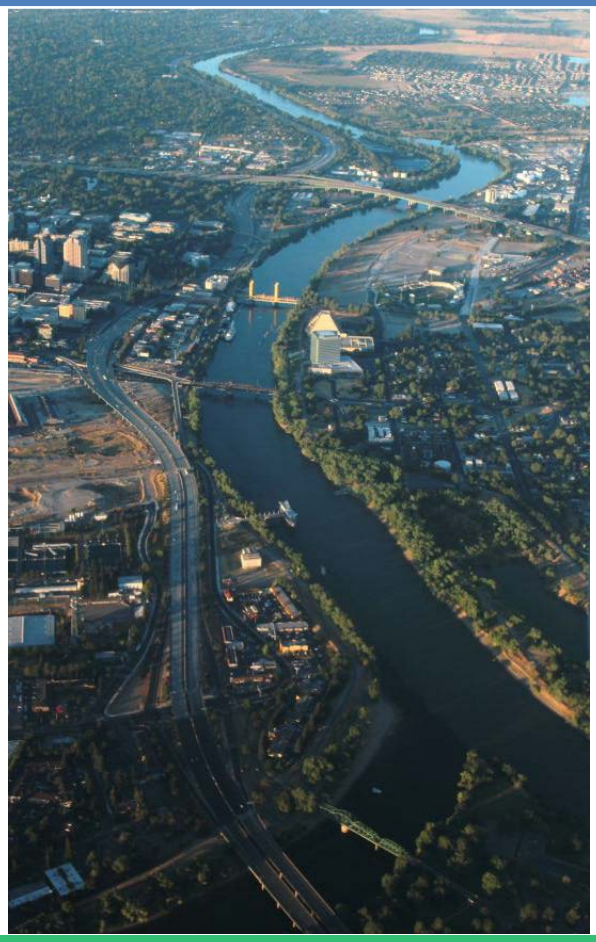
Lower Sacramento River 2011 Water Quality Report Card



The Sacramento River Watershed Program

Lower Sacramento River 2011 Water Quality Report Card

Sacramento River Watershed Program

Prepared by
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About the author Dr. Shilling is a research scientist at the University of California, Davis who studies how environmental sciences intersect with environmental policy. He has developed indicator systems and report cards for the Bay Area, Southern California, and the Sacramento River Watershed. He is currently developing the sustainability indicator system for the inter-agency California Water Plan. He also has projects in the area of environmental justice and transportation ecology.

Cover photo credit: Fraser Shilling

EXECUTIVE SUMMARY

Measuring the health of the Sacramento River is accomplished by evaluating indicators of physical, chemical, and biological conditions. Taken together, indicators provide a pulse of California's largest river, the Sacramento River. Measuring River health requires evaluating environmental conditions relative to reference healthy and unhealthy conditions.

The purpose of this report is to evaluate the health of the Lower Sacramento River, based upon water quality indicators: water temperature, nutrients (ammonia, nitrate, phosphate), turbidity/suspended sediment, dissolved oxygen, methylmercury in fish, fecal bacteria, and chlorophyll a (from algae). The current (2011) conditions were evaluated based on how well beneficial uses are being met and trends in condition were measured to determine whether health is improving or declining.

Water temperature conditions were good (low) when averaged over the year, though there are periods during the summer when temperatures were too high for young salmon and Delta smelt. Nutrients, a constituent of wastewater, agricultural runoff, sediment flux, and natural sources, were determined to be good relative to toxicity thresholds, but need more investigation, relative to the needs of the Delta food web. Turbidity conditions were poor (low turbidity) for most of the year, with periods of higher turbidity (beneficial for migrating Delta smelt) during Winter and Spring runoff. Dissolved oxygen conditions were good (high concentrations), except for late summer and early winter when concentrations were lower. Methylmercury conditions (2006 data) were moderate, meaning that limitations on fish consumption are needed. Fecal bacteria (E. coli) were present during limited times of the year, conditions were usually good.

Water quality condition (out of 100) and inter-annual trends ("+" means improving, "—" means declining, "0" means no change, and "ND" means not determined).

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Indicator	Condition	Trend
Water Temperature	89	—/0
Dissolved Oxygen	75	—/0
Turbidity	35	+/—
Nutrients (Ammonia)	100	—
Chlorophyll a	ND	—/0
Methylmercury	65 (2006)	ND
Fecal bacteria (E. coli)	88(2010)	ND

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	Indicator	**Condition**	**Trend**	**Explanation**
Aquatic habitat	**Water Temperature**	89	—/0	Temperatures were generally supportive of salmonid juvenile survival, except in the late Summer. Temperature conditions are staying the same or declining.
	Dissolved Oxygen	75	—/0	Dissolved oxygen conditions were good (high concentrations), except for late summer and early winter when concentrations tended to be lower. Conditions are declining in at least part of the River.
	Turbidity	35	+/—	Turbidity conditions were poor (low turbidity) for most of the year, with periods of higher turbidity (beneficial for migrating Delta smelt) during Winter storms and Spring runoff. Both upward and downward trends in condition were observed.
Food web	**Ammonia**	100*	—	Ammonia concentrations were below toxic levels for zooplankton, mussels and fish, but conditions are declining. Ammonia effects on dissolved oxygen and potential impacts on phytoplankton should be monitored. *It should be noted that the score would be considerably lower if based on a draft proposed standard for food web production rather than the toxicity standard.
	Chlorophyll a	ND	—/0	Chlorophyll a conditions were not determined for 2011. Conditions are either not changing, or declining (decreasing biomass) over time.
Human health	**Methylmercury**	65 (2006)	ND	Methylmercury conditions are moderate, meaning that limitations on fish consumption are needed, rather than this beneficial use being present. No trend was calculated.
	Fecal bacteria (E. coli)	88 (2010)	ND	The fecal bacterium E. coli is present during part of the year at concentrations that are harmful to people, but concentrations are
This report card is a product of the Sacramento River Watershed Program				

WHAT CAN BE DONE?

Report cards provide a broad synthesis of current conditions and trends, but tell only one side of the story – what is going right and wrong. Improving or degraded health for parts of the River, or during certain times of the year can often be linked to actions we are taking or could be taking. For each indicator, actions are discussed that would help to solve observed problems and deteriorating conditions.

INTRODUCTION

The Sacramento River is a major North American river, draining 27,000 square miles of California and emptying >30% of the state's runoff through the Delta into the San Francisco Bay. It provides water to 2/3 of California and habitat for some of the largest salmon runs on the West Coast. The river is both a legacy feature of California's landscape and a drain for various agricultural, municipal, and commercial activities. Land and water managers are in a constant balancing act between protecting the natural values of the River and using it as a resource for human economic benefits and disposal activities.

The Lower Sacramento River is defined here as the portion of the River that starts below the Feather River confluence and ends as the River meets the San Joaquin River in the western Delta. This section of the River receives the most influence from human activities and includes parts of the iconic Delta. It is channelized and for most of its length is treated as a drain and conveyance system, rather than as a natural river. It is managed to move drinking water, reduce flooding, and dispose of waste to the Bay and ocean. Stewarding the water quality of this stretch of River may be one of the most daunting such task for any of California's rivers.

Water quality is composed of multiple aspects of physical, chemical, and biological conditions, compared to social or legal standards for well-being. Social standards reflect social priorities, include things like "protecting the food web", and are useful when there are no legal thresholds protecting water quality. The purposes of the present study and report were: 1) to use a selected set of water quality parameters to evaluate the current health condition of the Lower Sacramento River and determine to what extent, if any, beneficial uses of the river are compromised by current conditions (beneficial uses of principal concern are protection of aquatic life, contact and non-contact recreational use, and water for municipal, industrial, and agricultural use); 2) Determine if there are trends in conditions (i.e. are conditions getting better, worse, or staying the same); 3) Present this information in a manner that is informative to the general public and to governmental decision makers.

We include indicators of physical, chemical, and biological condition to estimate the quality of water in the Lower Sacramento River: water temperature, turbidity/suspended sediment, nutrients, chlorophyll-a, fecal bacteria, and methylmercury. Although these are not all possible indicators of condition, taken together, these indicators are a measure of the health of the River.

APPROACH

Geography: Monitoring sites, timeframes, and parameters were reviewed in order to select a representative set for the Lower Sacramento River. The River was divided into three segments: Segment 1 – Verona downstream to Sacramento; Segment 2 – within and immediately downstream of Sacramento; Segment 3 – Delta reach, from Sacramento to Rio Vista.

Indicators and Data: The best situation would be to have representative indicators sampled during 2011 (for condition assessment) and for at least 10 years prior (for trends analysis). Not all monitoring sites' datasets cover all desired indicator types, or necessary timeframes. Data from different sources were combined from several sources at least within each segment and sometimes among them. The "Possible Indicators" column in the table below shows the parameters that are proposed as the super-set for condition assessment (2010/2011) and trends analysis (>10 years prior to 2011). The final analyzed indicators were chosen from within this super-set; the number of indicators was limited by resources for this project.

Table 1 Monitoring sites and proposed indicators for 3 segments of the Lower Sacramento River.

Segment	Monitoring Sites	Possible Indicators
1 (above Sacramento)	Verona Veterans Bridge	Condition: water temperature, electrical conductivity, turbidity (2011, USGS), metals, dissolved oxygen, pesticides, other organic chemicals, nutrients, fecal indicator bacteria, organic carbon (2010, CMP). Trend: 1968 -- 2011, few parameters; 1995 -- 2010, all selected parameters
2 (Sacramento to Hood)	Sacramento Freeport RM 44 Hood	Condition: water temperature, electrical conductivity, total suspended sediment, turbidity, nutrients, dissolved oxygen, metals, pesticides, other chemicals, fecal indicator bacteria, organic carbon (2011, CMP, USGS, DWR, SRWP). Trend: 1968 -- 2011, all selected parameters

3 (Delta portion)	Georgiana Slough Rio Vista Decker Island	Condition: water temperature, electrical conductivity, turbidity, pH, organic carbon, pesticides, chlorophyll-a, dissolved oxygen, total suspended sediment (2011, USGS, DWR); Trend: 1980 -- 2011, water temperature, electrical conductivity, pH, organic carbon, pesticides, total suspended sediment, turbidity

REPRESENTATIVE INDICATORS

There are many parameters representing the physical, chemical, and biological components of water quality. Although not all water quality parameters can represent each other, within categories of a water quality index (see diagram below), there may be opportunities to use one of several metrics to assess condition for that category. This is with the caveat that some metrics interact with each other (e.g., nitrate and ammonia). Conservatively, one would use most of the indicators shown in the diagram in order to assess environmental health. A sub-set of indicators may tell a partial story.

In the conceptual model of water quality diagrammed below (Figure 1), the green boxes distinguish indicators used in the report card because they were both representative of water quality and had data available for condition assessment and trends analysis at one or more sites. The yellow box (chlorophyll a) points to an indicator for which no reference condition was described, but trends analysis was conducted.

Ideally, there would be indicators representing each physical, chemical, and biological condition category. This is true for the indicators in this initial report card. In future report cards, more indicators should be added to provide a more complete picture of water quality and river health.

The following indicator types (and specific metrics) have sufficient data to conduct a condition assessment and/or trends analysis for the Lower Sacramento River, the ones used are in **bold**: **Water temperature** (average daily maximum, variation), **Dissolved oxygen** (concentration, saturation), Nutrients (**nitrate**, **ammonia**, **ortho-phosphate**), Metals (mercury, **methylmercury**, others), Suspended material (**turbidity**, **total suspended sediment**), Phytoplankton (**chlorophyll a**), and Fecal indicator bacteria (**E. coli**).

