114].


Starry Flounder is one of many fish species that respond positively to increases in freshwater flow into San Francisco Bay. Dramatic reductions in Bay inflow jeopardize the recreational and commercial fisheries for this species.
Photo Credit: David Csepp, NMFS/AKFSC/ABL

How much Bay inflow there is can help or hinder the spread of non-native species: The Bay estuary is one of the most highly invaded estuaries in the world, and the radical alteration of Bay inflows is believed to be a primary factor in successful colonization by invasive non-natives. The abundance of many non-native species shifts in inverse proportion to flow. For example, an extended drought in the 1980s coinciding with then record high levels of water diversion facilitated the establishment and explosive spread of the overbite clam. When, in contrast, Bay inflows increase, invasive clams and fish such as the small but voracious inland silverside decreases in abundance[115].

NUMBER OF FISH SALVAGED AT THE STATE AND FEDERAL PUMPS IN THE DELTA 1993 – 2011

STATUS KEY

Endangered - Federal	🇺🇸
Endangered - California	🐻
Threatened - Federal	🛡
Threatened - California	◉

LEGEND

Native to CA	🌉
Recent decline	📉
Important Fishery	🐟
Commercial/Sport Fisheries Destroyed	🎣
Protection Removed (for political reasons; species has not recovered)	🚫

Figure 12 Fish were selected to encompass the wide range of species and life history types that are affected by water pumps.

"Average annual salvage" is mean yearly salvage from 1/1993 through 12/2011; "Maximum salvage" is the value for the calendar year with the highest salvage numbers (years differ amoung species).

These numbers underestimate the actual fish kills by not counting the fish that slipped through the bypass system and were killed by the pumps, and by not including indirect mortality. "Yearly Total" refers only to the 20 species listed.

SELECTED FISH SPECIES	1993-2011 Average	ANNUAL SALVAGE Maximum	STATUS				
American shad	1,022,700	2,510,184				🐟	📉
Bluegill	127,133	394,952					
Channel catfish	45,799	131,484					
Chinook salmon (winter run)	51,955	183,890	🇺🇸	🐻	🌉	🎣	📉
Chinook salmon (spring run)			🛡	◉	🌉	🎣	📉
Chinook salmon (fall run)					🌉	🐟	📉
Chinook salmon (late-fall run)					🌉	🐟	📉
Delta smelt	29,918	154,820	🛡	🐻	🌉		📉
Green sturgeon	58	363	🛡		🌉		📉
Inland silverside	62,838	142,652					
Largemouth bass	54,180	234,198				🐟	
Longfin	6,228	97,686		◉	🌉		📉
Prickly sculpin	76,403	274,691			🌉		
Steelhead (Rainbow trout)	5,278	18,580	🛡		🌉	🎣	📉
Redear sunfish	1,609	5,611					
Riffle sculpin	155	798			🌉		
Sacramento sucker	3,443	27,362			🌉		
Sacramento splittail	1,201,585	8,989,639	🛡		🌉	🐟	📉
Striped bass	1,773,079	13,451,203				🐟	📉
Threadfin shad	3,823,099	9,046,050					📉
White catfish	296,543	941,972					
White sturgeon	151	873			🌉	🐟	📉
Yellowfin goby	193,399	1,189,962					

AVERAGE YEARLY SALVAGE TOTAL: 9,237,444

DIVERSITY: IT'S ALL IN THE TIMING

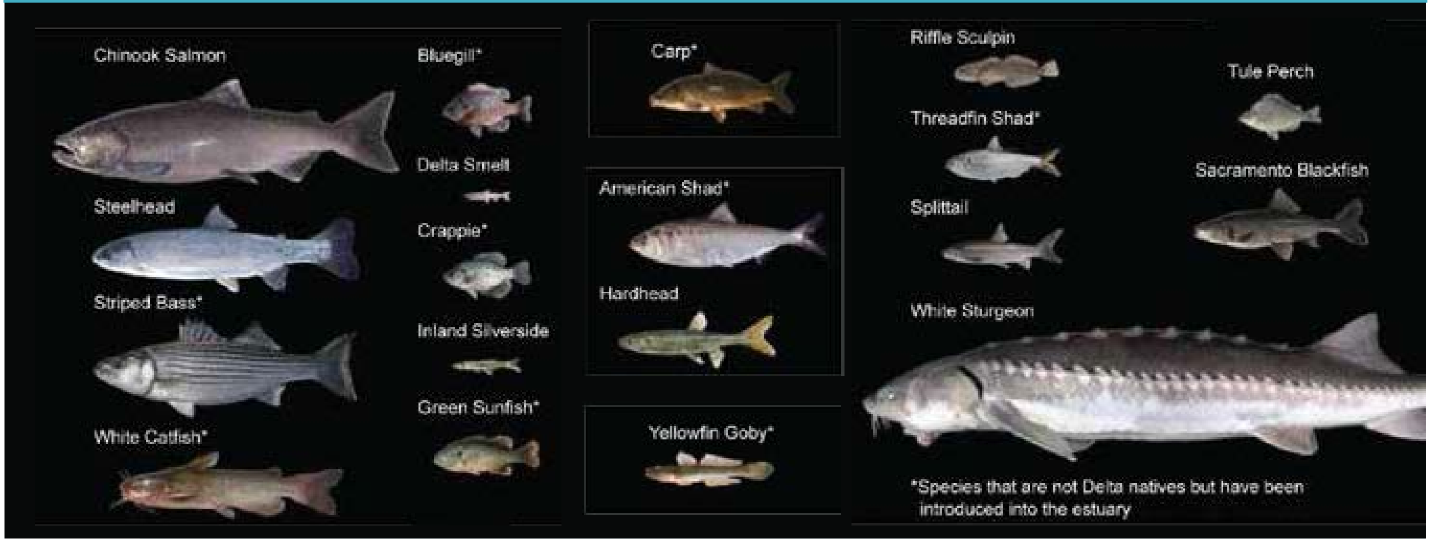
"Don't put all your eggs in one basket" is common advice for investors. Likewise, populations comprised of diverse individuals that exhibit a range of life history behaviors and genetic predispositions are more resilient to environmental disturbances of all kinds and less vulnerable to the risk of extinction. California's natural regime of extended winter rains and spring snowmelt and high year-to-year variability favors a wide variety of responses by the individuals within a population. Constraining the volume and timing of peak flows year after year selects for a small segment of behavioral and ecological responses that are able to utilize habitats during limited windows of availability (Figure 13). For instance, the dramatic decline of Bay inflows in the winter and spring limits the spawning period for Delta smelt, making the fish less able to capitalize on good conditions that may occur during the multi-month spawning and rearing seasons[116]. When the window of suitable spawning conditions for Delta smelt is reduced and limited to the same narrow timeframe year after year, some rare but valuable life-history strategies no longer pay off. The genetic variants that allow for these different strategies may decline or even disappear – meaning that the population's ability to grow is compromised, even when good conditions return[117].

Hedging your bets is the best way to plan a migration: Chinook salmon experience a similar dilemma. Historically, different juvenile migration strategies have succeeded under different conditions[118]. But, as shorter and less frequent peak flow periods and lower flow volumes occur with increasing regularity during their juvenile migrations, the salmon life history types that can survive such conditions are favored over other life-history types. The period when flows are provided to support the outmigration of juvenile fall-run Chinook salmon from the San Joaquin River (the state's second largest river) is limited to one month, and even that requirement was relaxed during the recent drought.

