Jones & Stokes

Memorandum

Date: May 17, 2005

To: Members of the San Joaquin River DO TMDL Technical Work Group

cc: Barbara Marcotte, Mary Menconi, CBDA

Mark Gowdy, CVRWQCB

From: Craig Stevens, Pete Rawlings, Megan Robinson, Russ Brown, Jones & Stokes

Subject: **Partial Preliminary Draft Conceptual Model for Dissolved Oxygen in the San Joaquin River**

Attached is a partial preliminary draft conceptual model of dissolved oxygen in the San Joaquin River. The conceptual model is intended to provide a summary of the current state of understanding of the physical, chemical, and biochemical processes that influence dissolved oxygen concentrations in the river, including episodes of dissolved oxygen impairment in the Stockton Deep Water Ship Channel.

The model currently exists in this paper form, but it is our intention that the model will ultimately exist in electronic form on the DO TMDL web site. The paper form of the model is organized to assist in the transition to the web-based model. This results in some awkwardness in the organization and repetitiveness of text that will be eliminated with the web-based model.

Some aspects of the model bare special mention:

1. The model is structured using the Driver–Linkage–Outcome format preferred by the CBDA Ecosystem Restoration Program, where outcomes are the conditions being examined (e.g. dissolved oxygen concentrations), drivers are the factors influencing the outcome, and linkages are the mechanisms by which the drivers exert their influence.

2. The model is organized on four levels, as described in Chapter 1 of the model. The first level of organization is geographic; the model is divided into three reaches of the San Joaquin River. The second level defines the primary drivers influencing dissolved oxygen levels. The third level defines the secondary drivers that influence the primary drivers. The fourth level provides detailed discussions of the secondary drivers.

3. The terms primary and secondary drivers should not be construed to imply relative importance. The terms are used in the context of cause and effect relationships, so that primary drivers are factors that **directly** affect dissolved oxygen concentrations, while secondary drivers are factors that **indirectly** affect dissolved oxygen by influencing the primary factors.

4. The model is intended to provide enough detail to allow the reader to understand the factors that influence dissolved oxygen concentrations and the mechanisms by which this influence is exerted. It is not intended to describe all knowledge about every topic.

5. The model acknowledges areas where knowledge is incomplete and where alternative hypotheses exist, as well as areas that are well understood and for which scientific consensus exists.

6. The model will ultimately highlight the factors having the most influence on dissolved oxygen concentrations, and of those, which are not yet well enough understood to help direct future experimentation and data gathering.

7. Although we would have preferred to provide you a complete draft for review, contracting constraints have required that we provide the model to you at this time in an incomplete state. As you are reviewing this, we will also be continuing to fill in gaps and reviewing the text for accuracy and completeness.

8. Citations in the model are currently represented by serial numbers. The bibliography in Chapter 4 has been organized in serial number order to make it easier for you to identify the literature cited.

TWG Review

We are interested in your comments and questions, any suggested text, and any new references. Please provide your input in electronic form either in the text or as an attachment to an e-mail to Pete Rawlings (prawlings@jsanet.com). **We would appreciate receiving your input by end of day May 31, 2005.** Of course, we are also available by phone to answer questions.

Preliminary Draft
Conceptual Model for Dissolved Oxygen in the San Joaquin River

Prepared for:

San Joaquin Dissolved Oxygen
TMDL Technical Work Group

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Introduction

Understanding the Conceptual Model

A conceptual model is a construct intended to show the current state of scientific understanding regarding a topic. In this case the topic is dissolved oxygen in the Stockton Deep Water Ship Channel (DWSC), and this conceptual model is intended to describe the factors that contribute to the levels of dissolved oxygen in the DWSC. This conceptual model is intended to provide enough detail regarding each model element to allow it to be understood at a conceptual level. It is not intended to be a mathematical model nor to provide comprehensive detailed information on every topic.