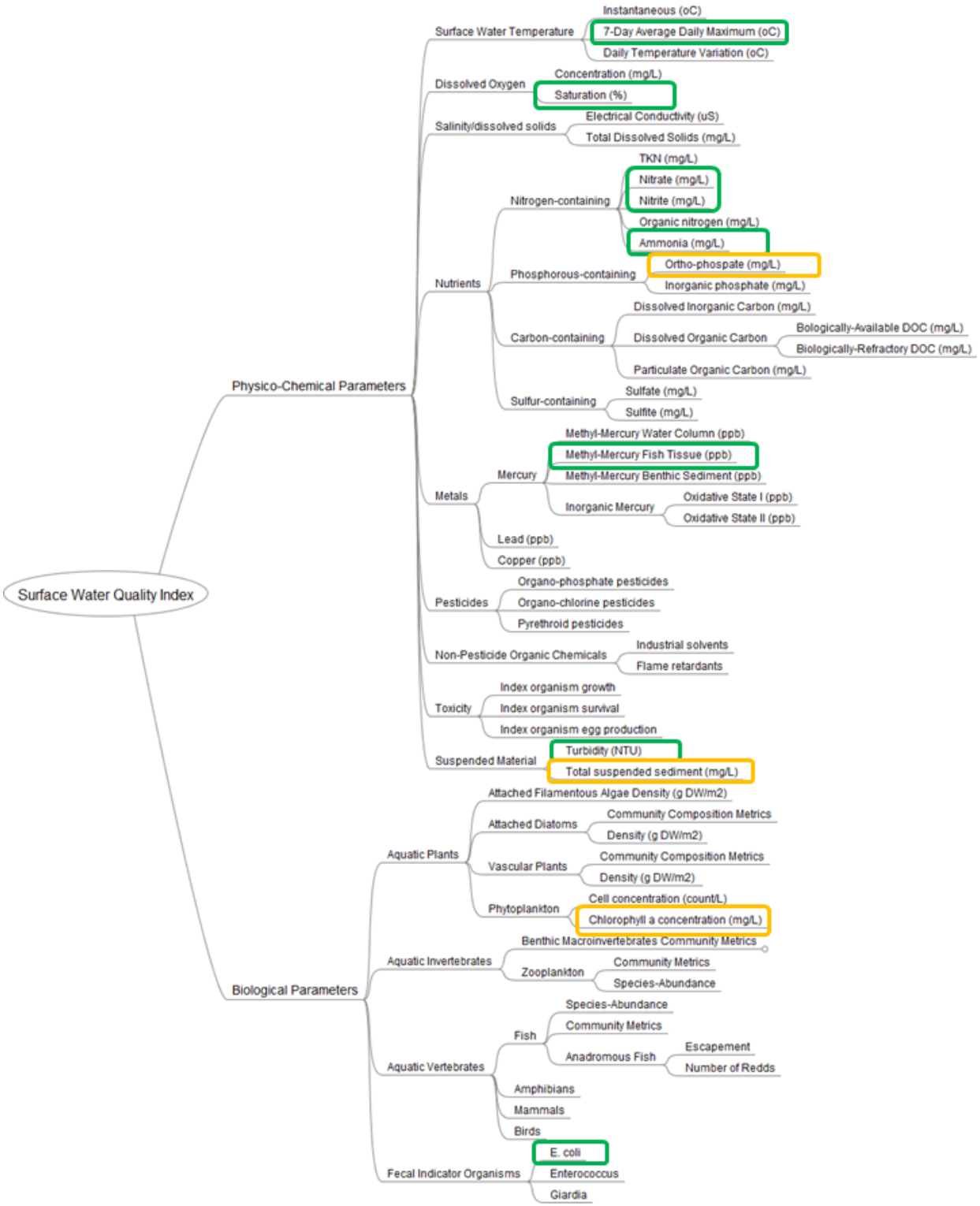

Figure 1 Conceptual diagram of the indicators that could be used and that were used to assess surface water quality trends (yellow boxes) or condition & trends (green boxes) in the Lower Sacramento River.

INDICATOR SCORING

Critical to evaluation of indicators is conversion to an equivalent score that has the same meaning regardless of the parameter. In other words, a "75" for water temperature should have the same meaning as a "75" for methylmercury. This is accomplished by describing the un-desired (unhealthy) and desired (healthy) conditions for each parameter in terms of native units (e.g., degrees Celsius). The relative distance between these conditions is then calculated for each parameter for any given monitoring data point through a normalizing function. This normalization process is identical to that used in previous studies led by the author in the Feather River basin, North Bay and Southern California. It is also identical to the approach for the California Water Plan, 2013 Update, known as the Water Sustainability Indicator Framework (Shilling et al., unpublished).

Table 2 Normalization approach for indicator scores

Indicator	**Minimum Score (=0)**	**Maximum Score (=100)**	**Normalizing function**	**Citations/Sources**
Water Temperature (^{o}C)	25	15	Y= 1/(1+e-(12-.56T)) (chinook salmon juvenile, Delta smelt)	Bennett (2005); Nobriga et al. (2008); Moyle (2002)
Dissolved oxygen	60% saturation,	90 or 100% saturation	Linear function (salmonid young)	Geist et al. (2011); Silver et al. (1963)
Turbidity (NTU)	10	23	Linear function (migrating Delta smelt)	Nobriga et al. (2008); Sommer et al. (2010)
Ammonia/um - toxicity (mg/L)	>1.8	<0.26	Linear function (toxicity for most sensitive freshwater mussels and fish)	EPA (2009)
Ammonia/um – food web (micromolar µM)	8	1	Ln(Y) = -1.28 *ln(X)-4.26 (ammonium inhibition of nitrate uptake)	Dugdale et al. (2007); Parker et al. (2012)

Methylmercury	>1 ppm tissue	<0.05 ppm	Linear function (health effects for humans)	Delta Methylmercury TMDL (2010)
Fecal pathogen bacteria	>576 MPN/100 ml	<235 MPN/100 ml	Linear function (health effects for humans)	US EPA; CA DPH

CONDITIONS AND TRENDS

This report describes the first measurement of health of the Lower Sacramento River, in terms of water quality. This health evaluation is based upon these indicators: water temperature, ammonia, turbidity, dissolved oxygen, methylmercury in fish, fecal bacteria, and chlorophyll a (from algae). Current (2011) conditions and trends in these indicators were evaluated both to measure health and to see whether health is improving or getting worse. Details of the evaluation are provided in the sections below. The indicator scores were reported as a report card as a product of the Sacramento River Watershed Program. Ideally, this will at some point be supported by an online report card, similar to the approach developed for the Feather River basin (http://ice.ucdavis.edu/waf).

Water temperature conditions are good (low) when averaged over the whole year, though there are periods during the summer when temperatures are too high for young salmon and Delta smelt. Ammonia conditions, a constituent of wastewater, were good relative to toxicity standards for sensitive animals, but were poor (high concentrations) when considered in light of metabolic processes of suspended algae in the Delta (a food source for other animals). This was primarily in the summer when freshwater flows are lower and wastewater is less diluted. Turbidity conditions were poor (low turbidity) for most of the year, with periods of higher turbidity (beneficial for migrating Delta smelt) during winter storms and spring runoff. Dissolved oxygen conditions were good (high concentrations), except for late summer and early winter when concentrations tended to be lower. Methylmercury conditions (based on 2006 data) are moderate, meaning that there limitations on fish consumption are needed, rather than this beneficial use being present.

Table 3 Water quality condition and inter-annual trends. Condition was for 2011, except where noted. "+" trend indicates improvement, "0" indicates no trend, and "—" indicates deterioration of condition; a combination of these indicates mixed results. Confidence is based on a combination of number of independent measurements, the standard deviation of the mean score, and the confidence bounds on the trend slope.

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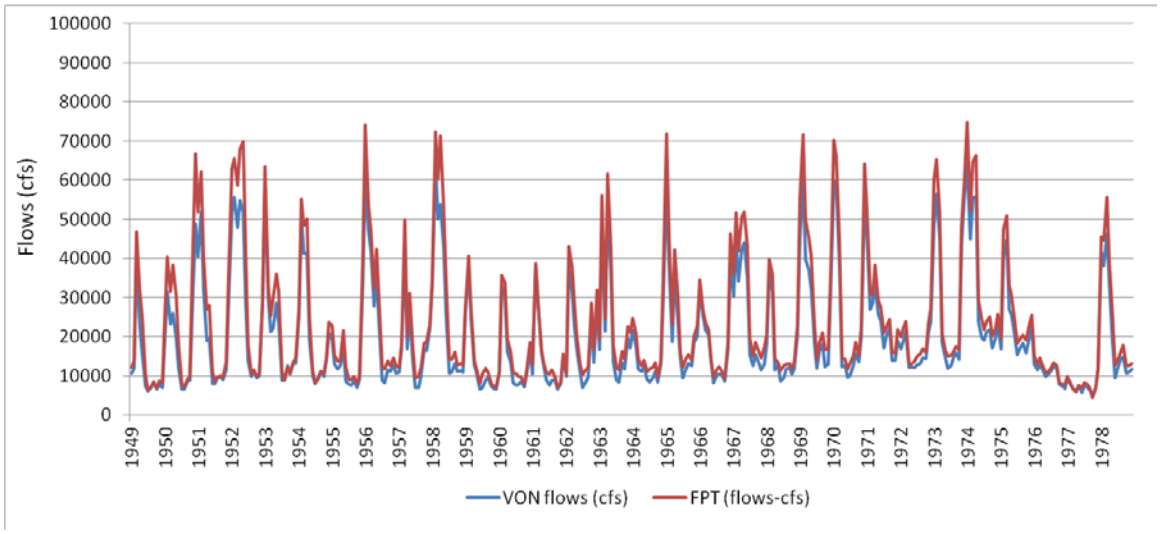
Indicator	**Condition 2011**	**Trend**	**Confidence**
Water Temperature	89	—/0 (1975 – 2011)	Medium-high
Dissolved Oxygen	75	—/0 (1975 – 2011)	High
Turbidity	35	+/— (1975 – 2011)	Low-medium
Ammonia	100	— (1975 – 2011)	Low-Medium
Chlorophyll a	ND	—/0 (1975 – 2011)	Medium
Methylmercury	65 (2006)	ND	Low-medium
Fecal bacteria (E. coli)	88 (2010)	ND	Low-medium

FLOWS

The amount of water flowing down a river is a defining characteristic of condition. Although there are no minimal flow criteria defined for the Lower Sacramento River, it is important to look at trends in flow, as well as how other conditions compare with flows.

Findings for Flows: There are two main characteristics of the River that have changed since record-keeping was begun: 1) an increase in inter-annual variability in flows and an increase in minimum flows (Figure 2).



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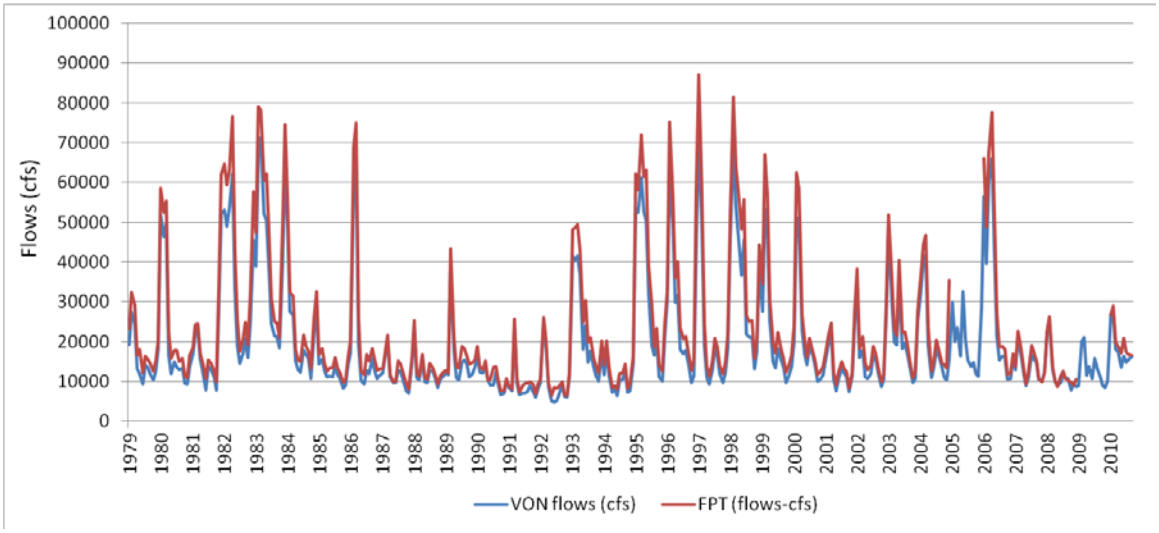

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Figure 2 A) Flows between 1949 and 1978; (B) flows between 1979 and 2011. VON = Verona, FPT = Freeport.

