

# Hypoxia mechanisms in the lower San Joaquin River (California): a retrospective analysis

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## Abstract

The Stockton Ship Channel, a stretch of the tidal San Joaquin River, is frequently subject to low dissolved oxygen conditions and annually violates regional water quality objectives. Underlying mechanisms are examined here using the long-term water quality data, and the efficacy of possible solutions using time-series regression models. Hypoxia is most common during June–September immediately downstream of where the river enters the Channel. At the annual scale, ammonia loading from the Stockton Wastewater Facility has the largest identifiable effect on year-to-year variability. The longer-term upward trend in ammonia loads, which have been increasing over 10% per year, also corresponds to a longer-term downward trend in dissolved oxygen during summer. At the monthly scale, river flow, loading of wastewater ammonia and river phytoplankton, Channel temperature, and Channel phytoplankton are all significant in determining hypoxia. Over the recent historical range (1983-2003), wastewater ammonia and river phytoplankton have played a similar role in the monthly variability of the dissolved oxygen deficit, but river discharge has the strongest effect. Model scenarios imply that control of either river phytoplankton or wastewater ammonia load alone would be insufficient to eliminate hypoxia. Either both must be strongly reduced, or one must be combined with increases in net discharge to the Channel. Model scenarios imply that the barrier at the head of Old River has had marked effects on hypoxia over the past two decades. In contrast, with the barrier in place, unimpaired or full natural flow at Vernalis would have led to about the same frequency of hypoxia that has occurred with actual flows since the early 1980s.

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# 1 Introduction

The lower San Joaquin River, one of two major rivers draining into the San Francisco Estuary, is frequently subject to low dissolved oxygen conditions and annually violates regional water quality objectives. The violations usually occur between June and November over a 20-km river reach immediately downstream of the city of Stockton. This reach is part of the Stockton Deep Water Ship Channel, a portion of the river between San Francisco Bay and the city that has been dredged to allow the passage of ocean-going vessels to the city's port. Dissolved oxygen concentrations can be chronically below water quality objectives (5 or 6 mg/L, depending on the month; CVRWQCB 1998), reaching below 2.5 mg/L at times. These low oxygen conditions interfere with several beneficial uses of the river, including spawning and migration of both warm (striped bass, sturgeon, and shad) and cold (salmon and steelhead) freshwater fishes, as well as warm and cold freshwater species habitat (CVRWQCB 2003). For example, oxygen depletion is believed to act as a barrier to migration of fall run Chinook salmon (*Oncorhynchus tshawytscha*) upriver between September and December to spawn in the Merced, Tuolumne, and Stanislaus rivers (Hallock et al. 1970). Moreover, low dissolved oxygen has recently been severe enough to kill both steelhead and salmon, as reported in *The Record* (Stockton), 8 July 2003.

Under Section 303(d) of the 1972 federal Clean Water Act, states are required to develop a list of waters that do not meet water quality standards, even after installation of minimum required levels of pollution control technology, and to develop an action plan to improve water quality. The Central Valley Regional Water Quality Control Board (Regional Board) adopted a revised 303(d) list that identified low dissolved oxygen levels in the lower San Joaquin River as a high priority problem, thereby committing to determining the assimilative capacity of the impaired river reach (Total Maximum Daily Load, or TMDL) and to allocating responsibility for the waste load among possible sources (CVRWQCB 2003). Under the auspices of the Regional Board, a group of interested parties or stakeholders organized the San Joaquin River Dissolved Oxygen TMDL Steering Committee, which initiated a series of field, laboratory, and modeling studies funded by the California Bay-Delta Authority and other sources.