Purpose of the Model

This conceptual model is being developed for two main purposes. First, it is intended to provide a comprehensive overview of the current state of scientific knowledge regarding the factors that affect levels of dissolved oxygen in the San Joaquin River. Special attention is paid to the Stockton Deep Water Ship Channel, where dissolved oxygen levels frequently drop below the standards contained in *The Water Quality Control Plan for the Sacramento River and San Joaquin River Basins* (Basin Plan) (Regional Water Quality Control Board, Central Valley Region 2005) adopted by the Central Valley Regional Water Quality Control Board. It is meant to be a living document so that new information can be added to it as new data or studies become available.

The second purpose of the model is to identify those factors that are thought to have a strong affect on dissolved oxygen levels but for which the mechanisms by which they exert their influence are not well understood. These are factors where new studies or data collection would have the highest priority because they would have the highest likelihood of leading to actions expected to significantly improve understanding of the problem and to have a significant beneficial affect.

Structure of the Model

This conceptual model is structured using the driver-linkage-outcome model form favored by the California Bay-Delta Authority. Outcomes are the environmental or physical conditions that are the target of management actions. In this instance the primary outcome is the concentration of dissolved oxygen in the DWSC. Drivers are factors thought to influence outcomes. Because of the complexity of the physical and chemical conditions in the San Joaquin River, this conceptual model consists of several connected nested models. As an example, one of the primary drivers for dissolved oxygen is biochemical oxygen demand (BOD) (the demand for dissolved oxygen created by oxygen consuming biochemical processes in the water). In turn, there are a variety of factors that determine the levels of BOD in the aquatic environment (e.g. algal load, non-algal organic matter load, residence time). These factors are called secondary drivers. At the first level, BOD is the driver and dissolved oxygen levels are the outcome. In the second level, BOD becomes the outcome for the secondary drivers.

It should be noted, that the designation of factors as primary or secondary drivers does not imply relative importance of these factors in influencing DO concentrations. Rather, the factors are organized by cause and effect relationships so that the primary drivers directly affect the DO concentrations and the secondary drivers indirectly affect them by affecting the primary drivers. In fact, secondary drivers such as channel geometry and algal biomass are thought to be among the more important factors influencing DO concentrations in the DWSC.

The structure of the conceptual model is presented in Figure 1-1. The model has four levels. The first level is geographic. The area of interest (study area) has been divided into three reaches (Figures 1-2a and 1-2b).

For each reach, the second level describes the primary drivers influencing dissolved oxygen concentrations (Figure 1-1). The discussion of the relationships between the drivers and dissolved oxygen concentrations at this level are general in nature. Direct linkages between the primary drivers and the dissolved oxygen levels are described. In addition, any linkages among the primary drivers are also discussed. As an example, the mechanisms by which residence time directly influences dissolved oxygen are discussed, but in addition, the mechanisms by which flow influences reaeration rates (which in turn influence dissolved oxygen levels) are also described.

The third level describes the secondary drivers that influence the primary drivers (Figure 1-1). The text at this level includes a general discussion of the relationships between the secondary drivers and primary drivers, and descriptions of linkages that occur amongst the secondary drivers.

Following this general discussion is the fourth level that presents a more detailed discussion of each linkage between secondary and primary drivers. This text describes: the hypothesis or hypotheses underlying the relationship; evidence supporting the strength of this linkage (how much influence does the secondary driver exert over the primary driver); the level of scientific certainty associated with this linkage (how well understood it is and how its influence may vary over time or geography); any known mathematical relationships between the secondary and primary drivers, including whether there are any critical thresholds; and the sources of the secondary driver within the reach. Where alternative hypotheses exist, each is presented, and the sources of data supporting each are listed.

Sources of Information

This model was created using a variety of information sources. The document Synthesis and Discussion of Findings on the Causes and Factors Influencing Low *DO in the San Joaquin River Deep Water Ship Channel near Stockton, CA: Including 2002 Data* (Lee and Jones-Lee 2003) was a primary source, but many other sources of information were also used. All of the source documents are listed in Chapter 4, "Bibliography".