Prior to 1975, the minimum flows (summer) steadily increased (statistically significant, P<0.001); since 1975, minimum flows have not increased (P>0.1) and maximum flows vary considerably (Figure 3). Inter-annual variation has recently increased (Figure 4).

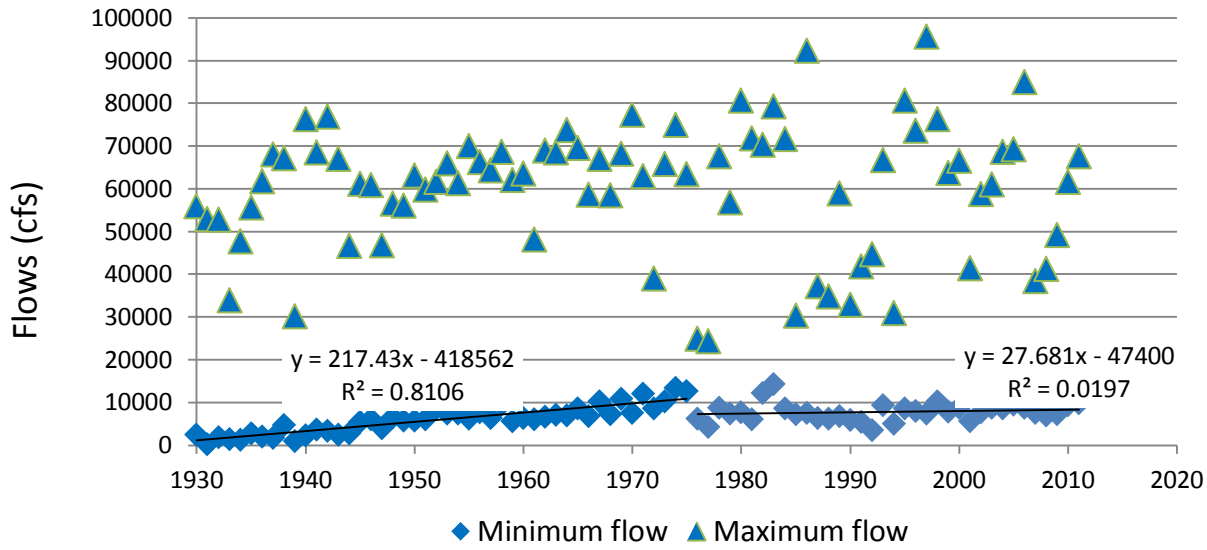


Figure 3 Annual minimum and maximum flows sine 1930.

Many organisms are adapted to seasonal changes in flow conditions, which in turn provide seasonal changes in habitat. Flows vary within an annual cycle from low summer flows to high winter and spring runoff flows. Although there seems to be no change in the range of annual flows over time (Figure 2, black line), the wider dispersion of the annual flow range recently suggests that the inter-annual difference (change from one year to the next) is increasing. This may be due to natural variation in runoff, or changing water management.

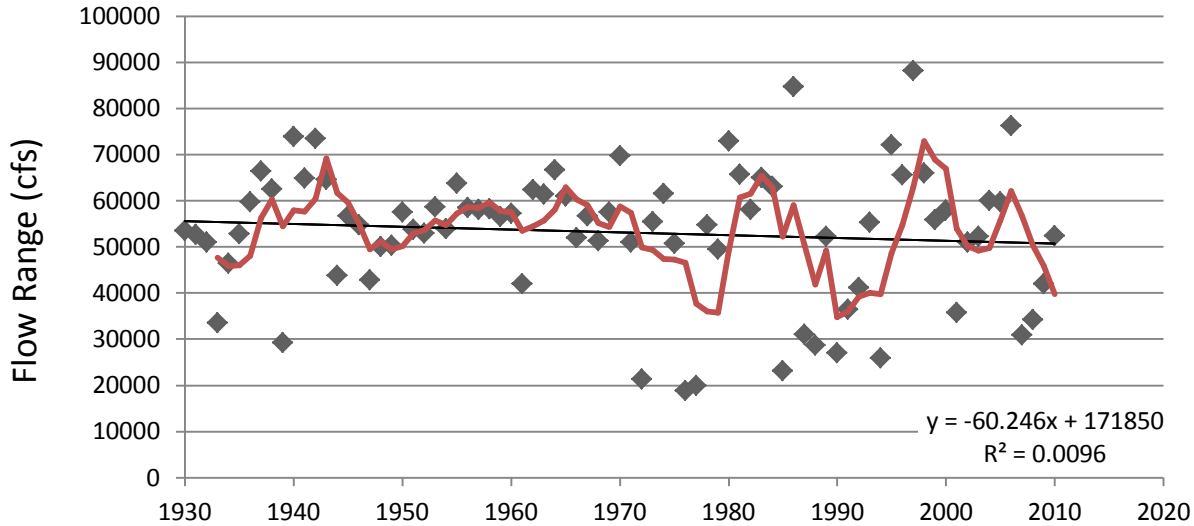


Figure 4 Difference between annual minimum and maximum flows (flow range) since 1930. The red line represents the moving 4-year average.

WATER TEMPERATURE

Young salmonids and other fish grow and survive best when water temperatures are below 13°C (Moyle, 2002; Bennett, 2005; Nobriga et al., 2008) and migrating adult winter-run Chinook salmon do best at water temperatures below 15°C (NMFS, 1997). A high score (100) is achieved when temperatures are below ~15°C, suitable for growth and survival of young salmonids and Delta smelt. A low score (0) is achieved when temperatures are high enough (≥ 25°C) to cause mortality of young salmonids. The Weekly Average Daily Maximum Temperature (WADMT) was used because it is based on multiple measurements per day, provides a good estimate of the average high temperature conditions experienced by fish and other biota, and is thus a conservative measure of warm water conditions. Surface water temperatures were assumed to be appropriate for this purpose because smaller fish (juvenile salmonids and smelt) may seek cover and forage in shallower waters, avoiding deep water where predation risk is higher. The maximum daily temperature was found and the average daily maxima for each week was calculated (WADMT). This WADMT value was converted to a score using the formula shown in Table 2. Out-migrating juvenile salmonid (e.g., Chinook Salmon) are present between August and the end of April (Myers et al., 1998; Martin et al., 2001; Snider and Titus, 2000; USFWS, 2001) and in-migrating adults may be present beginning in November through the end of July (Yoshiyama et al., 1998; Moyle, 2002). Consequently, the mean score and standard deviation were calculated for each river segment, for weeks when juvenile salmonids and Delta smelt could be present (Table 4).

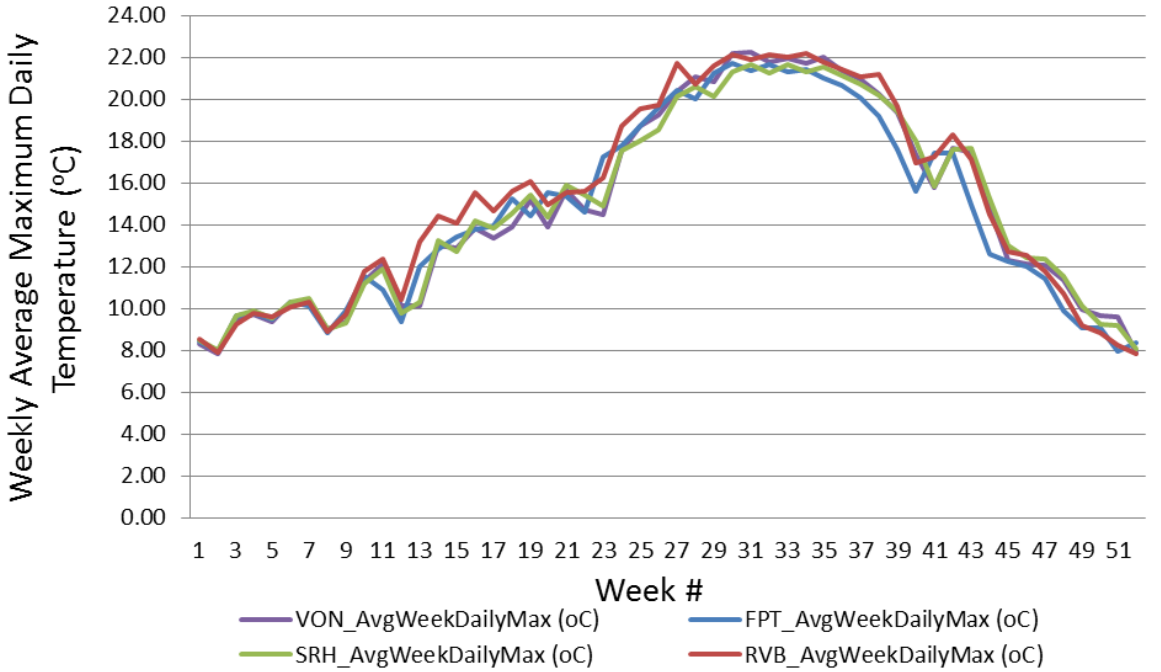
Findings for Water Temperature: Based on water temperature needs for juvenile salmonids, conditions are good, with excellent conditions in the winter and spring and declining conditions in the summer.

Table 4. Water temperature score based on Weekly Average Daily Maximum Temperature for the months when cold-water dependent fish are present.

	Verona	Sacramento – Hood (including Freeport)	Rio Vista	Combined
Mean Score	90	91	88	86
N	34	68	34	136
Standard Deviation (Score)	19.0	16.5	22.7	18.0

Water temperatures vary considerably over the year (between 8 and 22°C) and until the end of March are generally low enough to provide excellent habitat conditions for juvenile salmonid (Figure 5A). By the beginning of July, habitat conditions deteriorate as temperatures climb above 15°C, up to 22°C and the indicator score takes a corresponding

drop (Figure 5B). Water temperatures are high enough in the summer to inhibit growth and survival of young salmon and the well-being of Delta smelt.



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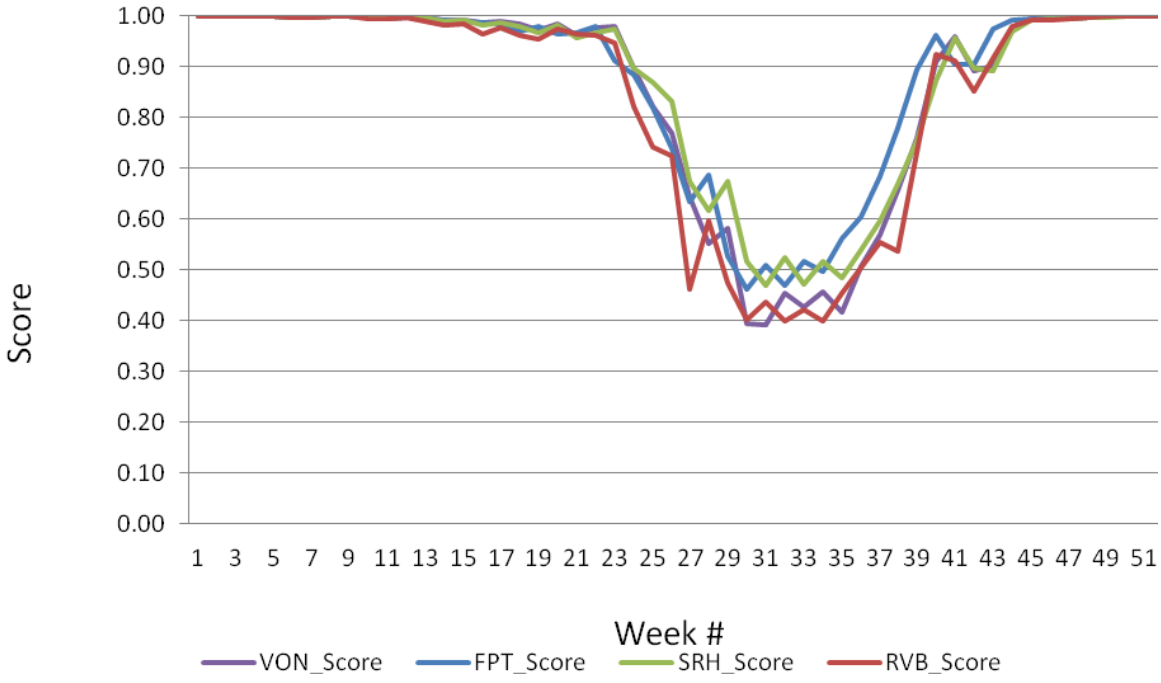

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Figure 5 Water temperatures and corresponding scores in the Lower Sacramento River. (A) Average weekly maximum daily temperaures (ºC, AWMDT), calculated from daily maximum temperatures. (B) Scores corresponding to the AWMDT fro each week. Sampling station codes: "VON" = Verona, "FPT" = Freeport, "SRH" = Sacramento River at Hood, "RVB" = Rio Vista Bridge.