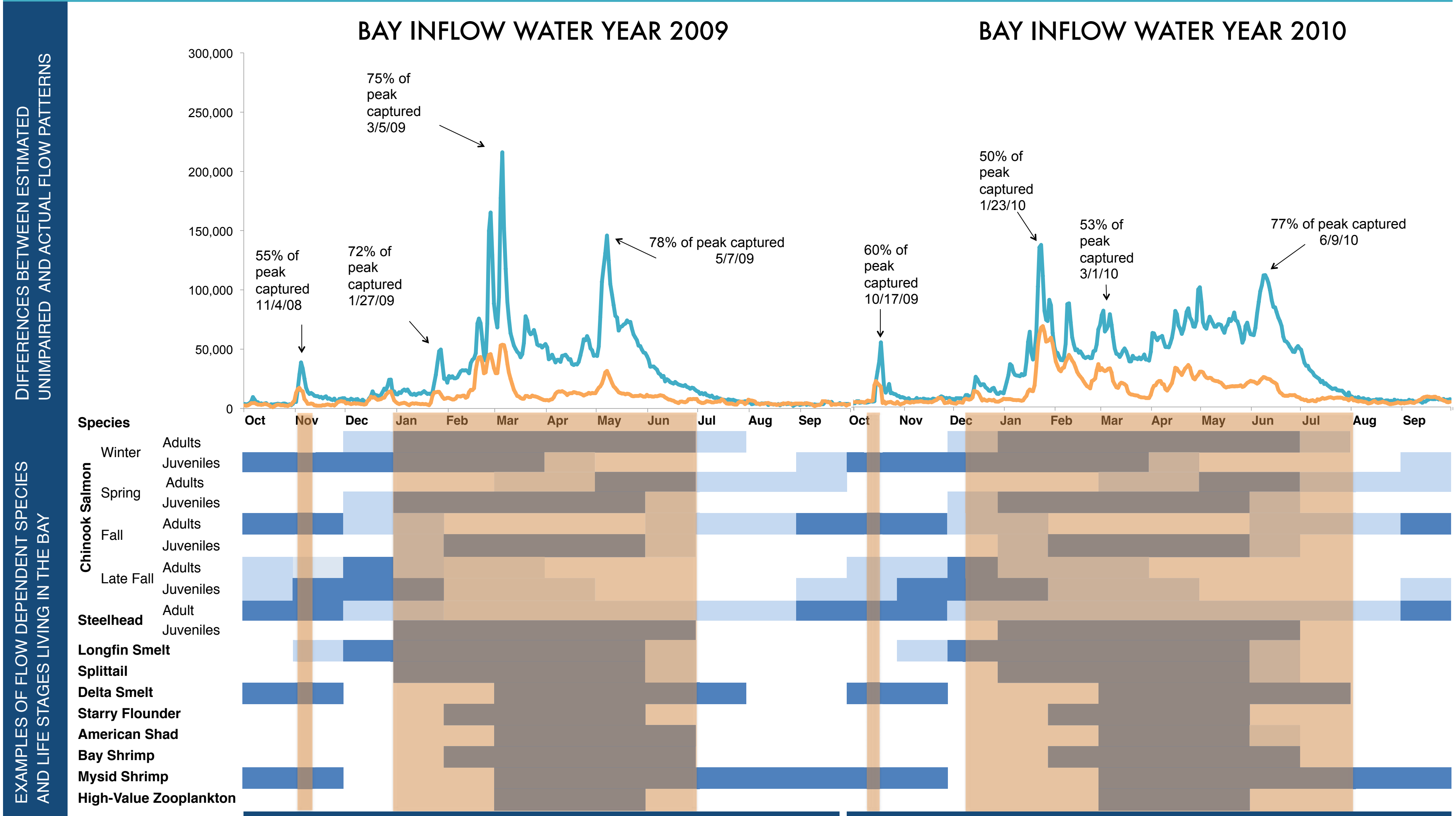
Restricting the migration window and limiting the flows that cue migration undermines the life-history diversity (in this case, the size and time at which juveniles migrate) that have allowed Chinook salmon to survive natural (and extreme) fluctuations in

SPECIES OF FISH COMMONLY COLLECTED AT THE STATE FISH SALVAGE FACILITY

PHOTO: CA DWR



*Species that are not Delta natives but have been introduced into the estuary


BAY INFLOW WATER YEAR 2009

BAY INFLOW WATER YEAR 2010

55% of peak captured 11/4/08

72% of peak captured 1/27/09

75% of peak captured 3/5/09

78% of peak captured 5/7/09

60% of peak captured 10/17/09

50% of peak captured 1/23/10

53% of peak captured 3/1/10

77% of peak captured 6/9/10

Only 28% of the Central Valley watershed's runoff made it to the Bay between February and June 2009, the lowest percentage of available flow since 1990. Peak flow events in January, February, March, and early May were virtually eliminated; this deprived juvenile salmon (all four distinct populations) and numerous other species of the ecological benefits associated with these short-term pulses of fresh water.

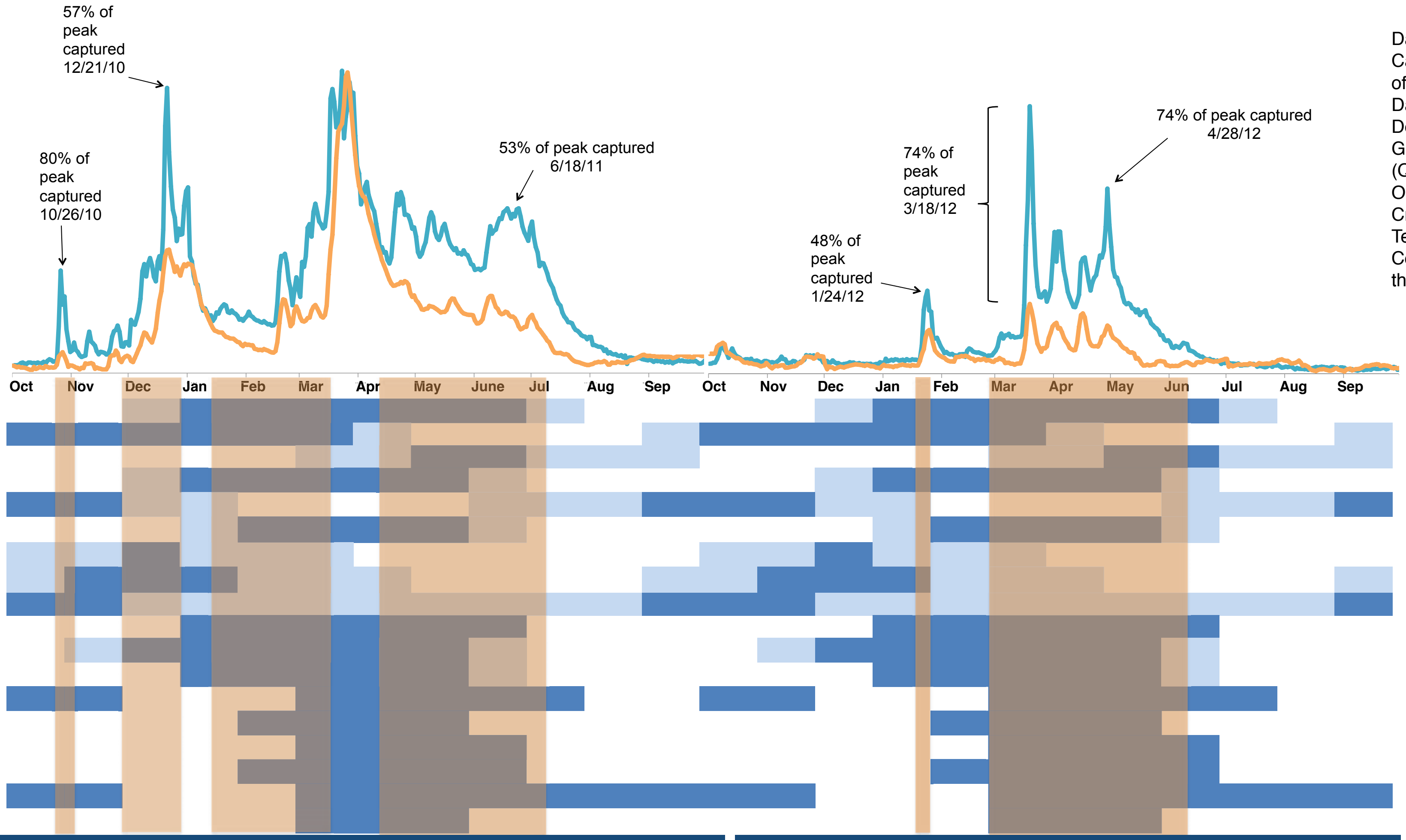
Sixty-five percent of Central Valley runoff was diverted during the winter-spring of 2010, and high percentages were diverted during peak flow periods that species like Chinook salmon rely on to find their way through the Delta to the Ocean.