Web-Based System

The conceptual model described in this document is a paper version of what will ultimately be a web-enabled conceptual model. It is envisioned that the model will eventually exist in electronic form with the elements of the model connected via hypertext links. The text contained in this document will be embedded within that structure. The web-based version will more easily accommodate the multi-dimensional structure of the model and will allow users to move easily up and down the levels of the model and across levels. This paper version is being provided to the San Joaquin Dissolved Oxygen TMDL Technical Work Group (TWG) members to allow the technical content of the conceptual model to receive a thorough peer review.

Links to Other Models

One advantage of a web-based model is that it makes linking related models easy. This conceptual model also will have links to a second, closely related conceptual model being developed. This second model will describe the current state of scientific understanding of the affects of low dissolved oxygen levels on biological and ecological systems. This model will provide information about the effects of dissolved oxygen levels on several species of fish, including direct (e.g. mortality, morbidity, growth) and indirect (e.g. food web, predation) effects, and on ecological functions.

Geographic Scope of the Dissolved Oxygen Conceptual Model

This conceptual model encompasses the San Joaquin River from Friant Dam to the central Delta.

For the purposes of this model, the river has been divided into three reaches (Figure 1-1). Reach 1 comprises the river from Friant Dam to Vernalis. The upstream terminus of Friant Dam was selected because although water released from Friant Dam does not frequently connect to the downstream portion of the river, important inputs of oxygen demanding substances occur on this portion of the river. Few if any inputs of oxygen-demanding substances or their precursors occur upstream of Friant Dam. Vernalis was chosen as the downstream terminus for two main reasons. First, it represents the downstream edge of the river unaffected by tidal influences. Second, it is a compliance location for water quality regulations, so a great deal of water quality data is available.

The second reach is from Vernalis to Channel Point. This encompasses the portion of the San Joaquin River that transitions from river to estuary. Channel Point was chosen as the downstream terminus because it is the upper boundary of the DWSC.

The third reach is the DWSC segment, from Channel Point to Disappointment Slough. Although the DWSC actually extends through the Delta and into San Francisco Bay, Disappointment Slough was selected as the downstream terminus because cross-Delta water flows typically reaerate the DWSC beyond this point, so it represents the downstream edge of the area of impairment.

Document Organization

Chapter 2, “Overview of Primary and Secondary Drivers that Affect Dissolved Oxygen” describes at a general level what is known about each of the primary drivers and how they affect dissolved oxygen concentrations, and what is known about each of the secondary drivers and how they affect primary drivers (Figure 1-1).

Chapter 3, “Reach-Specific Relationships Affecting Dissolved Oxygen in the Deep Water Ship Channel” presents:

- the reach-specific information that is available regarding each of the primary and secondary drivers;
- hypotheses about how the primary drivers in each reach may exert influence on dissolved oxygen concentrations in the DWSC;
- uncertainties associated with the understanding of how primary drivers operate in each reach; and
- research needs that have been identified in the relevant literature.

Chapter 4 presents the bibliography of citations and sources reviewed to construct the model.

Chapter 5 presents a glossary of terms used in the conceptual model.

Chapter 2
Overview of Primary and Secondary Drivers Affecting Dissolved Oxygen

Introduction

This chapter discusses general principals regarding the mechanisms by which the primary and secondary drivers affect concentrations of dissolved oxygen in the San Joaquin River. This includes discussion of the physical and chemical processes underlying these mechanisms and how the drivers interact with each other. Chapter 3 provides more detailed, site-specific information about how the drivers operate in each of the three reaches. The discussions in Chapter 2 have been segregated from the discussion in Chapter 3 to minimize repetition of this general information each time it is discussed in Chapter 3.

Factors that affect dissolved oxygen in the DWSC include: San Joaquin River flows; concentrations of oxygen demanding substances; residence time of water; algal biomass; concentrations of certain trace metals in river sediments; water temperature; storm water runoff; concentrations of suspended solids; and concentrations of organic compounds. The interrelationships among these factors, however, are not well understood (300001245, 300001112, 300001385).