WHAT CAN BE DONE TO IMPROVE WATER TEMPERATURE CONDITIONS?

High water temperatures in the Lower Sacramento River during the summer are linked to high air temperatures, low riparian cover and low flows. Water temperatures would naturally increase in the summer due to increased air temperature in source areas and in the vicinity of the River. However, current high temperatures are probably primarily due to low riparian cover, which would provide shade, low flows, and warming in source areas. Planting riparian cover along the river and tributaries would result in some shading and cooling of the River. A greater degree of cooling would occur from changing water release schedules from American River, Feather River, and Upper Sacramento River dams and making sure there is not a net flow of surface water toward depleted groundwater adjacent to the River. Higher flows through the Delta and into the Bay would help cool the River, providing needed habitat conditions for threatened salmonids and Delta smelt.

DISSOLVED OXYGEN

The assumption here is that saturated dissolved oxygen concentrations (100%) should be present near the surface for a high score (100). When saturation is below 60%, young fish and fish not adapted to low availability of dissolved oxygen may suffer harm, or leave the low oxygen area. Young salmonids will grow and survive at higher rates in cooler water with saturated oxygen (Moyle, 2002).

Findings for dissolved oxygen: Conditions are moderately good for dissolved oxygen. They vary seasonally, being generally good in the Spring and moderate to poor in the late Summer/early Fall.

Table 5. Dissolved oxygen condition in each stretch of the River. Data are from the Department of Water Resources for 2011.

	Sacramento – Hood	Rio Vista	Combined
Mean	73	78	75
N	8,743	8,743	17,486
Standard Deviation (Score)	13.4	9.2	11.7

Dissolved oxygen concentration is reported as milligrams of oxygen per liter of water. The equivalent "% saturation" of oxygen is dependent on temperature, with cooler temperatures having higher saturation concentrations. Both the concentration and % saturation of dissolved oxygen are useful indicators of oxygen conditions for many organisms. Oxygen saturation only approaches 100% in the spring, when runoff from snow-melt and spring storms causes turbulent flows and more oxygen to enter water from the atmosphere (Figure 6). Conditions in the Sacramento to Hood segment of the river were similar to the Rio Vista segment, except for late summer and fall, where the Sacramento to Hood segment deteriorated slightly (Figure 6).

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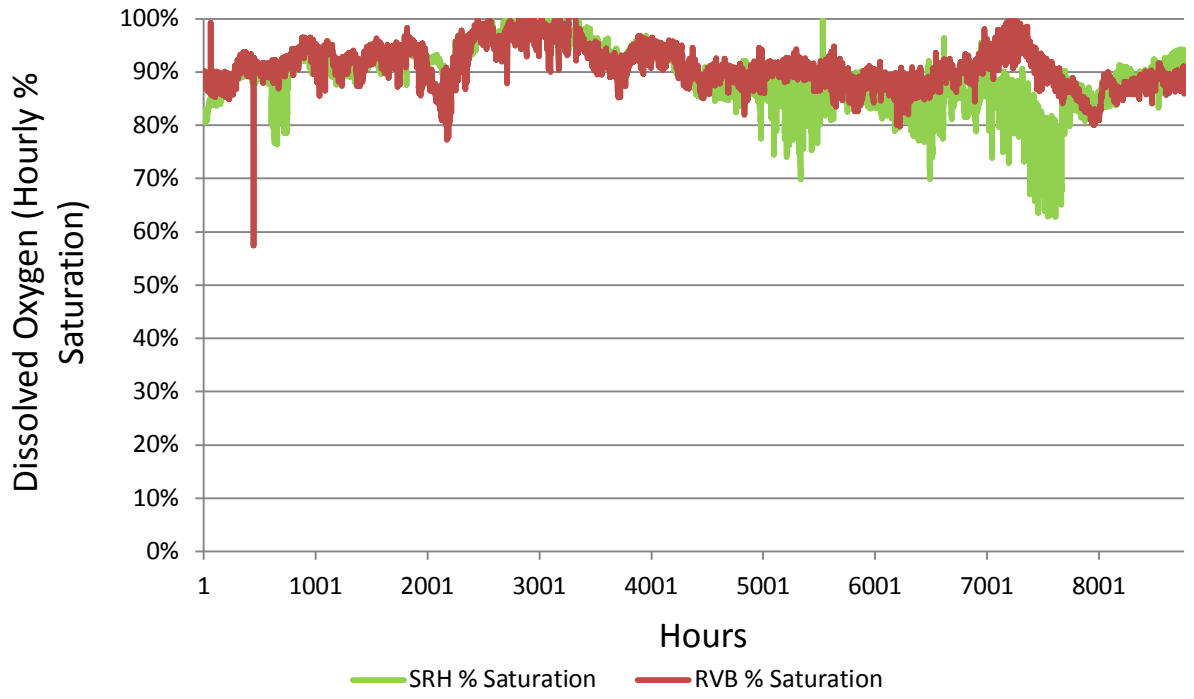

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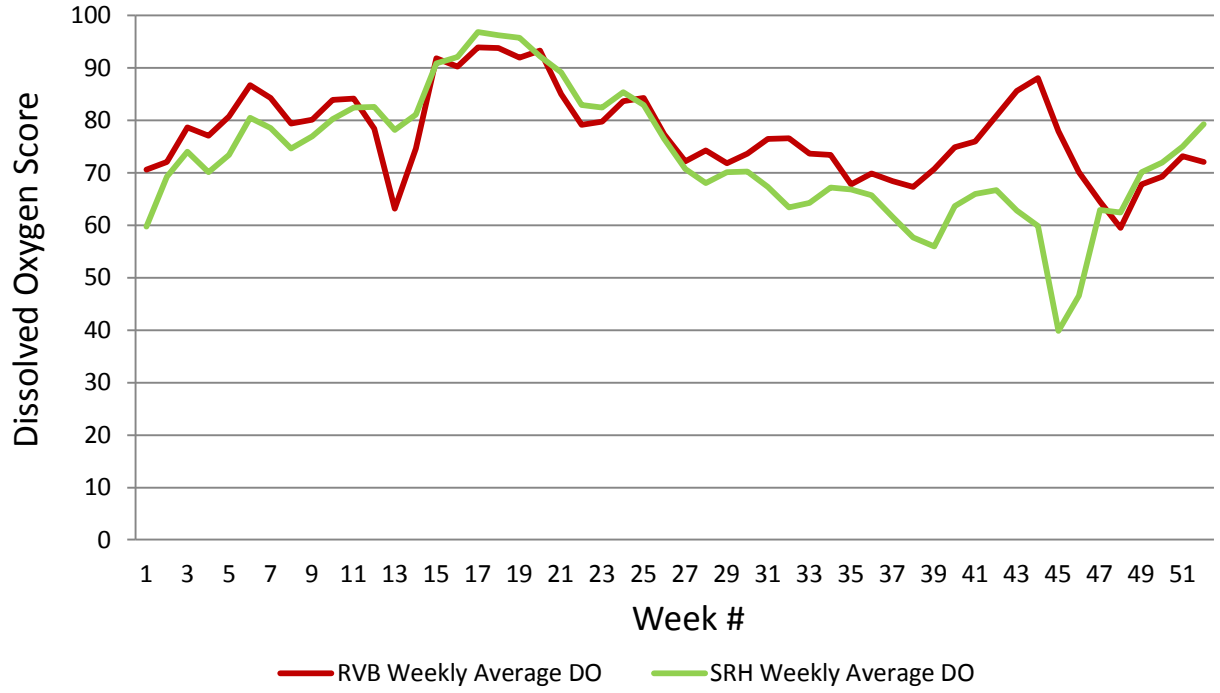

Figure 6 Dissolved oxygen and corresponding scores in the Lower Sacramento River. (A) Hourly measured % saturation of oxygen. (B) Average weekly score calculated from hourly measurements.

WHAT CAN BE DONE ABOUT DISSOLVED OXYGEN AVAILABILITY?

Low dissolved oxygen concentrations and % saturation are often related to higher water temperatures, low primary productivity (photosynthetic production of oxygen), and high chemical and biological (from bacterial growth) oxygen demand. Increased flows would increase turbulence and thus oxygen exchange at the water surface, increasing oxygen saturation. Increased flows would have the added advantage of reducing water temperature, increasing the chance of higher oxygen concentrations and limiting bacterial and other biological oxygen demand.

TURBIDITY

It may be counter-intuitive, but for a large and productive river like the Sacramento River, clearer water is not necessarily preferable. Large rivers move sediment and other materials and most native resident and anadromous species have adapted to these conditions. The assumption here is that a certain level of turbidity is beneficial in this large slow-moving river, especially for Delta smelt as they migrate up-river. A high score (100) is achieved when turbidity is > 23 NTU, equivalent to turbidities where there is a higher chance of finding Delta smelt during trawls. A low score (0) is achieved when turbidity is < 10 NTU, equivalent to turbidities where there is little chance of finding Delta smelt during trawls.

Findings for Turbidity: Turbidity is highly variable during the year (Figure 7). Delta smelt may be migrating and spawning during any time of year, so average scores were calculated across the whole year. The combined score was poor. Turbidity measured in NTU and as concentration of suspended sediment has decreased significantly at Freeport and Rio Vista, and increased significantly at Hood.

Table 7. Average weekly water column turbidity for each stretch of the Lower Sacramento River. (Number of individual measurements: VON: 34,728; FPT+SRH: 70,051; RVB: 8761)

	Verona	Sacramento – Hood	Rio Vista	Combined
Mean	45	35	23	35
N	52	104	52	208
Standard Deviation (Score)	41.1	41.4	32.2	36.7

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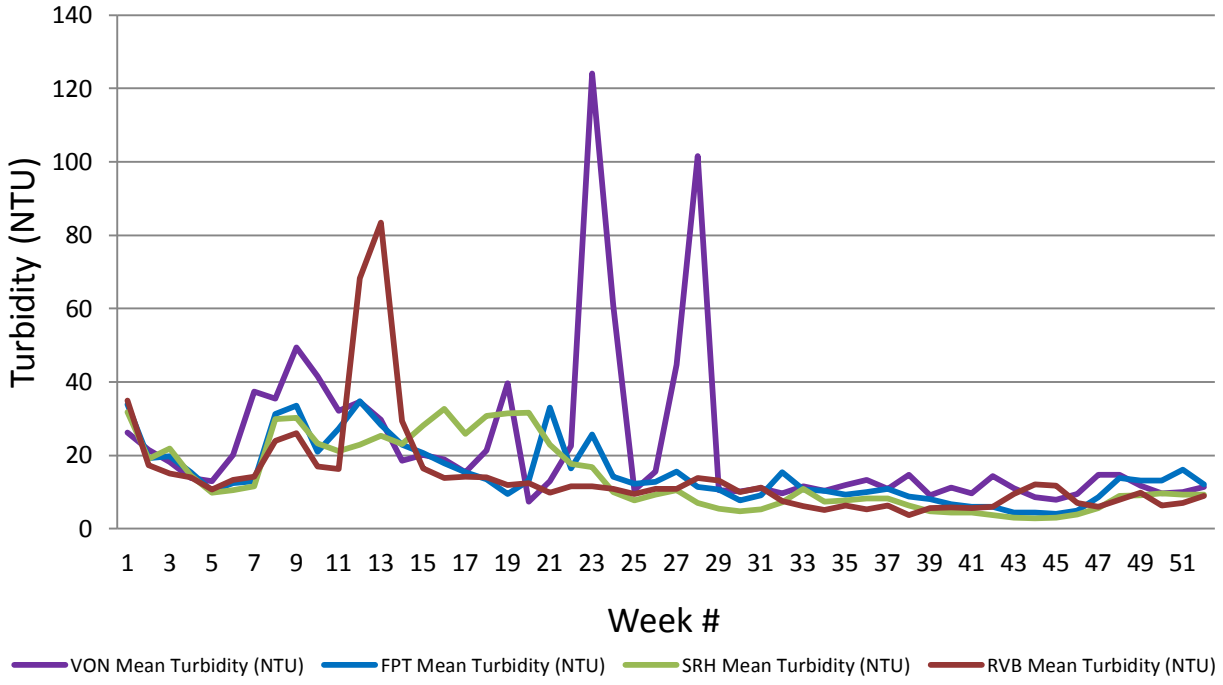