Figure 13: Overlap in timing of freshwater flow and presence of different species life-stages in San Francisco Bay and the Delta. Top panels show, for years 2009-2012, the rate of freshwater flow into the Bay (Bay Inflow, orange line) in comparison to what would have flowed had there been no dams or diversions upstream of the estuary (unimpaired flow, blue line). Lower panels show the seasonal timing of several species that use the estuary to

FLOW AND SPECIES 2009-2012

BAY INFLOW WATER YEAR 2011

BAY INFLOW WATER YEAR 2012



Data sources: California Department of Water Resources Dayflow and California Department of Fish and Game Report, 2010 (Quantifiable Biological Objectives and Flow Criteriafor Aquatic and Terrestrial Species of Concern Dependent on the Delta).

Even when wet conditions returned in 2011, most of the winter flows were captured until Central Valley reservoirs were filled in March. After that, runoff was allowed to reach the estuary. Fish and wildlife usually receive their share of life-giving flows only when humans run out of space to store extra water.

When dry conditions returned in 2012, most of the available fresh water runoff was diverted again. Only 38% of the critical winter-spring flows reached the estuary, plunging the Bay’s ecosystem back into a severe, man-made drought. Again, species like salmon and splittail were deprived of the short-term peak flows upon which they rely.

complete their life cycle (light blue bars indicate when a life stage may be present; dark blue bars indicate the life stage is definitely present at that time). The overlap between species presence and periods when flow volume was significantly reduced by water diversions and exports in each year (red shading) reveals likely impacts of Central Valley water management on major fish and invertebrate populations in San Francisco Bay.

their environment for millennia. This loss of diversity in juvenile migration strategies likely led to the unprecedented closures of California's ocean fishery in 2008 and following years[119]. The net effect of reducing migration diversity is to gamble that a small subset of the fish that migrate during such short windows will reach the ocean exactly when food supplies, temperatures, and other conditions are adequate. Salmon thrived in the Bay estuary by hedging their bets about when to go to the ocean; restricting those opportunities eliminates large portions of the population that might capitalize on changing conditions, and makes the dwindling remnant much more susceptible to extreme population swings.

PRODUCTIVITY

In the context of what defines a viable population, productivity refers to a population's ability to grow; it is the balance between birth rate and death rate. Populations that have a high capacity for population growth can rebound quickly after periods with poor environmental conditions[120]. In estuaries, both river inputs and ocean conditions affect productivity of different species to different degrees. Scientific research in the Bay estuary suggests that freshwater inflows have greater ecological effects on this particular estuary than the effect of ocean waters moving inland into less saline environments[121] (Figure 14).

As with abundance, there is strong scientific evidence linking population growth in native fish species like longfin smelt and Chinook salmon to freshwater inflows to the estuary[122]. In the variable conditions that typify an estuary, many aquatic organisms evolved to rebound rapidly in wetter years following poor conditions in drier years. But these species must now contend with the Bay's human-made "permanent drought". In terms of the actual conditions experienced by the estuary's fish and wildlife, wet years are infrequent and much less wet, and drier years are extremely dry and nearly continuous. As a result, in most years the population's rate of growth is constrained, and the higher flows that would allow the population to rebound rarely occur.

Food web productivity also improves with increases in freshwater flow to the estuary. Productivity in this sense has been degraded by the direct and indirect effects of reducing inflows, as described in the previous chapter. One of those effects is the successful establishment of invasive species, whose growing numbers can displace native fish and wildlife populations by competing for food and habitat. The effects are not confined to the winter and spring months. For example, the prevailing theory about why anchovies are no longer abundant in the upper estuary in summer and fall is that the local population simply left the area when food web productivity was reduced[123]. This effect has been attributed to the effect of the overbite clam on production of anchovy prey; however, the clam's invasion itself appears to have been facilitated by the extreme reduction in inflow. Species such as Pacific herring feeding in the summertime may also be negatively affected by reduced food web productivity in the Bay[124].

Salmon   Photo Credit: Bay.org

GENERALIZED MODEL OF BAY FISH ABUNDANCE

	SPAWNING SUCCESS		JUVENILE AND ADULT SURVIVAL				
ECOLOGICAL FEATURE	FECUNDITY	SPAWNING HABITAT	PREY DENSITY	DISEASE	CONTAMINANTS	PREDATION	REARING HABITAT
IS THE PRODUCT OF...	Flow and ocean conditions affect prey abundance in the Bay which can affect female growth and body size	Suitable spawning substrate with appropriate temperature, salinity, and flow rate	Water temperature, nutrient and food transport, productivity of microscopic organisms, contaminants, disease	Water temperature, flow rates through the estuary (residence time), fish distribution	Toxin concentrations, frequency of harmful algal blooms	Turbidity, flow rate, and predator abundance	Prey abundance, flow rates, temperature, salinity, turbidity, contaminant loads
PRINCIPALLY MODIFIED BY...	☾ ≈	≈	☾ ≈	≈	≈	≈	☾ ≈
FLOW AFFECTS...	Prey abundance which can affect female size	Amount of spawning habitat available for species that spawn in the Bay watershed's rivers and in the estuary by modifying temperature, salinity, and other environmental conditions	Prey production and distribution throughout the Bay by influencing nutrient, and food transport, contaminant concentrations, and disease spread; ocean conditions affect abundance of certain prey species that enter the Bay	Residence time and fish distribution	Conditions that promote harmful algal blooms and dilutes concentrations of other contaminants	Transport of small fish and turbidity (cloudiness) of water, which hide small fish and reduce predation rates	Salinity, turbidity, flow rates, and prey availability that affect rearing success. Ocean conditions (such as upwelling) influence rearing success for some species in the lower Estuary

FRESHWATER FLOW DRIVES MULTIPLE MECHANISMS THAT AFFECT PRODUCTION OF FISH IN THE BAY

Figure 14: A generalized view of factors driving population fluctuations for many of the fish populations that depend on the Bay to complete their life cycle. The forces that produce each ecological feature and their impact on different fish species are too numerous to list; the key point is that freshwater flows into the estuary affect each of these drivers. The strength of the influence of freshwater flow or ocean impacts varies by species and by location of the life-history stage in question.