These ongoing studies have resulted in many useful details concerning the mechanisms underlying hypoxia in the river and the role of different organic matter sources and other contributory factors (Lee and Jones-Lee 2002). As a whole, they also confirm early research that identified the main factors affecting hypoxia in the Ship Channel (Bain and et al. 1968). According to these studies, there are two main sources of oxygen-demanding materials: the Stockton Regional Wastewater Control Facility, which discharges into the San Joaquin River just upstream of the Ship Channel, and materials from nonpoint sources further upstream. The actual effect of these materials on Ship Channel dissolved oxygen depends on three main factors: morphometry of the Ship Channel, which affects the impact of natural aeration mechanisms and of oxygen-demanding reactions on dissolved oxygen concentrations; flow rate through the Ship Channel, which affects loading rates of oxygen-demanding materials and dissolved oxygen, as well as the residence time during which potential oxygen demand is actually realized in the Ship Channel; and environmental factors such as temperature. Because of gaps and uncertainties in current understanding, however, the TMDL is phased to allow for further technical studies of the relative roles of different oxygen-demanding substances and their interactions with Ship Channel morphometry and flow.

One relevant resource that has not been utilized extensively in this research effort is the large collection of retrospective data for the upper estuary. Several government agencies have maintained monitoring programs for decades, mostly for determining compliance with water quality objectives. Recently, we used these data to investigate regulation of phytoplankton concentrations in the tidal San Joaquin River upstream of the Ship Channel (Jassby submitted). Our purpose here is to determine what this extensive historical monitoring dataset going back to the 1960s can tell us about the nature of hypoxia in the Ship Channel and the mechanisms underlying it. The scope is limited in that we confine ourselves to the ramifications of the monitoring dataset rather than attempt to include the large amount of current and recent field research on the issue. The historical dataset is a rich resource and it allows us especially to examine hypotheses based on one or a few years in a much longer context. Observations over shorter time scales, in which a causative factor remains relatively constant, can lead to distorted views about the underlying mechanisms.

The interannual variability in runoff to the Delta varies by an order of magnitude, which is sure to change the relative importance of different mechanisms in different years. The nature of the historical data, in the end, dictates the specific issues that can be addressed and the approaches that are feasible. Specifically, the data allowed us to undertake the following analyses: First, the spatial and temporal patterns of hypoxia are summarized from a long-term perspective. We then examine the statistical evidence for the relative importance of different causal factors. Finally, we use a time-series model to examine how the historical patterns might have been different under different management scenarios.

## 1.1 Study Area

The tidal San Joaquin River is located in the upper part of the estuary known as the Delta, a mosaic of waterways linking the great rivers of northern California to the downstream embayments comprising San Francisco Bay; together, the Delta and Bay form the San Francisco Estuary. The San Joaquin River extends from the westernmost Delta upstream past the city of Fresno, draining a watershed area of about 19,000 km<sup>2</sup>. Its river valley is a major center of agricultural production. Despite the loss of most of its wetlands, it also remains a critical habitat for fish and wildlife, including many federally listed threatened and endangered plants and animals. Hydrology of the river and its major tributaries—the Merced, Tuolumne, and Stanislaus rivers—upstream of the Delta is highly managed through dams, diversions, and artificial conveyances. The river reaches the southern boundary of the Delta near the town of Vernalis, where estuarine tides begin to affect its flow (Figure 1). The long-term (1956–2002) mean flow at this point is about 130 m<sup>3</sup> s<sup>-1</sup>, with annual means ranging from 13 m<sup>3</sup> s<sup>-1</sup> in 1961 to 650 m<sup>3</sup> s<sup>-1</sup> in 1983 (IEP 2003). For comparison, the unimpaired or full natural flow for the period 1951–2000 was about 240 m<sup>3</sup>/s, of which about 72 m<sup>3</sup>/s was provided by the mainstem above the major tributaries (CDWR 2004a). The construction of Friant Dam and formation of Millerton Lake in the 1940s, and subsequent diversion of these mainstem waters for irrigation, has led to a dewatering of about 100 km of the river. Past Mossdale, a portion of the water is diverted down Old River to Clifton Court Forebay, where it is exported for