Episodes of low dissolved oxygen concentrations in the DWSC are generally caused by high concentrations of biological oxygen demand (BOD) that decay within the DWSC during periods of relatively long residence time. Residence time is the amount of time that water remains in a water body prior to exiting which, in the DWSC, is controlled by its geometry (deep and wide), tidal cycles, and San Joaquin River inflows to the DWSC. The basic physical and bio-chemical principles useful for the evaluation and assessment of low dissolved oxygen episodes in the DWSC are briefly reviewed first below to provide background for the conceptual model of the San Joaquin River dissolved oxygen concentrations.

Dissolved Oxygen Saturation in Water

Dissolved oxygen concentrations are controlled by Henry’s law which indicates that a small fraction of a gas will dissolve in a liquid. The maximum concentration of dissolved oxygen in freshwater is calculated from Henry’s constant, which is a function of temperature. For oxygen, the saturated dissolved oxygen concentration decreases with increasing water temperature.

Table 2-1 [to come] gives the saturation dissolved oxygen for a range of water temperatures. During the summer, with a water temperature of 75°F, the dissolved oxygen saturation is about 8 milligrams/liter (mg/l). During the winter, with a water temperature of 50°F, the dissolved oxygen saturation concentration is about 12 mg/l. This physical chemistry principle explains why dissolved oxygen are generally higher in the winter and lower in the summer in the San Joaquin River and the DWSC.

Dissolved Oxygen Deficit

The dissolved oxygen deficit is the decrease from dissolved oxygen saturation that will occur when water with an initial BOD concentration is placed in a bottle or decays within the DWSC. The dissolved oxygen deficet is generally a function of the initial BOD, the BOD decay rate, and the time that the water sample or water remains within the DWSC. This can be generally described with the following simple equation:

dissolved oxygen deficit = (BOD concentration [mg/l]) x (BOD decay rate [1/day]) x (decay time [days])

The basic measurement of BOD is the dissolved oxygen decline that is measured when water is held for 5 days in a dark bottle at 20°C.

Load

A load (mass/time) is the mass (i.e., pounds [lbs]) of material entering a water body during a time period (i.e., day). The load increases with higher concentration and with higher river flow (volume/time). River flow is usually measured in units of cubic feet per second (cfs). The San Joaquin River load of a substance can be calculated as:

load (lbs/day) = (5.4) x (concentration [mg/l]) x (flow [cfs])

where 5.4 is the conversion constant between liters and cubic feet. This simple relationship can be used to calculate the BOD load, the algae load, or the dissolved oxygen load.

Reaeration

Reaeration is the transfer of oxygen from the atmosphere to a water body. The transfer occurs at the air/water interface. The transfer of dissolved oxygen (or other gas such as nitrogen or carbon dioxide) from the atmosphere at the surface of water is controlled by the transfer rate and the dissolved oxygen deficit. Reaeration is calculated as:

reaeration (g/m2/day) = (transfer rate [m/day]) * dissolved oxygen Deficit (mg/l)

Reaeration is 0 when the dissolved oxygen is saturated and will be maximum when dissolved oxygen concentrations are 0. The transfer rate is generally increased with water surface turbulence, caused by high water velocities or high wind speed (that creates surface waves).

Primary and Secondary Drivers

Primary and secondary drivers affecting dissolved oxygen concentrations are presented in Table 2-2 and Figure 2-1 (to come).