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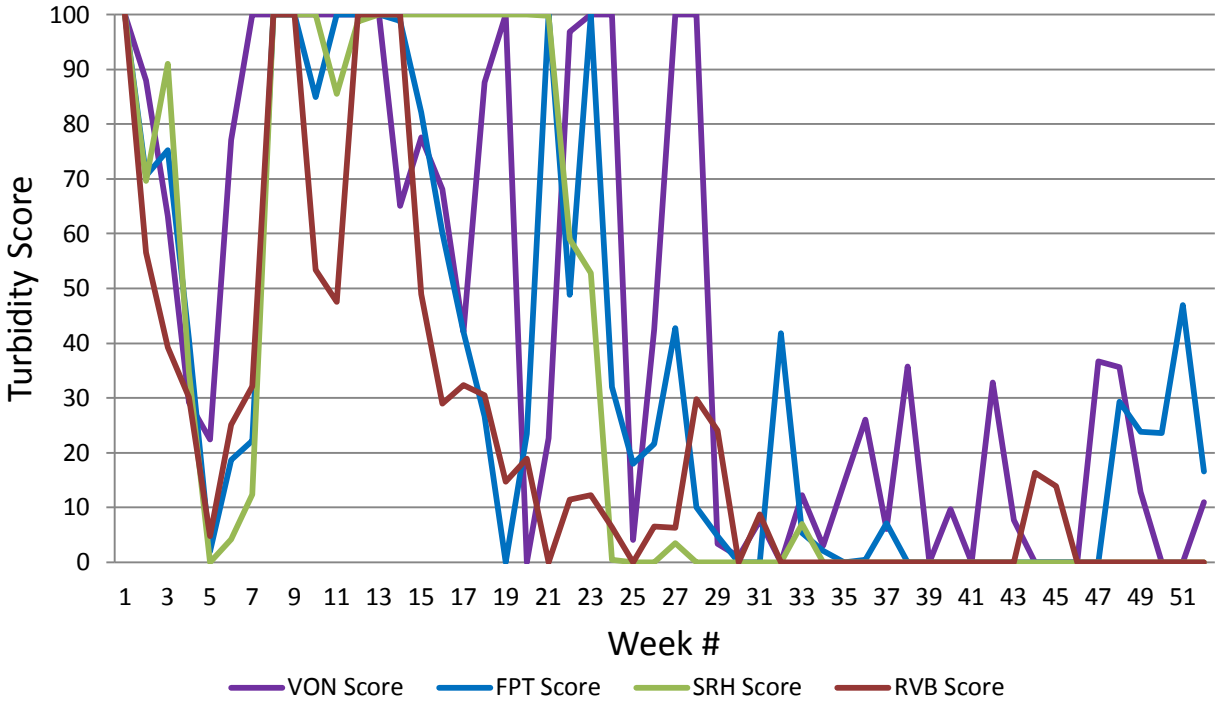


Figure 7 Turbidity (NTU) and corresponding scores for the Lower Sacramento River during 2011. (A) Weekly average turbidity (nephelometric units) and (B) equivalent weekly score.

WHAT CAN BE DONE ABOUT TURBIDITY CONDITIONS?

Dam construction on many tributary rivers to the Sacramento River has limited fine and coarse sediment delivery to the River. Various factors have also limited growth of algae in the water column, further reducing turbidity. Finally, invasive clams (Corbicula fluminea) and submerged vegetation rapidly clear the water of particles, reducing turbidity. Increasing the rate of sediment delivery from upper watershed reservoirs and increased natural algal growth in the River will increase turbidity. Allowing the banks and floodplains of the River to naturally interact with the channel would also lead to natural rates, timing, and levels of turbidity to be restored.

NUTRIENTS: AMMONIA

Ammonia is a naturally-occurring nitrogen-containing compound that is found in partially-treated municipal wastewater and runoff from agricultural lands. Ammonia and its ionized form ammonium can be used as a source of nitrogen by benthic and floating algae (i.e., phytoplankton) at low concentrations but can alter natural systems and can even be toxic at higher concentrations. The EPA has developed draft criteria for ammonia toxicity, based on the most sensitive biota in streams that might be affected – freshwater mussels, rainbow trout young, and frogs (USEPA, 2009). Ammonia is considered toxic to freshwater mussels at concentrations >0.26 mg-N/L (at pH 8 and 25°C), though the effect does not start occurring suddenly at that concentration. The most sensitive fish (rainbow trout) are affected at 2-3 mg-N/L.

Findings for Ammonia: There are many occasions over the last 30 years when dissolved ammonia concentrations have been high enough to be toxic to the most sensitive aquatic biota. These have been during low flow conditions, during the summer (Figures 8&9). Although there may be other effects of ammonia and ammonium (discussed in the phytoplankton and dissolved oxygen sections), from a toxicity point of view, recent conditions have been good.

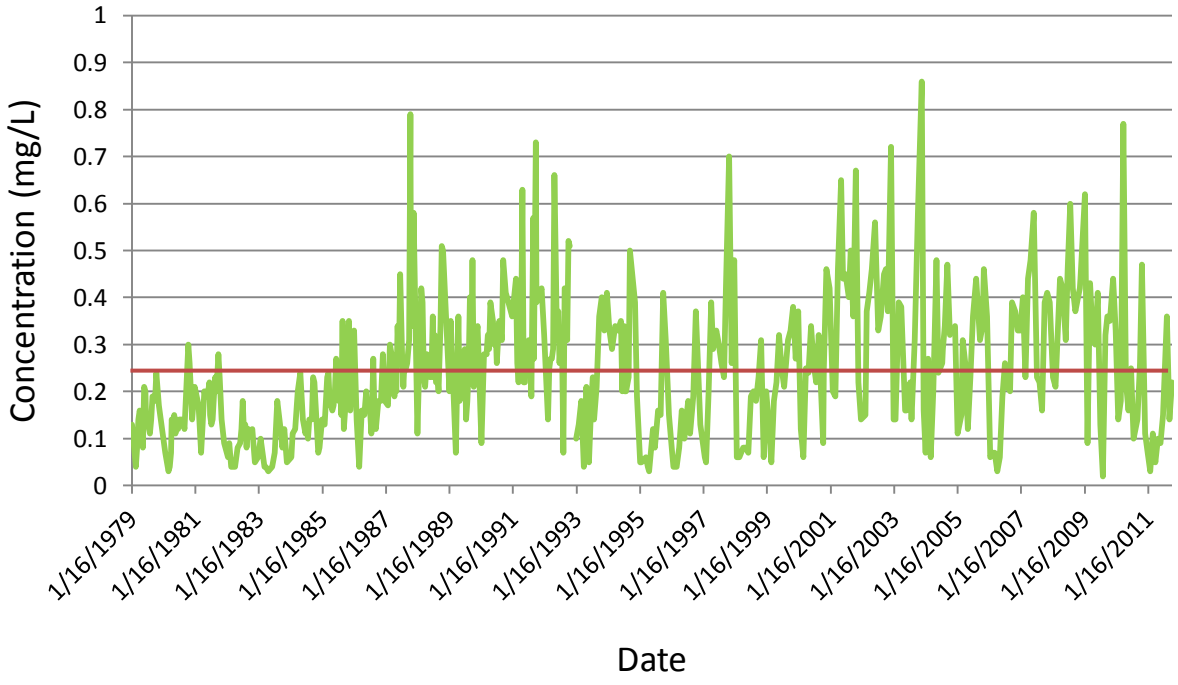


Figure 8 Monthly dissolved ammonia concentrations (mg/L) for the Lower Sacramento River (measured at Hood). The red line is the USEPA (2009) draft ammonia toxicity criterion for the most sensitive aquatic biota (0.26 mg/L).

Measured ammonia concentrations are related to flows (Figure 9) – the higher the flow, the lower the concentrations. This suggests that runoff (Winter rains or Spring snow-melt) are diluting ammonia present in urban and possibly agricultural discharge.

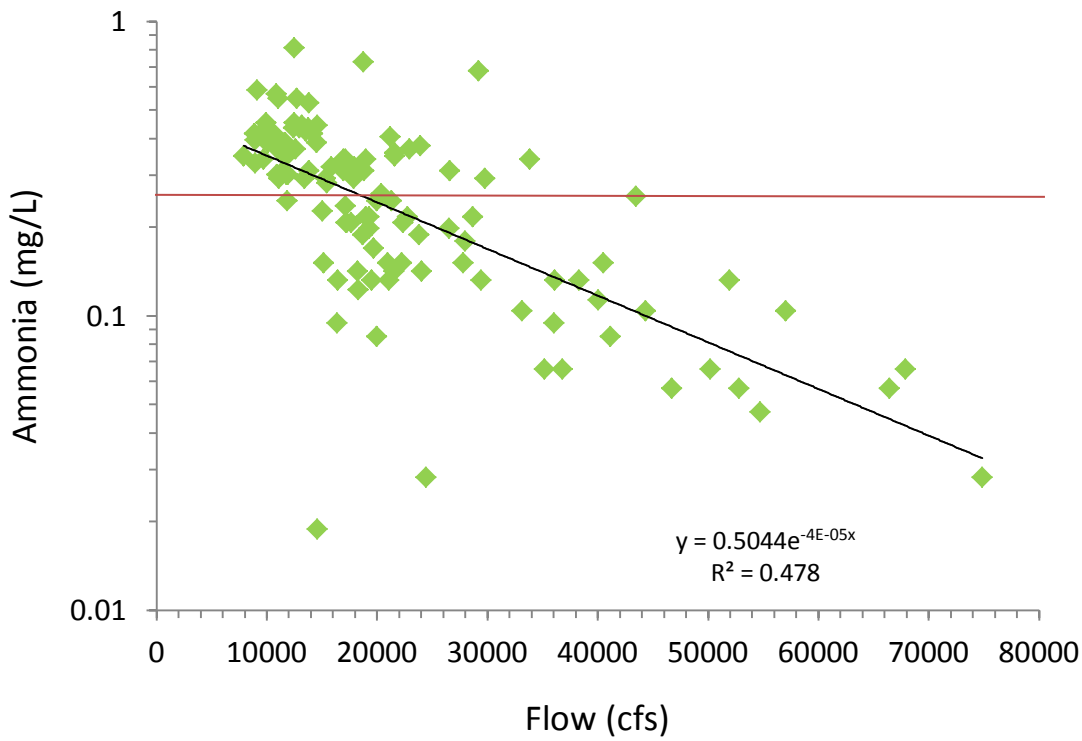


Figure 9 Relationship of ammonia concentrations to flows (2002 – 2011) at Hood. The red line corresponds to the USEPA (2009) draft ammonia toxicity criterion (0.26 mg/L).

Ammonia/ammonium is naturally oxidized by nitrifying bacteria in the water column to nitrites and nitrates through a process called "nitrification", a process which uses dissolved oxygen. This process reduces ammonia and dissolved oxygen concentrations and produces nitrites and nitrates. Increases in nitrate/nitrite concentrations in the Sacramento River have been shown to be correlated with decreases in ammonium concentrations (Hager and Schemel, 1992; Parker et al., 2012).

Nitrification

$$NH_4 + O_2 \rightarrow NO_2 \quad NO_2 + O_2 \rightarrow NO_3$$

WHAT CAN BE DONE ABOUT AMMONIA CONDITIONS?