agricultural, industrial, and domestic use, including drinking water for 22 million state residents, through large pumping facilities feeding the State Water Project (California Aqueduct) and federal Central Valley Project (Delta–Mendota Canal). Annually, temporary barriers have been placed at the head of Old River to increase flows down the mainstem, with the intention of alleviating low dissolved oxygen conditions downstream and facilitating fish migration. Water is also diverted for irrigation in the Delta by numerous siphons; much of this water is lost to evapotranspiration, although some returns through many agricultural drainage points. The river is about 2.5–3.5 m deep and 50 m wide between Vernalis station and the Ship Channel. Just upstream of the Ship Channel, the Wastewater Facility discharges its effluent into the river. The river enters the Ship Channel at Channel Point. River width increases to about 75 m in the Ship Channel, and it is dredged to a depth of 11 m between the Port of Stockton and the Bay (Figure 2). The tidal range is about 1 m in this region. Low dissolved oxygen conditions occur in the Ship Channel from approximately the Turning Basin at the Port of Stockton downstream to Turner Cut, sometimes extending to Disappointment Slough.

## **2 Methods**

### **2.1 Data Sources**

A variety of data sources were used in this study, some of them extending back to the 1960s (Table 1). The frequencies shown are approximate, and some datasets have large gaps in them. Relevant stations are indicated on the maps (Figures 1 and 2).

A California Department of Water Resources (CDWR) monitoring program measures surface and bottom dissolved oxygen (DO) at 14 stations in the San Joaquin River, from Prisoners Point to the Stockton Turning Basin, biweekly to monthly during July–December (Table 2). These data are useful for showing the spatial and seasonal extent of hypoxia over the years, although they are not sufficient for detailed analysis of mechanisms.

The discrete water quality monitoring program collects data from throughout the Delta on a

monthly basis, approximately. The program was originally started by the U.S. Bureau of Reclamation in the late 1960s. It is now carried out jointly with the California Department of Water Resources, assisted by the California Department of Fish and Game and the U.S. Geological Survey (USGS), under the auspices of the Interagency Ecological Program (IEP) Environmental Monitoring Program (EMP). Its primary purpose is to provide information for compliance with flow-related water quality standards specified in water rights permits that allow export by the state and federal water projects. The stations relevant to this study are the Vernalis and Mossdale stations on the tidal river upstream of the Ship Channel, and Buckley Cove station (P8) in the Ship Channel itself (Figures 1 and 2). Water quality variables utilized here include mainly chlorophyll  $\alpha$  and temperature. A detailed description of the sampling and analytical methods can be accessed at [http://www.iep.ca.gov/emp/Metadata/metadata\\_index.html](http://www.iep.ca.gov/emp/Metadata/metadata_index.html).

The continuous water quality monitoring program collects data from seven fixed sampling stations throughout the Delta, averaging and recording on an hourly basis. This effort is also part of the EMP. The data are used to track environmental conditions in the Sacramento-San Joaquin Delta and Suisun Bay, for operation of the State Water Project and Central Valley Project, and as input to hydrodynamic and water quality models. Water is collected from about one meter below the surface. The only time series from the program used here are the dissolved oxygen data from the Stockton station (RRI) at Rough and Ready Island near Burns Cutoff (Figure 2).

Daily ammonia loads from the Wastewater Facility were calculated as follows: If the record had entries for effluent discharge and ammonia concentration, they were simply multiplied together. If the record had entries for discharge but not concentration, the daily load was estimated using the flow-weighted mean concentration for the month. If there was no record for discharge, then the load was assumed to be zero for that day. Monthly averages were then estimated by the arithmetic mean of daily loads. The proportion of BOD due to ammonia in Wastewater Facility effluent was estimated by  $4.57N_{amm} / (4.57N_{amm} + 4.57N_{org} + 2.5C_{bod5})$ , where  $N_{amm}$  is ammonia nitrogen,  $N_{org}$  is organic nitrogen, and  $C_{bod5}$  is the 5-day carbonaceous BOD. The conversion of ammonia to nitrate is assumed to require  $4.57 \text{ g O (g N)}^{-1}$  (Chapra 1997). The factor of 2.5 for converting