☾ Ocean Impacts

≈ Freshwater Impacts

SPATIAL DISTRIBUTION: THE ADVANTAGES OF SPREADING OUT IN THE LANDSCAPE

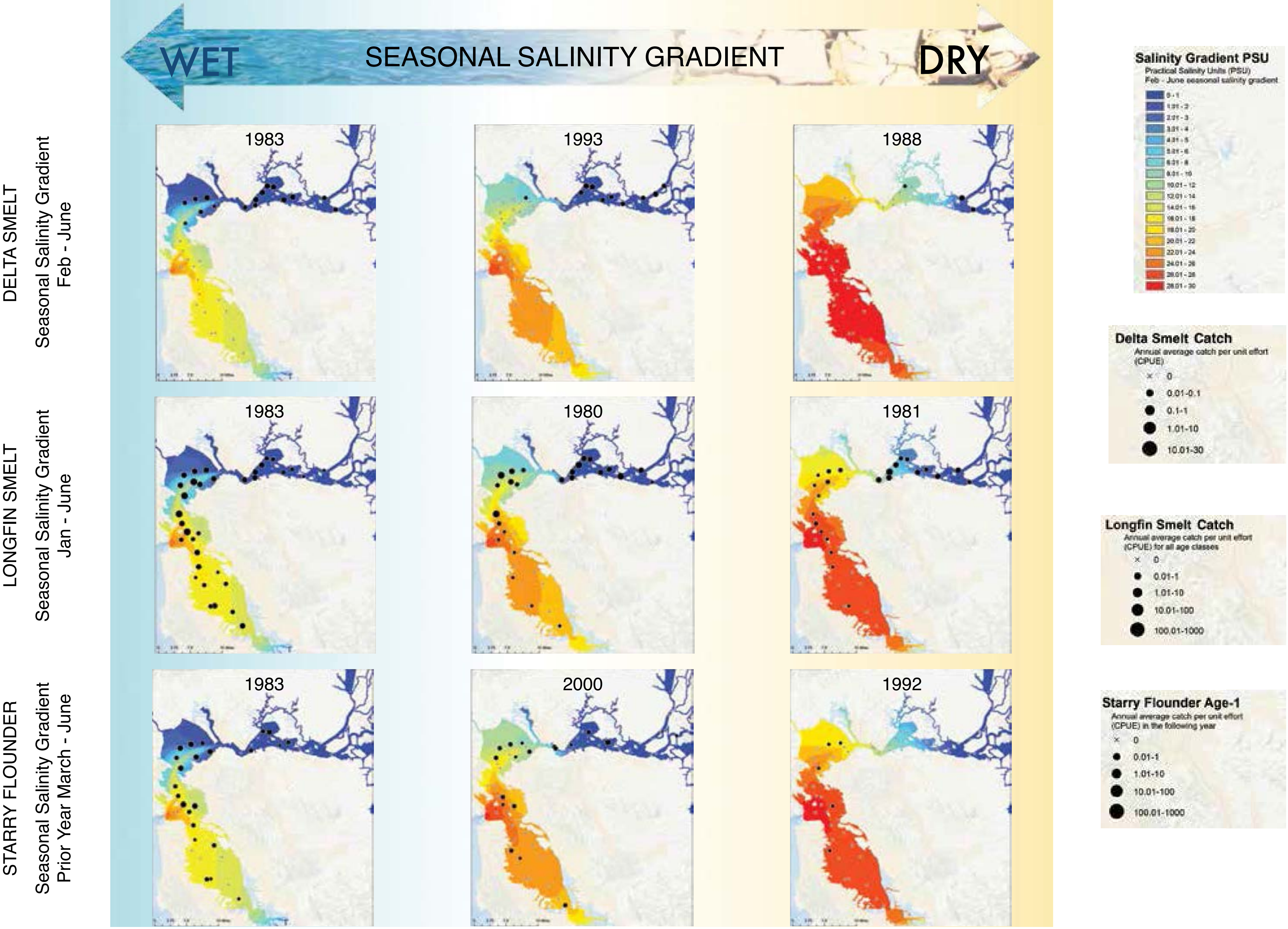
Populations are less vulnerable to extinction risk from both degraded local conditions and catastrophic events when they are more widely distributed in the landscape[125]. How much freshwater flow makes it downstream has a profound effect on how much habitat of different types is created and where it is located throughout the landscape of the estuary, in turn affecting where particular species can be found and how many individuals of that species can utilize a particular habitat (Figure 15). Because many native aquatic organisms in the Bay estuary have evolved to exploit its unique brackish water habitats, resident species such as Delta smelt and longfin smelt are typically associated with a narrow band of habitat in the Low Salinity Zone. When inflow to the estuary is reduced, the LSZ contracts in response, shrinking available habitat for the smelt and related species[126]. As the band of usable LSZ habitat contracts, it also moves upstream, shifting the distribution of longfin and Delta smelt upstream towards the Delta and increasing the number of fish that are lost to the giant south Delta pumps run by the federal Central Valley Project and State Water Project[127].

Adequate distribution isn't just a problem for resident fish. Flows can be so low in reaches of the southern Delta and the San Joaquin River basin that their use as migratory corridors by Chinook salmon and other species is impaired or eliminated[128], and water quality becomes so degraded that fish passage is blocked[129]. The inability to sustain the distribution of Chinook and other salmonids in the San Joaquin Valley portion of the Bay's watershed is highly problematic as a result of reduced freshwater flows[130]. In effect, this loss of spatial distribution makes all of the estuary's salmonid populations dependent on conditions in the Sacramento River valley; any problems there (e.g., a spill of toxic chemicals, disease outbreaks) could eliminate the Central Valley's production of salmonids.

Figure 15: The spatial distribution of many species changes in response to variation in freshwater inputs to the estuary. These maps show the distribution of three fish species across a range of Bay inflows and salinity gradients during the spring. For example, in an extremely wet year (like 1983) the distribution of Delta smelt (top row) extends throughout the upper estuary during the spring. In contrast, distribution of this native fish is limited to Suisun Bay and the Delta when the combined effect of drier conditions and high diversion levels makes Bay inflows extremely low, such as 1988. Starry flounder (bottom row) prefer habitats with intermediate salinities that are broadly available under high flow conditions, but less widespread when conditions are very dry. The wettest year (1983) is depicted for each species on the left hand side of the figure; drier years are shown to the right hand side. In the absence of water diversions or exports, salinity conditions similar to those depicted on the left would have occurred in 10 years between 1975-2014, but they actually occurred in only 4 of those years. By contrast, Super Critically Dry years only occurred naturally in one year (1977) during this four decade period, but similarly extreme conditions in the estuary actually occurred for 19 years – almost half the time.

Data sources: U.S. Environmental Protection Agency; California Department of Fish and Wildlife and the Interagency Ecological Program San Francisco Bay Study; Delta Modeling Associates (Salinity Gradient, Coarse-grid version of UnTRIM San Francisco Bay-Delta Model); and ESRI, DeLorme, BEBCO, NAANGDC, & other contributors (Basemap).

FISH DISTRIBUTION CHANGES IN RESPONSE TO THE SALINITY FIELD



FORAGE FISH – WHEN THE FOOD WEB IS THE SUM OF ITS PARTS

Collectively, small fish and large invertebrates that swim in open water are known as "forage fish." They represent the prey base for larger fish, sea birds, and marine mammals, which often do not distinguish one kind of fish from another. Declines in forage fish populations are a known threat to populations of seabirds[131] and marine mammals[132]. Because of their crucial function in estuarine and marine food webs, global declines in forage fish have become a concern for scientists, ecosystem managers, and some fishing communities.

The populations of many forage fish species that were historically the most abundant in the estuary, such as longfin smelt, striped bass, American shad, Bay shrimp, and mysid shrimp, have declined dramatically in recent decades. Unlike many other areas of the world where they are overfished, forage fisheries are generally well managed in the Bay and nearshore coastal waters of California. Instead, these population declines are directly related to the long-term trend of reducing Bay inflow – indeed, a reliance on freshwater flow is the only thing some of these forage fish have in common (Figure 9). Forage fish have an ecological value much greater than their physical size. Without sufficient Bay inflow to provide the habitat conditions that allow forage fish populations to thrive, populations of other fish, birds, and marine mammals that rely on forage fish in the Bay and the Gulf of the Farallones are at risk of collapsing too.

Great Egret, one of many native bird species that relies on the fish and invertebrates produced by the San Francisco Bay foodweb. The effects of freshwater flow rates extend throughout the Bay ecosystem and beyond. Photo credit: David Sanger

FLOW IS FOR THE BIRDS, TOO

Fish, invertebrates, and other aquatic plants and animals aren't the only creatures that benefit from Bay inflows, and suffer when they are reduced. The Bay estuary is also home to a diverse community of both resident and migratory birds. A critical part of the Pacific Flyway, the estuary provides crucial habitat for millions of migrating waterfowl and shorebirds, representing over 200 species. However, many bird populations that use the estuary are declining, and currently twenty-two bird species are listed as threatened, endangered, or species of special concern in this estuary[133].

It takes a fishery to support an aviary: Many factors are to blame for declines in bird populations, including urbanization, contaminants, and direct habitat loss. But long-term reductions in freshwater flows to the estuary likely contribute significantly to the pressure on the Bay's waterbird populations because of the resulting decline in the abundance of forage fish and the degradation of wetland habitat and water quality. Protecting fish-eating birds, such as pelicans, terns, and cormorants, requires production of a sufficient forage fish prey base. But populations of many fish species that depend on adequate inflows to the estuary have dropped well below the levels that are needed to maintain viable populations of pelagic seabirds[134].