Table 2-2. Primary and Secondary Drivers Affecting Dissolved Oxygen Concentrations

Primary Drivers	Secondary Drivers
Sources of Oxygen Demand	
Biological Oxygen Demand (BOD) Concentration	Imported BOD Concentration Algal Biomass Concentration Non-Algal Organic Matter (NOM) Concentration Ammonia Concentration Residence Time
Sediment Oxygen Demand (SOD) Concentration	Imported BOD Concentrations (Settling) Particulate BOD Concentration Iron and Sulfate Compounds Concentrations Residence Time
Residence Time	Flow Volume Channel Geometry
Sources of Dissolved Oxygen	
Imported Dissolved Oxygen	A variety of factors related to source waters
Reaeration	Water temperature Wind Flow Channel geometry
Photosynthesis	Imported Algal Biomass Algal Biomass Turbidity Sunlight Water Temperature

BOD Concentration

Biochemical oxygen demand (BOD) is the potential of certain materials to decrease dissolved oxygen concentrations as they are converted to other substances by microorganisms. BOD is often measured as two components, carbonaceous biochemical oxygen demand (CBOD) and nitrogenous biochemical oxygen demand (NBOD). The source material for CBOD is organic matter. The source materials for NBOD include organic matter that decays to ammonia, and ammonia entering the San Joaquin River through wastewater and stormwater systems. Nitrification, the process of oxidizing ammonia to nitrates by microorganisms, requires almost 5 mg/l of DO for every mg/l of ammonia.

It should be understood that organic materials create both CBOD and NBOD through different biochemical pathways, making it difficult to separate out the potential oxygen demand of each pathway. Measurement of BOD is usually accomplished through laboratory experiments with water samples from the target water body. BOD and CBOD are directly measured, and NBOD is inferred by subtracting the CBOD from the BOD. The nitrification-inhibitor method that has been used to measure CBOD may yield unreliable results, because the inhibitor also inhibits the growth of some bacteria that use CBOD (300001245).

Known and potential sources of BOD in the study area include algae, aquatic plants, dead plant and animal matter, and other soluble and insoluble organic materials. It is difficult to determine the contribution of specific organic materials to BOD, but it is known that each compound is subject to a specific rate of biochemical reaction that consumes dissolved oxygen (300001245).

CBOD results when oxygen is consumed by microorganisms in converting organic material into CO_2, H_20, nutrients, energy and new cells. (300001245). Algal cells contain organic chemicals that will consume oxygen during decomposition. The following chemical equation provides estimates of the quantity of CBOD that will be produced during the decomposition of an algal cell. (300001302)

$$C_{106}H_{263}O_{110}N_{16}P \text{ (algae)} + 138\ O_2 \rightarrow 106\ CO_2 + 16\ NO_3^- + HPO4^{2-} + 122\ H_2O + 18\ H^+$$

The current body of information indicates that algae and algal detritus are the primary source of BOD in the DWSC (300001245). Each 1 mg/l of algae will yield a theoretical total oxygen demand of 1.2 mg/l, which represents the sum of CBOD and NBOD. The CBOD from the decomposition of 1 mg/l of algal biomass is 0.9 mg/l or 75% of the total oxygen demand, while the NBOD is 0.3 mg.L or 25% of the total oxygen demand (3000001302). The algae pigments chlorophyll *a* and phaeophytin are used to represent the concentrations of living and dead algae, respectively, within a water column. Therefore, the phaeophytin concentrations indicate the quantity of dead algae that might be a source of CBOD. However, the chlorophyll *a* and phaeophytin content of algal biomass is somewhat variable.

There are two sources of NBOD in the study area. The first is organic nitrogen (the nitrogen contained in organic material) that is converted by microorganisms to ammonia (NH_3). This process is called ammonification. In the presence of oxygen, microorganisms convert the ammonia into nitrites (NO_2^-) and nitrates (NO_3^-), consuming dissolved oxygen in the process.

This process is called nitrification. The second source of NBOD is direct inputs of ammonia from wastewater treatment plants and other sources. Ammonia and organic nitrogen compounds vary in their NBOD exertion rates, which are also dependent on the number and species of microorganisms acting on the material (300001245).

Secondary Drivers that Influence BOD Concentrations

Secondary drivers that contribute to BOD are shown in Table 2-2.