The Sacramento Regional County Sanitation District (District) is committed to removing approximately half of its ammonia load due to possible future dissolved oxygen issues downstream of its discharge. The Regional Water Quality Control Board and others have recognized the possible contribution of discharged ammonia from wastewater treatment plants and agriculture to reduced productivity in the Delta due to potential effects on nitrate uptake by phytoplankton (single-celled algae). Further research is warranted to resolve this potential effect and to decide if greater regulation of ammonia is needed.

NUTRIENTS: NITRATE

Nitrates and nitrites are nitrogen-containing compounds (similar to ammonia) that occur naturally and in the Sacramento River are produced by nitrification of ammonia in wastewater (Parker et al., 2012), or as the product of agricultural fertilizer. Nitrate is used by phytoplankton (single-celled algae) in the water column for growth and can be a limiting factor for their growth, or a cause of excess growth.

Finding for Nitrate: Nitrate and nitrite concentrations have been measured since 1975 at Hood and between 1975 and 1995 at Rio Vista (Figure 10) and cycle annually. Monthly average concentrations at Hood have increased significantly ($P<0.001$) since 1975 (Figure 11). This increase may be because of increased nitrogen release (in the form of ammonia) from wastewater treatment plants and from fertilizer application in agriculture. Compared to the drinking water standard for nitrate (10 mg/L), conditions in the River are very good. There may be other impacts from nitrate to the food web in the River.

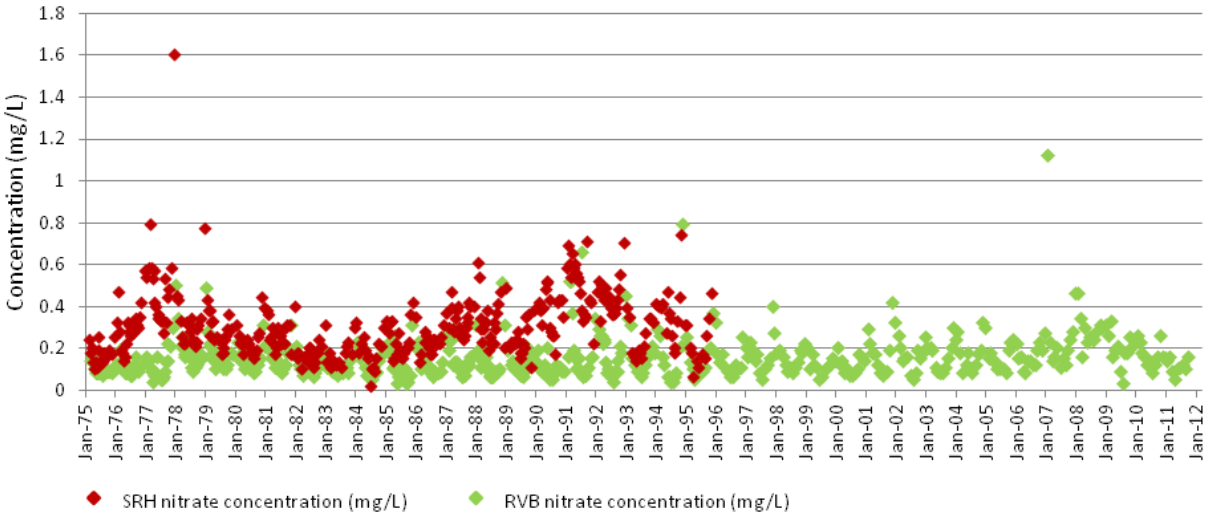


Figure 10 Nitrate+nitrite concentrations (mg N/L; measured 1-4 times per month) at Hood and Rio Vista. Data are from the IEP.

Although ammonia concentrations declined with increased flow rate, nitrate+nitrite concentrations seem to have no relationship with flow (Figure 12).

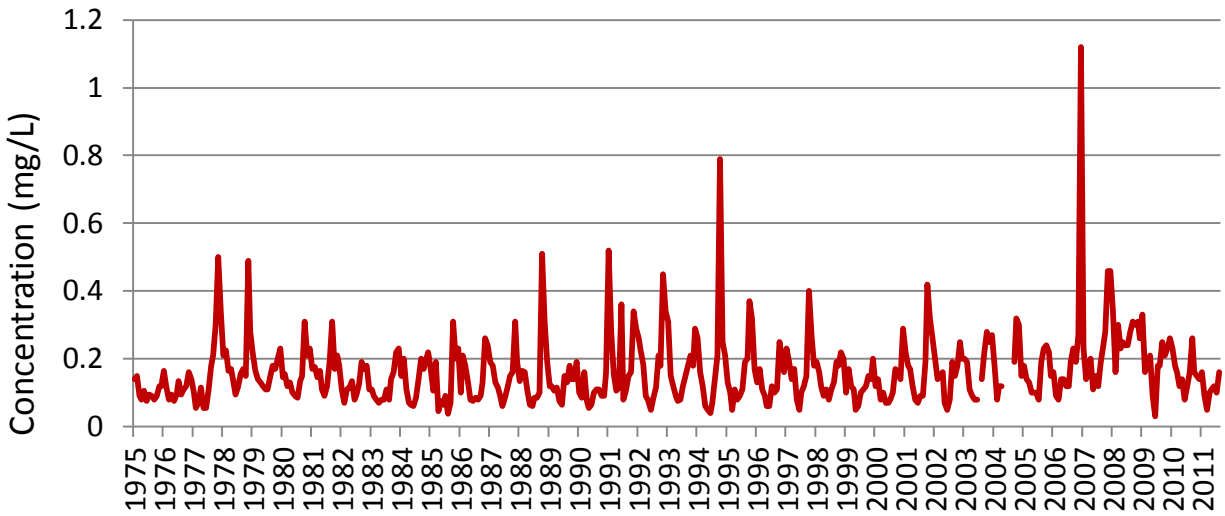


Figure 11 Average monthly nitrate+nitrite concentrations (mg N/L) at Hood. Data from IEP.

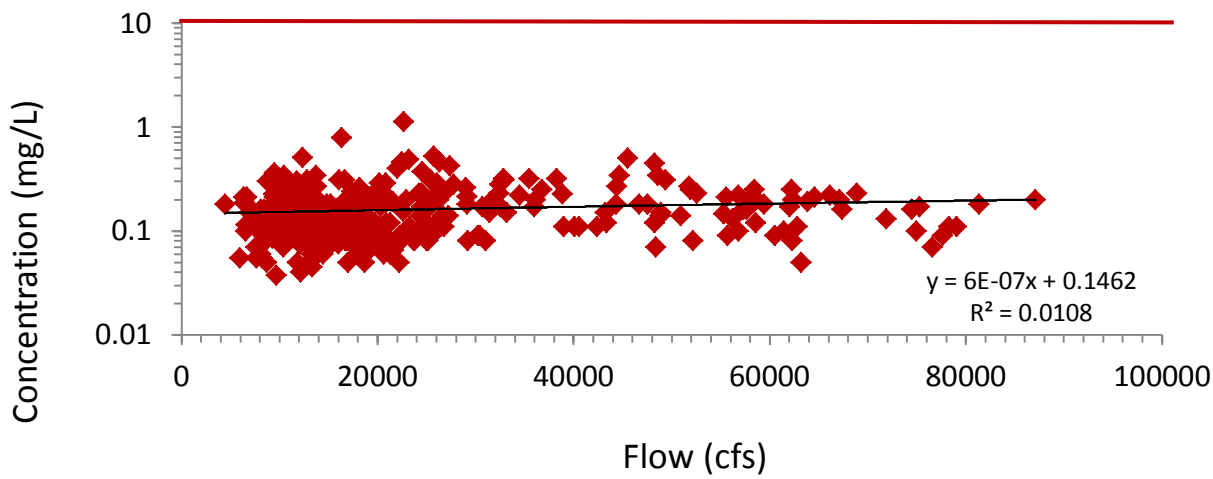


Figure 12 Average monthly nitrate+nitrite concentrations and average monthly flow rate. The red line corresponds to the drinking water standard set by the USEPA.

WHAT CAN BE DONE ABOUT NITRATE CONDITIONS?

Nitrates may increase locally due to oxidation of ammonia. In general, it is preferable for nitrate to be the main source of nitrogen for phytoplankton in the River, without exceeding drinking water or potential eutrophication standards. The Sacramento Regional County Sanitation District (District can play a stewardship role by removing nitrogen in their wastewater, or by oxidizing ammonia (nitrification) before it enters the River.

NUTRIENTS: PHOSPHATES

Ortho-phosphate is the reactive form of phosphorous and results from both natural and artificial processes in aquatic systems. In the Lower Sacramento River, concentrations of ortho-phosphate increase by 2- to 3-fold below the Sacramento Regional Wastewater Treatment Plant at Freeport. Algae in the water column (phytoplankton) require phosphate as a nutrient for growth. Above concentrations of 0.1 mg/L, streams or rivers may become eutrophic (EPA, Mueller and Helsel, 1999). Water-bodies can also become phosphate-limiting for phytoplankton when phosphate concentrations get too low.

Findings for Phosphorous: In the Lower Sacramento River, concentrations have significantly declined ($P<0.001$) since 1975 (Figure 13) and are now well below the threhold for eutrophication (0.1 mg/L) and for limiting impacts to drinking water treatment (1 mg/L). There was no apparent relationship between ortho-phosphate concentrations and flows.

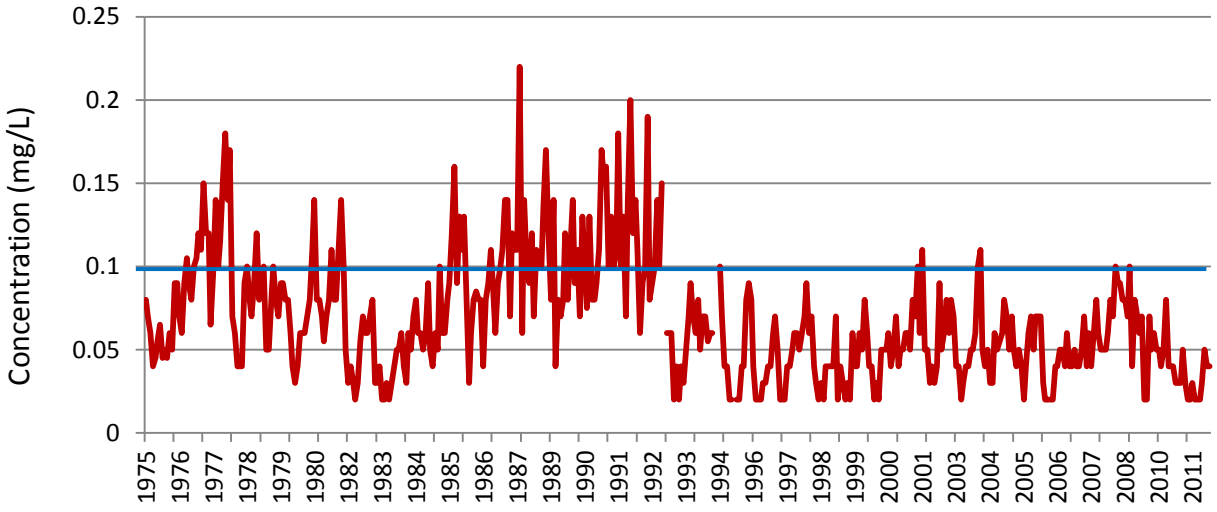


Figure 13 Average monthly ortho-phosphate concentrations at Hood between 1975 and 2011. The blue line corresponds to the EPA recommendation for limiting eutrophication of natural waters.