Throughout the estuary many bird species are closely associated with wetland marshes[135], and large areas of the upper estuary, especially in Suisun Marsh, are managed to provide fresh and slightly brackish habitat for ducks. As reducing inflows makes the estuary more saline over time, the diversity and composition of wetland vegetation will change as well, affecting its habitat value for bird species. Salinity-induced wetland vegetation shifts in recent years have been as extreme as experienced in the most severe natural drought periods in California's history[136]. Changing salinities can limit the diversity of seeds stored in the soil and the productivity, diversity, and composition of wetlands[137]. Animal species that depend on these marshes are likely also impacted by salinity and vegetation changes resulting from reduced inflow[138]. Finally, impaired water quality that is exacerbated or caused by low inflows also harms the Bay's many bird populations.

DRIVING RECREATIONAL AND COMMERCIAL FISHERIES INTO THE ABYSS?

It would be a sadder and poorer world if Californians allow the San Francisco Bay estuary to become so impaired that its unique and wonderful aquatic life, and the birds and mammals that feed on it, disappears forever. But the consequences are not only ecological, or spiritual, or esthetic – there are extremely significant economic costs as well. The Bay Area has always been a major hub of the Pacific Coast's commercial fishing industry. Bay Area residents and tourists from across the globe come to San Francisco Bay in order to enjoy the pursuit of salmon, sturgeon, and many other game fish and, if they're lucky, to bring home a delicious dinner.

"Fish-friendly water management" is the only option: Today, Chinook salmon are one of the most recognizable and cherished fish on the Pacific Coast, and their production in the Bay's watershed supports a commercial and ocean recreational fishery that extends all the way from Monterey Bay to Oregon. But these valuable fisheries are extremely vulnerable to changes in Bay inflows. The long-term trend of flow alteration (combined with habitat degradation and poor hatchery management) in the watershed, and the associated declines in salmon production, has been a contributing factor to the loss of thousands of jobs and the beaching of hundreds of boats in the fishing industry[139]. When these long-term problems overlapped with poor ocean conditions, fishing for Chinook salmon off the California coast was closed completely in 2008 and 2009 (and through most of 2010). At the time, much attention was focused on the role of ocean conditions (and their relationship to global climate change); however, the most comprehensive scientific study of the unprecedented closure of the fishery noted that decades of poor habitat conditions in their freshwater nurseries

San Francisco Bay is home to both commercial and recreational fisheries such as Pacific herring pictured in this photo. Fisheries for many species like salmon and starry flounder depend on the health of the Bay ecosystem, including numerous ecological processes that are driven by freshwater flows to the estuary. Photo Credit: David Sanger had set the stage for this collapse and called for "…more fish-friendly water management…" as one of the few actions that might prevent the problem from recurring[140]. If California wants to preserve its salmon fisheries, the only effective antidote for poor ocean conditions is to improve flow conditions upstream of the Golden Gate.

It's not just salmon on the plate: The Bay supports many other important fisheries, including the nation's last major urban commercial fishery (for Pacific herring). For instance, there is a valuable sport and recreational fishery for starry flounder, a predatory fish, which once produced hundreds of metric tons in California[141]. The flounder population in the estuary grows or contracts depending on how much water flows into the Bay during the spring[142]. In addition, tourists and Bay Area residents pay substantial amounts of money (for tackle, licenses, and a boat ride) to try to catch white sturgeon in the Bay; the spawning success of these giant fish is directly related to flow from the watershed into the estuary[143]. Sacramento splittail, an endemic species that depends on periodic flooding to inundate its spawning habitats, are also a staple of recreational and subsistence fishing in the upstream portions of the estuary. Invertebrates, like oysters and Dungeness crab, are also much sought after, and again maintenance and restoration of their habitats and populations requires more careful management of freshwater flows to the Bay. Unless flow conditions are improved, these fisheries could all go the way of the once vibrant fisheries for Delta smelt and longfin, two species that were once ubiquitous in the estuary but are now so rare that they are listed as endangered. As these fisheries disappear, the fishing communities that depend on them – from small towns along the coast to families who rely on subsistence fishing in the Delta to the seafood-related businesses of Fisherman's Wharf – are at risk as well.

MARINE MAMMALS SUFFER WHEN REDUCING FLOWS REDUCES THEIR FOOD SUPPLY

There are few more amazing and thrilling experiences for Bay Area residents and visitors than to observe sea lions and seals hauling up onto local docks and piers, or to take a whale-watching trip to see the Orca whales (the "Southern Resident killer whale" population) that feed and migrate right outside the Golden Gate. These protected marine mammal species eat fish and other organisms that rely on the estuary and its Central Valley watershed as spawning and rearing grounds. By diminishing the estuary's productivity and changing its food web, reducing Bay inflows can produce cascading effects that eventually create problems for local marine mammal populations. For example, the local Southern Resident killer whale population specializes in eating Chinook salmon; the abundance, reproductive success, and mortality rates of resident Orcas are linked to prey limitation caused by recent Chinook salmon declines[144]. Orca whales have come to rely on Chinook salmon because they are large fish with a high fat content that were historically abundant throughout the year, so the decline of salmon stocks has had dire consequences for resident Orcas. Dwindling supplies of salmon are believed to restrict the recovery of the local population[145]. As a result of mismanaging flows in the estuary and its watershed, the future of these two iconic species in the Bay Area is uncertain.

CASCADING EFFECTS OF FRESHWATER FLOW IN THE SAN FRANCISCO BAY ESTUARY

	NEARSHORE OCEAN	SAN PABLO, CENTRAL, AND SOUTH BAYS	SUISUN BAY AND MARSH	DELTA
PROCESSES AFFECTED BY FRESHWATER FLOWS	• Sediment transport (turbidity) • Nutrient transport • Beach formation	• Sediment transport (turbidity) • Nutrient transport • Marsh accretion • Changes in the availability of habitats with different salinities • Water column stratification	• Sediment transport (turbidity) • Nutrient transport • Marsh accretion • Changes in the availability and location of habitats with different salinities • Residence time • Food web productivity • Gravitational circulation, fish and wildlife migrations	• Sediment transport (turbidity) • Nutrient transport • Marsh accretion • Residence time • Floodplain innundation • Fish and wildlife migrations • Contaminant loading • Toxic algal production • Keep brackish water “at bay”, maintains agricultural and drinking water quality
BIOLOGICAL EFFECTS ASSOCIATED WITH FRESHWATER FLOWS	• Increase food web productivity • Improve survival and fitness of resident Orca whales and other marine mammal populations • Create/maintain/improve beach habitats • Increase fishery productivity	• Control wetland plant species composition and distribution • Improve abundance and distribution of many native species including those that become food for other species • Increase fishery productivity • Create/maintain/improve brackish marsh habitat	• Improve abundance and distribution of many native species, including those that become food for other species • Increase fishery productivity • Create/maintain/improve brackish marsh habitat	• Prevent harmful algal blooms • Improve abundance and distribution of many native species • Increase fishery productivity • Control spread of invasive species • Reduce entrainment of endangered fish at Delta export pumps

Figure 16: Most fresh water comes to San Francisco Bay from rivers of the Central Valley’s watershed, via the Sacramento-San Joaquin Delta (upper right). The effects of flowing fresh water (including the transport of food, nutrients, sediments, and organisms produced upstream) can be felt throughout San Francisco Bay and into the nearshore Pacific Ocean. Along the journey from the rivers to the ocean, freshwater flows affect numerous processes and habitats, generating a variety of biological outcomes. Generally speaking, managing water diversions upstream of the Bay in a more sustainable manner will lead to higher flow rates, more natural variability in those flow rates, and increasing benefits for the larger San Francisco Bay ecosystem and the people who live in and visit the Bay Area.

PEOPLE ARE THE ULTIMATE LOSERS FROM LOW BAY INFLOWS

Clearly, people benefit from a healthy San Francisco Bay in many ways (Figure 16). When the Bay's fish and wildlife populations are thriving, they provide enormous commercial and recreational opportunities, from taking your family to discover the unique plants and animals of the Bay's wetlands and beaches to going whale watching or salmon fishing, and they feed millions of people each year. Collectively, the Bay's natural resources make San Francisco one of the most attractive places in the world to live and visit.