Imported BOD Concentration

Imported BOD concentration is the concentration of BOD generating substances (e.g., algal biomass) that are contributed to the San Joaquin River in water from tributaries, return flows, and other flow sources. Sources of imported BOD are described for each study area reach in Chapter 3.

Algal Biomass

Algal biomass in the San Joaquin River both increases dissolved oxygen concentrations through photosynthesis and decreases dissolved oxygen concentrations through respiration, and specifically in the DWSC, when slow flow rates allow the algae to sink, die, and decompose. This section addresses the latter mechanism. Photosynthesis is discussed in Section 2.2.6.

Algal biomass in each study area reach is derived from algae that enter the reach from upstream sources (imported BOD) and algae that is produced within each reach. Within the study area, algal growth is primarily a function of water temperature, the amount of available light, and the amount of available algal nutrients (3000001708). In addition, algal biomass is also affected by the time available for algae to grow in the study area. For example, increased algal biomass in the DWSC will generally occur during periods of increased residence times (300001039).

Water temperature affects algal biomass and dissolved oxygen concentrations in several ways. As water temperatures in the San Joaquin River rise, algal growth rates increase, as do the rates of dissolved oxygen depleting reactions (300001245). Some of the year-to-year variations in dissolved oxygen depletion in the DWSC may be related to temperature differences, which influence algal growth in the San Joaquin River watershed and oxygen depletion within the DWSC (300001245, 300001005).

Nitrogen and phosphorus are important nutrients for algal growth. Major sources of these nutrients in the study area are derived from soils, fertilizers, animal waste from dairies and other livestock-related operations, and discharges from wastewater treatment facilities that enter the

San Joaquin River (300001310). Ammonia inputs to the San Joaquin River from the Stockton Regional Wastewater Control Facility (Stockton RWCF) appear to remain steady from June through August and steadily increase in September and October (300000940). One indication that human activities may substantially contribute nutrients to the San Joaquin River is that nitrogen isotopes in the San Joaquin River (upstream of Vernalis) appear to be derived from animal waste and sewage discharges (300001856). The nitrogen isotope analysis also indicated that soil nitrogen and/or fertilizer are the most important nitrogen sources to tributaries to the San Joaquin River (300001856). Nutrient concentrations indicate that available nitrogen and phosphorus exceed the suggested algal growth limiting values by at least 60 and 5 fold, respectively (300002003).

Non-Algal Organic Matter (NOM)

Although algae are believed to be the principal source of organic matter in the San Joaquin River, there are other sources as well. Limited information is available on these other non-algal organic matter (NOM) sources. However, potential sources of NOM include:

- aquatic plants and other organisms present in the San Joaquin River; and

1. dead plant and animal matter (e.g., leaves, manure) that enter the San Joaquin River from agricultural drainage, storm water runoff, riparian vegetation, and drainage from managed wetlands (300001880).

Total organic carbon is a chemical measurement technique that indicates all oxidizable carbon within a sample. Some of this material is only partially decayed by microorganisms (i.e. refractory) and does not contribute to BOD. Salt Slough, Mud Slough, and the Tuolumne and Stanislaus Rivers are the most significant tributary sources of dissolved organic carbon to the San Joaquin River and accounted for as much as 24 to 45 percent of the 2000 and 2001 dissolved organic carbon loads in the San Joaquin River at Vernalis (3000001856) (see Table 2-X [to come]). Dissolved organic carbon concentrations, measured at a number of locations in the San Joaquin River upstream of Vernalis, were relatively constant from June through September in 2000 and 2001 (300001856). Organic carbon loads in the San Joaquin River increased in October and November because of wetland drainage into Mud Slough and reservoir releases on the Merced River (300001856). One study suggests that algae are the primary source of BOD in the DWSC (300001054). However, another study suggests that in the San Joaquin River and in the DWSC, live and detrital algae comprised, on average, only 20 to 40% of the organic carbon (300001054). Therefore, non-algal organic matter loads may be an important source of BOD.