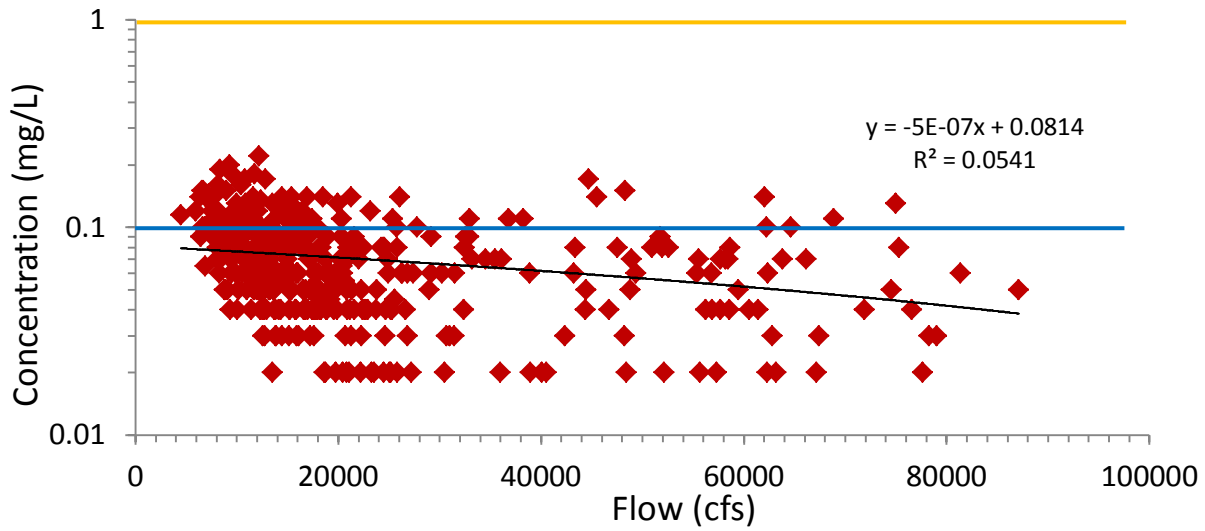


Figure 14 Ortho-phosphate concentrations compared to flow. The blue line corresponds to the EPA recommendation for limiting eutrophication of natural waters. The orange line corresponds to the EPA recommendation for limiting impacts to drinking water purification.

WHAT CAN BE DONE ABOUT PHOSPHATES?

Phosphates may increase due to waste discharge from industrial and urban areas. In general, it is preferable for phosphate to be available for phytoplankton, without violating drinking water or eutrophication standards. Maintaining allocthonous (external to the River) sources of natural organic material can maintain decomposition as a source of phosphate for phytoplankton.

PHYTOPLANKTON (CHLOROPHYLL A)

Single-celled algae (phytoplankton) suspended in the River and associated sloughs, flooded islands, wetlands, and other water-bodies are a critical food source for microscopic, swimming larval and adult crustaceans, bivalves, and various worms (zooplankton). Together, phytoplankton and zooplankton are a very important part of the food web, providing food for fish and other organisms at higher trophic levels. Measuring the chlorophyll a in the water column is one way of measuring the total amount of phytoplankton present. By itself, it doesn't tell us anything about the composition of the phytoplankton community (which species are present), but lower-than-expected or declining concentrations of chlorophyll a can indicate that the food web is deteriorating.

Findings for Chlorophyll a: Chlorophyll a concentrations have been declining in certain segments of the River over the last 36 years. This may indicate that chemicals in the water are poisoning the algae, that some nutrient is less available, that invasive clams (Corbicula fluminea) are suppressing phytoplankton concentrations, or a combination of these effects.

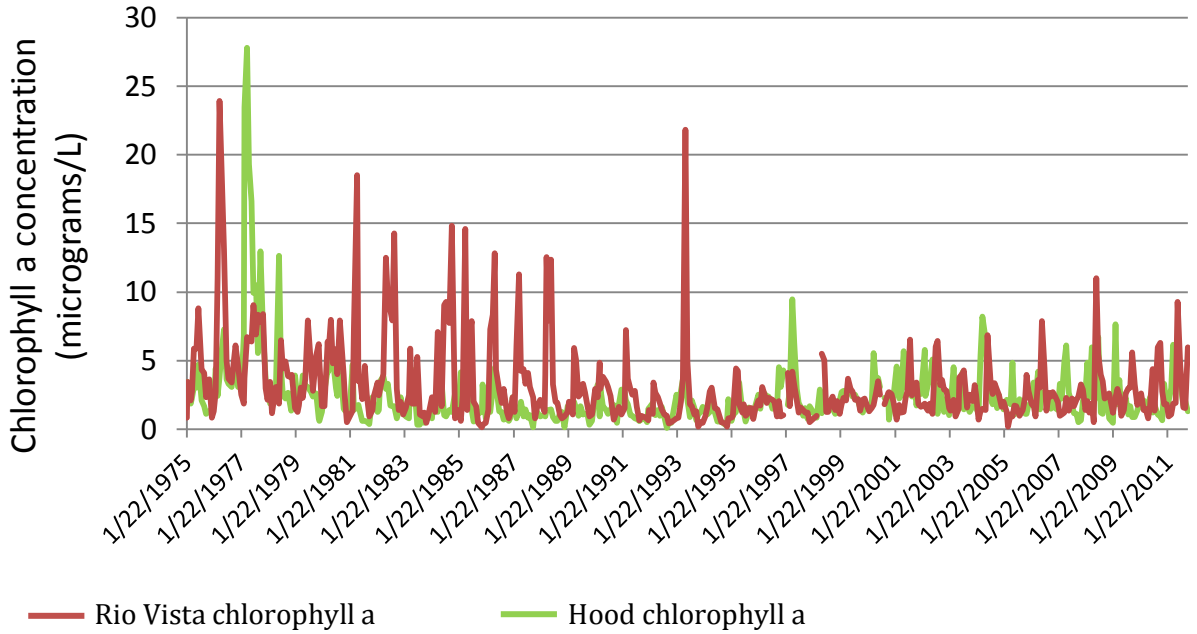


Figure 15 Chlorophyll a concentrations at Hood and Rio Vista since 1975.

Foe (2010) claims that the primary effect of ammonia and ammonium dissolved in the River may not be toxicity to sensitive animals, but rather the effect of the ionized form (ammonium) on nitrate uptake by phytoplankton species such as diatoms (Dugdale et al., 2007). Although ammonium can be used as a source of nitrogen by phytoplankton, Dugdale et al. (2007) and Parker et al. (2012) have proposed that ammonium could be competitively suppressing nitrate and ammonium uptake at concentrations found in the River, resulting in reduced primary productivity and potential changes in the phytoplankton community (i.e., replacement of diatoms by dinoflagellates and cyanobacteria).

WHAT CAN BE DONE ABOUT CHLOROPHYLL A/PHYTOPLANKTON?

It is possible that high ammonia concentrations may limit nitrate uptake by certain native algae (diatoms) growing in the water column of the River. When this occurs, there may be reduced growth of diatoms, which are the preferred and sometimes necessary food source for many zooplankton species, which are the basis for the Delta's food web. There may be an increased chance of "harmful algal blooms" occurring (e.g., the cyanobacterium genus Microcystis). Because of the importance of diatoms and the risk of harmful algal blooms, this process deserves additional investigation. If ammonium is having the effects proposed, then the scoring for dissolved ammonia would change, i.e., the effect thresholds would drop to lower concentrations that are often observed in the River.

METHYLMERCURY

The assumption here is that a high score (100) is achieved when all people can eat fish freely from the Lower Sacramento River, including the most sensitive populations – children and pregnant women. This is equivalent to a fish tissue concentration of ≤0.05 ppm. A low score (0) is achieved when people cannot eat fish freely from the River, equivalent to fish tissue concentrations of ≥ 1 ppm.

Findings for Methylmercury: Based on the combined average concentration of methylmercury in tissue, edible fish are not particularly safe (0.45 ppm) and the corresponding score is moderately poor.

Table 8. Fish tissue concentrations of methylmercury for edible fish (>6 inches and >6 oz) in each stretch of the Lower Sacramento River. These data are from a database compiled by the Regional Water Quality Control Board (Michelle Wood). It contains data until 2006.

	Verona		Sacramento – Hood		Rio Vista		Combined	
	Concentration (ppm)	Score	Concentration (ppm)	Score	Concentration (ppm)	Score	Concentration (ppm)	Score
Mean	0.35	72	0.52	51	0.30	74	0.45	58
N	27		215		96		338	
Standard Deviation (Concentration)	0.158		0.420		0.237		0.371	
Species*	BG, Carp, CF, LMB, Shad, SpB, SPM, SS, Stur		Carp, CF, CS, LMB, RSF, RT, SB, SMB, SpB, SPM, SS, St		SB, Stur, CF, Carp, CP, Hitch, LMB, RSF, SPM, SS, SMB			

* -- BG (Bluegill), Carp (Carp), CF (Catfish), CP (Crappie), CS (Chinook Salmon), Hitch (Hitch), LMB (Largemouth Bass), RSF (Redear Sunfish), RT (Rainbow or Steelhead Trout), SB (Striped Bass), Shad (American Shad), SMB (Smallmouth Bass), SpB (Spotted Bass), SPM (Sacramento Pike Minnow), SS (Sacramento Sucker), Stur (Sturgeon)

WHAT CAN BE DONE ABOUT METHYLMERCURY?

Methylmercury in fish tissue limits the amounts of fish that people can safely eat from the River. Contaminated sediments (a legacy of mercury and gold mining that used mercury), mineral springs, wastewater discharge, and atmospheric deposition (from coal burning, oil refining, volcanic ash, fuel, and dust) contribute inorganic and organic mercury. Some fraction of the inorganic mercury is converted by bacteria into methylmercury in productive ecosystems, which then bioaccumulates through the food web into edible fish. Limiting mercury inputs by cleaning up abandoned mines, retrieving and removing the mercury from sediment behind upstream dams, and reducing the inputs into the River of material and chemicals that can contribute to methylation of the mercury (permitting its entry into the food web) are all actions that can reduce methylmercury/mercury concentrations in edible fish. The Sacramento River Watershed Program's Strategic Plan (2002; http://www.lwa.com/news/pdfs/Mercury_Strategic_Plan_1202.pdf) describes many of these linkages and potential solutions.

FECAL PATHOGENIC BACTERIA

Fecal bacteria in recreational and drinking water can cause enteric and other diseases. These bacteria originate from stormwater runoff from agricultural and urban areas, wastewater discharge, and natural sources. The US Environmental Protection Agency and California Department of Public Health have bacteria-concentration standards for freshwater bodies like the Sacramento River. These standards are based on "fecal indicator bacteria" (FIB), which are bacteria that are easily measured and can indicate that fecal matter is present in the water-body. These indicator bacteria may have their own pathogenic effect. The most stringent state and federal concentration standard is for frequent contact recreation (swimming) and is 235 viable Escherichea coli (E. coli) cells per 100 ml. For freshwater bodies with infrequent recreation, the standard is 576 E. coli per 100 ml.

Findings for Fecal Bacteria: Based on 2010 measurements by the Sacramento-based Coordinated Monitoring Program, FIB conditions are mostly excellent, below the lower concentration threshold. There are occasional days where concentrations are well above both the lower and higher standards. There can be considerable variation in concentration across the year.

Table 9. Fecal indicator bacteria (E. coli) concentrations in each stretch of the Lower Sacramento River. These data are from the Coordinated Monitoring Program and contains data from 2010. "MPN/100 ml" means the most probable number (of bacterial cells) per 100 ml of sampled water, based on the ability of bacterial cells to grow in favorable media.