People don't just benefit from observing wildlife and eating seafood, but regularly enjoy direct contact with the Bay. Many "play in the Bay" when they wade, swim, sail, or kayak in its waters; these activities are only enjoyable when the Bay's waters are clean and there are wetlands and beaches to visit. When Bay inflows decline, water quality and the ability to resupply beaches and wetlands with sediment declines as well.

Don't go near the water without a hazmat suit: We now know that low inputs of Bay inflow not only degrade water quality but also are beginning to cause periodic harmful algae blooms in the estuary. These harmful "algae" (actually, cyanobacteria) produce neurotoxins powerful enough to make humans sick and even to kill dogs, otters, and other small mammals[146]. The Microcystis cyanobacteria blooms more frequently when low fresh water flows reduce flushing and decrease turbidity in the Delta[147]. Although this species blooms only in the fresh water of the upper estuary, its toxin can be transported downstream; in fact, the neurotoxin was recently detected in invertebrates in the saltier waters of the Central Bay[148]. Thus, the problem of low Bay inflow not only harms fish and wildlife but also threatens water quality and recreational opportunities for people throughout the larger Bay Area. This alarming development has the potential to reverse the positive effects of our decades old, multi-billion dollar investment in cleaning up the Bay's waters.

The reduction of Bay inflows also poses a threat to the continued existence of the beaches and wetlands that surround the Bay and the coastal areas nearby the Golden Gate, popular recreational sites that attract both residents and tourists throughout the year. These special environments rely on a continuous supply of sediments to maintain themselves in the face of ongoing erosion from storm runoff and waves. Delivery of sediments to the Bay and coastal environments, and our ability to maintain these important features, is controlled in part by how much freshwater inflow we allow to reach the estuary. As Bay inflows are constricted by human water diversions, they mobilize less sediment; many of the Bay Area's beaches and wetlands are rapidly eroding for lack of sediment resupply. As sea levels rise, the resupply problem will become even more critical.

> A Bay Area where it's hard to catch salmon, see pelicans or Orca whales, find a bowl of cioppino made with today's local catch, hang out at the beach, or even be in contact with the water? This is a high price to pay for tolerating California's unsustainable approach to managing its aquatic resources, where so little freshwater flow is allowed to make the life-giving journey to San Francisco Bay and the Golden Gate.

The time is now for Californians to decide whether we really want to pay that price – or the choice will be made for us; the loss of the many ecosystem services and economic benefits the Bay still provides today will become just another cautionary tale to pass on to future generations.

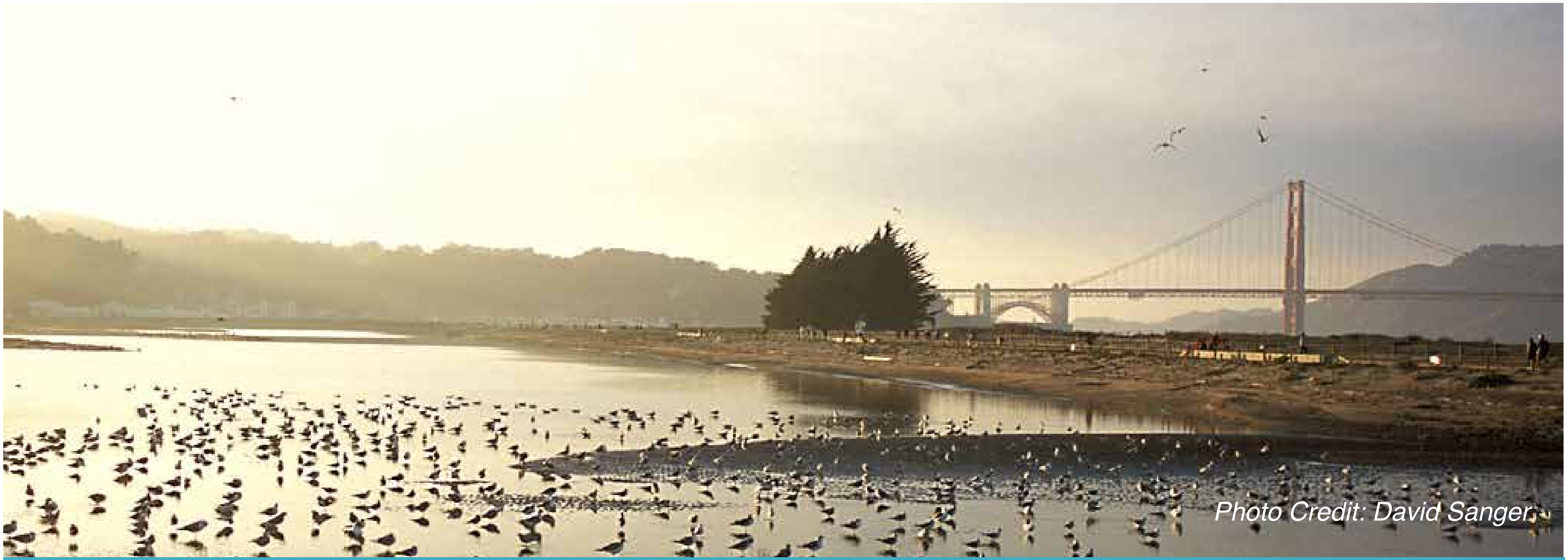


Photo Credit: David Sanger.

TURNING THE FLOW BACK ON

WHAT CAN BE DONE TO REVIVE THE FRESHWATER-STARVED ESTUARY?

Fortunately, there's still time to avoid the increasingly likely scenario where native fish species go extinct; toxic algal blooms become common; recreational and commercial fisheries are permanently closed; marshes erode, grow more saline and less diverse; and the Bay Area's tourism and recreational portfolio loses value.

To avoid that scenario, Californians must choose a different pathway for how we manage flows and water supplies in the future. As mentioned in the beginning of this report, while most of the outcomes of water management conflicts are experienced downstream in the Bay, most of the causes – and the solutions –

manifest themselves in the Bay's watershed. Here are some of the essential elements of a watershed-wide solution pathway.

ADOPT STRONGER WATER QUALITY STANDARDS FOR THE BAY ESTUARY NOW, AND UPDATE THEM BASED ON WHETHER ECOLOGICAL TARGETS ARE BEING MET

The federal Clean Water Act requires the states to adopt, and obtain federal approval of, standards that fully protect designated beneficial uses of water, and then to review them every three years to ensure they are achieving their purpose. California last updated water quality standards for the Bay estuary, over 20 years ago, in 1995. In this estuary, the beneficial uses of water most sensitive to human alteration and degradation and most at risk of being extinguished are related to fish and wildlife, including estuarine habitat, fish migration, and coldwater habitat. Many policy-makers, regulators, and independent scientific reviewers have concluded over the last decade that the freshwater flows required by the 1995 standards are not sufficient to protect fish and wildlife beneficial uses of the estuary. For example, the Governor's Delta Vision Task Force, the California State Water Resources Control Board, the California Department of Fish and Wildlife, the National Research Council, and the U.S. Environmental Protection Agency[149] have all made such findings. The promulgation of new, more protective flow standards by the Water Board and the EPA that require substantially more inflow to San Francisco Bay is the single most pressing item on the agenda for saving the estuary. Delays in completing the update, begun in 2009, must come to an end, and new standards updated in short order.

A wealth of scientific evidence supports increasing required flows to save native fish and wildlife populations and restore productivity of the estuarine. But the record also indicates that increased flows and flow variability help control the spread or damage caused by invasive species that have colonized the estuary, and suggests that they might control new invasions as well. Federal and state regulators should consider developing and adopting additional flow requirements that are specifically designed to provide conditions that inhibit the establishment and spread of invasive species.

Get SMART: The new standards for flow (and other water quality parameters) should not only be fully protective of the most sensitive fish and wildlife beneficial uses, but also be linked to a set of biological performance measures that define the desired outcomes for fish and wildlife beneficial uses using SMART (specific, measurable, achievable, relevant, and time-bound) objectives[150]. These SMART objectives should include targets for population viability of key species (i.e., abundance, diversity, productivity, and distribution, as discussed in the previous chapter) and targets for ecological conditions associated with population response (e.g., temperature or habitat availability). Although the Clean Water Act requires triennial review of standards, most standards are not updated more often than once in a generation, and the process is usually politically controversial. Measuring progress toward achieving SMART biological objectives can allow regulators to adjust flows and other environmental safeguards, within a narrow pre-determined range, to achieve better, more timely protection of fish and wildlife uses of the estuary. This adaptive management approach also lends itself to efforts to improve our understanding of the flow regimes, including magnitude, duration, seasonality, and frequency of flows, that will effectively suppress invasive species.

REQUIRE ALL WATER DIVERTERS TO CONTRIBUTE THEIR FAIR SHARE

Currently, the federal Central Valley Project and the State Water Project are assigned the primary responsibility for releasing water from their reservoirs to achieve the flow and water quality standards for the Bay estuary. Strictly speaking, this first and foremost affects the contractors served by the projects, who have water rights that are junior to others in the watershed. The strange reality is that irrigation districts and cities with senior rights, including those parties who exchanged their senior water rights for delivery contracts with the projects, are not directly required by regulators to help attain water quality standards set for the Bay and Delta. This leaves a subset of water users, representing a quarter or less of total diversions, as the parties primarily responsible for meeting water quality standards for the entire estuary[151]. Updated water quality standards that require all water users, including senior water rights holders, to contribute a fair share of the total flow needed to meet standards that are designed to stablize and restore the estuarine ecosystem could generate millions of acre-feet of additional freshwater flows to the Bay Estuary; spreading the obligation among a larger group of water diverters would reduce inequities in current water allocations, as well. Everyone should be responsible for protecting public resources before anyone receives the public's water to use for their own private gain. Any pathway that fails to set and integrate the obligations of this larger subset of water users will not generate sufficient flow to solve the estuary's problems.

More broadly, California's archaic water rights system needs to be modified to reflect the realities of twenty-first century society, law and climate. Not only are different water users treated differently based on priority in time rather than urgency of need, but the state's water resources are wildly over-allocated as a result of historically awarding the right to use water without examining whether adequate supplies exist. Total water rights allocations in California equal five times California's mean annual runoff, and water rights in major river systems in the Bay's watershed account for up to 1000% of natural supply[152]. As long as water rights are so over-allocated, there will always be pressure to withdraw more water from the Bay's watershed than is sustainable in the long term, and corresponding political pressure to weaken water quality standards or other flow-related environmental protections. In the past, water rights reform and groundwater management were both considered third rails in California politics; now the first phases of groundwater reform have become a reality, but not before over-exploitation of these resources caused some communities to run out of water and the earth's surface to subside. The time to consider updating our water rights system has also come; reform needs to happen before the even more awful to contemplate impacts of over-allocation become irreversible.

REDUCE RELIANCE ON THE DELTA AS A SOURCE OF WATER SUPPLY

The upper estuary is ground zero in the battle over how water is managed – and mismanaged – in California, and it is here that the magnitude of the effects of unsustainable water diversions on fish, wildlife, habitat, and ecological processes are most apparent. In 2009 the California Legislature recognized the vulnerability of the upper estuary and the need to reduce human pressure on this ecosystem by passing the Sacramento – San Joaquin Delta Reform Act, which among other things set a new state policy:

> … to reduce reliance on the Delta in meeting California's future water supply needs through a statewide strategy of investing in improved regional supplies, conservation, and water use efficiency. Each region that depends on water from the Delta watershed shall improve its regional self-reliance for water through investment in water use efficiency, water recycling, advanced water technologies, local and regional water supply projects, and improved regional coordination of local and regional water supply efforts.[153]

Regional self-reliance in areas now exporting water from the Bay's watershed means using less water to provide the same goods and services (e.g., through water efficiency, conservation, leak reduction); using water more than once before disposing of it (water recycling); cleaning up degraded water so that it can be used for productive purposes (brackish water reclamation); using local runoff for nonpotable water use (stormwater capture and reuse); and storing water underground in groundwater aquifers during wet years (conjunctive use, water banking, stormwater recharge). According to a 2014 review by the Pacific Institute and the Natural Resources Defense Council, up to 14 million acre-feet of water per year – over half the total amount of water used for human use throughout the Bay's watershed each year – could be saved from combined investments in these strategies[154].

These approaches can also reduce the carbon footprint of water management and respond to shifts in hydrology caused by climate change. Increasing local self-reliance avoids expending the energy needed to transport imported water long distances from its source. For instance, transporting water via the State Water Project represents about 3% of the state's total energy consumption[155]. Using the natural capacity of groundwater basins to clean and store storm runoff for later use reduces much of the energy and expense associated with capturing, treating, and disposing of stormwater. Expanding that capacity by enlarging flood basins and floodways and reoperating existing reservoirs can temporarily capture more of the larger floods that will be typical of a warming climate, and then divert these flows to groundwater recharge areas.

Town and country together: Regional self-reliance also requires that the inequities between urban and agricultural water uses be addressed. Urban water users generally pay a much higher cost for water, invest more in conservation and other demand management strategies, and are held to a higher standard for using water efficiently (e.g., the state's mandated target of reducing per capita water use in the urban sector by 20% vs. the absence of any quantitative target for reducing use in the irrigation sector). Targets for saving water and becoming locally self-reliant should be set as appropriate for each economic sector and each region of the state; permitting and funding decisions by local, state and federal agencies should be linked to performance in meeting these targets.

INTEGRATE FLOW AND HABITAT RESTORATION TO BATTLE CLIMATE CHANGE

The decline of sediment inputs from reducing Bay inflows has contributed to the erosion of marshlands and beaches throughout the Bay estuary and nearby coastal areas. That problem is now greatly magnified by the effect of climate change on sea levels. Rising sea levels are a challenge to the continued existence and quality of the Bay estuary's marshes and to life and property for human communities along the shoreline of the Bay and coastal areas. Significant efforts have been underway for decades to acquire and restore wetland areas around the estuary; more recently, there is serious interest in innovative approaches like combining marsh restoration with construction of earthen levees in order to establish a low-cost and effective regional network of flood barriers[156]. Providing for a more natural pattern of higher winter and spring inflows to the Bay will increase sediment resupply to restored marshes and "horizontal levees," helping maintain them long after the initial construction effort. Restored freshwater and brackish marshes also need enough freshwater inflows at the right times of year to maintain their species composition and diversity. Marsh restoration and flood protection efforts, as well as beach rehabilitations, should consider flow regime requirements during design and evaluation of projects, and as part of the permitting process where appropriate.

Wetlands Photo Credit: David Sanger

WE MUST ACT NOW

The science overwhelmingly indicates that more freshwater flow, following a more natural pattern, must reach the San Francisco Bay estuary to restore its fish, wildlife, water quality, food web, marshes, beaches, coastal fisheries, and other public benefits. The only barriers to action are the general lack of understanding about the severely degraded condition of this freshwater flow-starved estuary and the lack of political will to change the unsustainable way California manages its water resources. Can Californians be made aware of the pending collapse of the Bay estuary ecosystem – and the loss of all which that ecosystem provides us – and motivated to demand action now? Can decision-makers at every level – federal, state, and local – be prevailed upon to take the steps necessary to prevent the destruction of California's greatest aquatic ecosystems before it is too late? The window of opportunity to protect this treasure is closing rapidly.

ENDNOTES

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GLOSSARY

Abundance

The number of individuals in a population. Often measured as an index calculated based on the number of individuals detected per sample.

Actual Flow or Runoff

The amount of fresh water flowing past a point, measured or calculated at that point or calculated based as the sum of upstream measurements throughout a watershed; in contrast to unimpaired flow or runoff (see below).