	Veterans bridge		Freeport/River mile 44		Combined	
	Concentration (MPN/100 ml)	Score	Concentration (MPN/100 ml)	Score	Concentration (MPN/100 ml)	Score
Mean	164	89	136	88	146	88
N	9		17		26	
Standard Deviation Score (Concentration)	33.3 (426.3)		33.1 (212.4)		32.5 (295.3)	

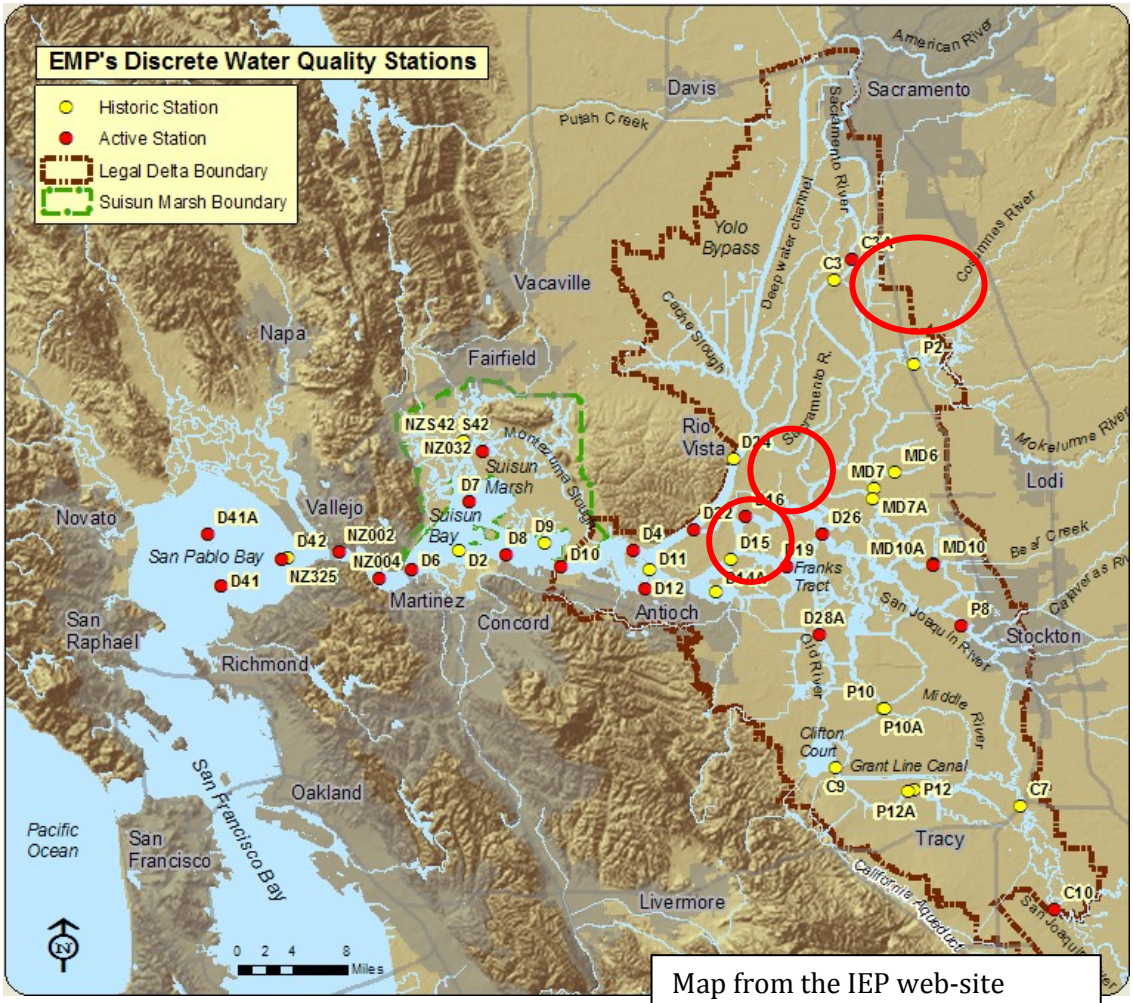
WHAT CAN BE DONE ABOUT FECAL BACTERIA?

High concentrations of E. coli occurred in January, February, and October. This may be due to storm-water runoff from rural developed areas and agricultural areas (Jan & Feb) and less dilution of wastewater by the River during low flow conditions (Oct). Continuous monitoring of discharged wastewater can ensure compliance, however, non-point sources of fecal matter are more difficult to monitor and regulate. Investigative monitoring, or searching for the source, when high concentrations occur, could help identify persistent or occasional inputs of fecal material to the River.

DATA SOURCES

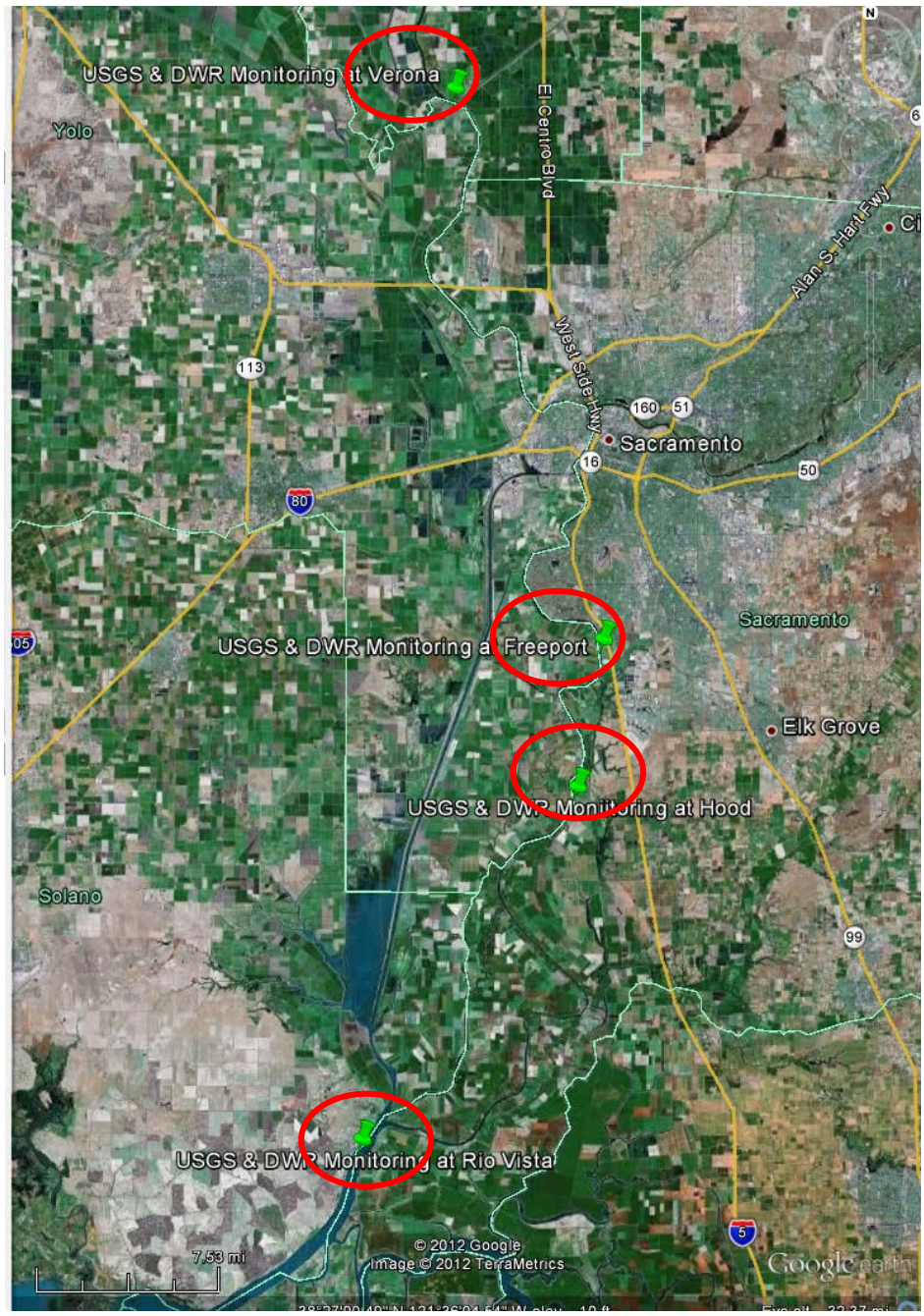
Water temperature, turbidity, chlorophyll a, ammonia, and dissolved oxygen data for 2011 condition was obtained from the Department of Water Resources, California Data Exchange Center (http://cdec.water.ca.gov) and for trends analysis, from the Interagency Ecological Program, Bay-Delta Monitoring and Analysis Section (IEP, http://www.water.ca.gov/bdma/meta/index.cfm). Fish-tissue methylmercury concentrations were obtained from the Central Valley Water Quality Control Board (contact: Michelle Wood). Flow and suspended sediment data were obtained from the USGS, National Water Information System (http://waterdata.usgs.gov/nwis). Fecal bacteria (E. coli) data were from the Coordinated Monitoring Program.

The IEP sites used are shown below (C3/A = Hood, D24 = Rio Vista, D22 = Decker Island). Site C3 is an historic monitoring site, which was functionally replaced by site C3A.



Map from the IEP web-site

The DWR-CDEC sites (Verona, Freeport, Hood, and Rio Vista) are shown in the map below, circled in red.



CITATIONS

Baker P.F.; Speed T.P.; Ligon F.K. 1995. Estimating the influence of temperature on the survival of chinook salmon smolts (Oncorhynchus tshawytscha) migrating through the Sacramento - San Joaquin River Delta of California. Canadian Journal of Fisheries and Aquatic Sciences, 52(4):855 -863

Brett JR, Clarke WC, Shelbourn JE. 1982. "Experiments on thermal requirements for growth and food conversion efficiency of juvenile chinook salmon, *Oncorhynchus tshawytscha*." Can Tech Rep Fish Aquat Sci 1127. 29 p.

Dugdale, R.C., Wilkerson, F.P., Hogue, V.E. and Marchi, A. 2007. The role of ammonium and nitrate in spring bloom development in San Francisco Bay. Estuarine, Coastal and Shelf Science. 73: 17-29.

Geist, D.R., Abernethy, C.S., and Hand, K.D. 2006. Survival, development, and growth of fall Chinook salmon embryos, alevins, and fry exposed to variable thermal and dissolved oxygen regimes. Transactions of the American Fisheries Society 135:1462-1477.

Hager, S.W., Schemel, L.E., 1992. Sources of nitrogen and phosphorus to Northern San-Francisco Bay. Estuaries 15, 40–52.

Marine, K R; Cech, J J. 2004. Effects of high water temperature on growth, smoltification, and predator avoidance in juvenile Sacramento River chinook salmon. North American Journal of Fisheries Management, 24(1): 198-210

Moyle, P. B. 2002. Inland Fishes of California. Berkeley, CA: University of California Press.

Mueller, David K. and Helsel, Dennis R. 1999. Nutrients in the nation's waters--too much of a good thing?" U.S. Geological Survey Circular 1136. National Water-Quality Assessment Program. http://water.usgs.gov/nawqa/circ-1136.html

Myers, J. M., R. G. Kope, G. J. Bryant, D. Teel, L. J. Lierheimer, T. C. Wainwright, W. S. Grant, F. W. Waknitz, K. Neely, S. T. Lindley, and R. S. Waples. 1998. Status Review of Chinook Salmon From Washington, Idaho, Oregon, and California. Report No. NMFS-NWFSC-35. NOAA Tech. Memo. U.S. Department of Commerce.

National Marine Fisheries Service (NMFS). 2009. Public draft recovery plan for the evolutionarily significant units of Sacramento River winter-run Chinook salmon and Central Valley spring-run Chinook salmon and distinct population segment of Central Valley Steelhead. Sacramento Protected Resources Division. October, 2009. 254 pp.

Parker, A.E., R.C. Dugdale, and F.P. Wilkerson. 2012. Elevated ammonium concentrations from wastewater discharge depress primary productivity in the Sacramento River and the Northern San Francisco Estuary. Mar. Pollut. Bull. (in press), doi:10.1016/j.marpolbul.2011.12.016

Silver, S. J., C. E. Warren, and P. Doudoroff. 1963. Dissolved oxygen requirements of developing steelhead trout and Chinook salmon embryos at different water velocities. Transactions of the American Fisheries Society 92:327–343.

Snider, B. and R. G. Titus. 2000b. Timing, composition and abundance of juvenile anadromous Salmonid Emigration in the Sacramento River Near Knights Landing October 1998 - September 1999.

U.S. Environmental Protection Agency (USEPA). 2003. "USEPA Region 10 Guidance for Pacific Northwest State and Tribal Water Quality Standards." Region 10, Seattle, WA. USEPA 910- B-03-002. 49pp. Available online at: <http://www.epa.gov/r10earth/temperature.htm>.

Yoshiyama, R.M., Gerstung, E.R., Fisher, F.W., and P.B. Moyle. 1996. Historical and present distribution of Chinook salmon in the Central Valley drainage of California. pp. 309-362 In: Sierra Nevada Ecosystem Project: final report to Congress, vol. III - Assessments, commissioned reports, and background information. Centers for Water and Wildland Resources, Univ. of California, Davis. Davis CA.