Acre Foot (AF)

The amount of water required to cover 1 acre to a depth of 1 foot (approx. the area of an American football field). An acre-foot is approximately 326,000 gallons or 1,233.5 cubic meters.

Algae

Chlorophyll containing single or multi-celled organisms that lives in fresh or salt water.

Anadromous Fish

Fish that are born in freshwater, migrate to the ocean, and return to fresh water in order to as adults to spawn. Anadromous fish in the Bay's watershed include Chinook salmon, steelhead, striped bass, white sturgeon, green sturgeon, and American shad.

Aquifer

An underground geological formation that holds water.

Bay

A body of water connected to an ocean or lake, formed by an indentation of the shoreline.

Bay Inflow

Freshwater flows to San Francisco Bay, originating upstream from its Central Valley watershed, measured or estimated where the Delta enters Suisun Bay (the uppermost portion of San Francisco Bay), and not including the relatively small amount of flow from the local watersheds directly surrounding the Bay.

Benthic

Bottom-dwelling. Refers to organisms that live on the bottom of a water body or the habitat along the bed of a river, estuary, lake, or sea.

Brackish water

Slightly salty water, characteristic of estuarine habitats.

Central Valley Project (CVP)

The federally operated water storage, diversion, and conveyance system that provides water from California's Central Valley and the Trinity River to agricultural, municipal, and industrial users in the Central Valley and Bay Area. Major facilities include Shasta, Trinity, Folsom, Friant, and New Melones Dams (and their reservoirs), the Delta Cross Channel, the Delta-Mendota Canal, the Jones (Tracy) Pumping Plant, and San Luis Reservoir among others.

CFS

Cubic feet per second, a rate of flow measured as a volume of water (cubic feet) passing a point in one second. A flow of 1cfs equals about 2 acre-feet per day or enough to fill a 32-gallon trashcan in just over 4 seconds.

Delta

The uppermost portion of the San Francisco Bay estuary, the Delta is the roughly triangular area formed at the western edge of the Central Valley by the confluence of the Sacramento and San Joaquin Rivers. Bay inflow from the Central Valley passes through the Delta as do numerous types of migratory fish species.

Diversion

See "Water Diversion"

Drought

An extended period, lasting more than one year, during which precipitation and runoff is well below average. Different from the seasonal drought experienced in California every year from late spring through early fall when very little or no rain falls.

Ecosystem

The biological and abiotic (non-living) parts of the environment in a particular area and the interaction of those parts.

Endangered Species

Species or distinct populations of plants and animals that are protected by federal or state laws that are specifically intended to prevent extinction and to protect habitats of those species.

Erosion

The wearing away of the land surface by wind or water.

Export

See “Water Export”

Estuary

A partly enclosed coastal body of brackish water with one or more rivers or streams flowing into it, and with a free connection to the open ocean. Estuaries are formed by the mixing of fresh water and saline water and represent a transition zone between river environments and marine environments.

Habitat

The physical, chemical, and biological context within which an organism or assemblage of organisms live.

Harmful algal bloom (HAB, aka Toxic algal bloom)

A proliferation of cyanobacteria that cause negative impacts to other organisms via natural production of toxins.

Introduced (or “exotic”) species

Populations of plants and animals that are not native to a specific area, which become established and self-sustaining after individuals have been transported into an ecosystem intentionally or unintentionally. Introduced species may alter the natural ecology of an area, via competition for resources, alteration of ecosystem processes and native habitats, and/or predation on native species.

Microcystis

A genus of cyanobacteria that lives in fresh water and produces a powerful toxin (microcystin).

MAF

Million acre-feet.

Nutrient

Any substance, which enhances the growth of plants and animals.

Pacific Flyway

A major north-south corridor for migratory birds on the west coast of the Americas, extending from Alaska to Patagonia. Every year, migratory birds travel some or all of this distance both in spring and in fall, following food sources, heading to breeding grounds, or travelling to overwintering sites.

Plankton

A diverse group of organisms that live in the water column of large bodies of water and that cannot swim against a current. Includes photosynthetic organisms (phytoplankton) and tiny primary consumers (zooplankton). They provide a crucial source of food to many large aquatic organisms, such as fish and whales.

Population Viability

The ability of a population to persist and to avoid extinction. The viability of a population reflects the number of individuals, changes in the birth rate, mortality rate, fecundity, genetic and life-history diversity of individuals in a population, and geographic distribution.

Productivity

Relates to factors such as birth, maturation, and death rates that determine a population’s growth rate.

Residence Time

The average amount of time that a moving particle (e.g., molecule of water) spends in a particular area.

Runoff

The portion of precipitation that enters surface waters during a given period of time. In California, on average about one-third of the precipitation becomes runoff while the rest is “consumed” – evaporated and transpired – by plants or evaporated from the ground.

Salmon

A common name for at least six species of fish. Four races of Chinook salmon reproduce in the rivers of the Central Valley – more distinct populations of this species than in any other single watershed in their range. Named for the time of year during which they re-enter freshwater and begin their migration upstream to spawn, these races (or “runs”) are the spring, fall, late-fall and winter runs.

Salinity Gradient

The spatial distribution of the range of salinities between fresh and marine that is one of the defining characteristics of any estuarine ecosystem. This gradient generates a range of habitats and ecological assemblages composed of organisms with different tolerances for salinity.

San Francisco Bay

The central portion of the Bay estuary, composed of the open water embayments (from north to south, Suisun, San Pablo, Central and South Bays) upstream of the Golden Gate and downstream from the Delta.

San Francisco Bay Estuary

The area – of which San Francisco Bay is the central region – where fresh water and salt water mix, from the tidally influenced portions of the Sacramento – San Joaquin Delta where river flows enter the estuary to local nearshore waters in the Gulf of the Farallones outside the Golden Gate.

Sediment

Fine soil or mineral particles that settle to the bottom of the water or are suspended in the water.

Spatial Distribution

The arrangement of a population in space. Not to be confused with dispersal, which is the movement of individuals away from the area where they were born. Distribution patterns can change throughout a species’ life cycle – the population is generally considered to be at greatest risk when its geographic range is most limited or in life stages that are least mobile.

State Water Project (SWP)

The state-operated water storage, diversion, and conveyance system that provides water from the Feather River and “surplus” water to agricultural, municipal, and industrial users. Major facilities include Oroville Dam and Reservoir, the Banks Delta Pumping Plant, the California, South Bay, and North Bay Aqueducts, San Luis Reservoir, and Castaic Lake.

TAF

Thousand acre-feet.

Toxic Algal Blooms

(see Harmful Algal Blooms)

Trophic Levels

The relative position an organism occupies in a food web – what it eats and what eats it. The word trophic derives from the Greek trophē referring to food or feeding. Phytoplankton are primary producers. Organisms that eat phytoplankton are primary consumers. Organisms that eat animals (either as part of their diet or exclusively) are secondary consumers. These organisms all exist at different trophic levels. Individuals may change trophic levels as they pass through different life stages.

Turbidity

The cloudiness or haziness of water caused by tiny particles -- similar to smoke in air. Turbidity is roughly the opposite of water clarity.

Unimpaired Flow or Runoff

Quantity of water that would have flowed passed a point without upstream dams or water diversions (which would “impair” the runoff from reaching that point). Unimpaired runoff is calculated with existing land use (but without dams and diversions) and does not assume that the landscape has been returned to its historic, “natural” state.

Watershed

The total land surface that drains water to a particular waterbody.

Water Diversion

Removal of water from its natural course in order to serve human purposes (e.g., agricultural irrigation).

Water Export

A specific type of water diversion where water is removed from its watershed of origin and transported to an entirely different watershed or moved back upstream in the same watershed. The largest export project involves pumping water from the Delta portion of the San Francisco Bay Estuary via the State Water Project and federal Central Valley Project pumps to the San Joaquin Valley and Southern California.

Wetlands

Areas where saturation with water is the dominant factor determining the nature of soil development. These areas can be identified, even when soils are temporarily drier, by unique plants that have adapted to oxygen-deficient (anaerobic) soils. Wetlands may be very productive and diverse habitats and influence the rate of flow and water quality in adjacent environments.