Ammonia Concentrations

Direct inputs of ammonia to the San Joaquin River include discharges from wastewater treatment plants, and wastewater from dairies and other animal husbandry-related operations (300001773, 3000001302). Wastewater treatment plant (WWTP) dischargers to tributaries of the San Joaquin River include Newman WWTP, Turlock WWTP, and Los Banos WWTP. The City of Modesto WWTP and the City of Manteca WWTP discharge directly to the San Joaquin River (300001039). The City of Stockton river discharge is the largest source of ammonia to the San Joaquin River upstream of the DWSC. The contribution of ammonia concentrations to oxygen demand in the Deep Water Ship Channel was identified as early as the late 1960s (McCarty 1969) (30001054).

Residence Time

Residence time affects BOD concentrations by controlling the period over which BOD substances can exert an oxygen demand within a segment of channel. The larger the residence time, the more of the BOD will decay and the DO concentration will decline.

Relationship between BOD Concentration and Other Primary Drivers

Residence time (see Section 2.2.3) affects BOD concentrations because particulate BOD, such as dead algae, that settle from the water column contribute to SOD (see Section 2.2.2).

SOD Concentration

Sediment oxygen demand (SOD) is created by chemical oxidation reactions and the decomposition of organic matter that occur in channel bed sediments. SOD produces an oxygen depletion rate that is dependent on the SOD rate (grams/meter/day [g/m/day]) and the depth of the water over the sediment. The dissolved oxygen decline is calculated as:

dissolved oxygen decline (mg/l/day) = (SOD rate [g/m^2/day])/(depth [m]) x (travel time [days])

For example, in a river with a depth of 1 m, the dissolved oxygen decline is equal to the SOD rate times the travel time (which may be relatively short). In the DWSC, where the depth is about 10 m, the dissolved oxygen decline will be only about 10% of the SOD rate times the travel time. Consequently, substantial dissolved oxygen decline may only occur when the travel time in the DWSC is long, during low flow events.

SOD is caused by the consumption of oxygen by bacteria as they respire and decompose algae and other organic materials that have settled to the San Joaquin River channel bottom (300001773). Nitrification of ammonia present in the water column near the sediments can be an additional source of SOD (300001245). Another potential source of SOD are ferric iron and reduced sulfur compounds that are present (under anaerobic conditions) in the bed sediments of the San Joaquin River and DWSC (300001773). If these reduced forms of iron and sulfur (i.e ferrous iron and sulfides) are exposed to dissolved oxygen, they will rapidly undergo oxidation reactions and, in the process, exert a high oxygen demand for a short period of time (300001773).

Only sediments on the river-bottom exert an SOD (300001096). Particulate forms of BOD may contribute SOD through settling. Algae and suspended particles entering the DWSC from the San Joaquin River can settle out of the water column at an average rate of approximately 1 meter per hour (or 3.28 ft per hour) and provide a source of SOD (300001559). The potential sources of organic particles entering the study include agricultural return flows, domestic and industrial wastewater sources, and stormwater runoff (300001773).

Upstream of the DWSC, where the San Joaquin River channel is relatively narrow and shallow compared to the DWSC, the San Joaquin River is turbulent and has sufficient flow velocities to suspend algae and other organic particulates in the water. However, as the San Joaquin River flows into the DWSC, the flow velocities dramatically decline because of the greater width and depth of the DWSC. This velocity reduction causes some of the suspended load to settle out and become SOD (300001096). The quantity of SOD in the DWSC decreases with distance downstream suggesting that particulates in the water column continue to settle out as the water flows downstream (300001302).

Secondary Drivers that Contribute to SOD Concentration

Secondary drivers that contribute to SOD are shown in Table 2-2.

Imported BOD Concentrations

Imported BOD concentrations are the concentrations of BOD generating substances (e.g., algal biomass) that are contributed to the San Joaquin River in water from tributaries, return flows, and other flow sources. Sources of imported BOD and SOD are described for each study area reach in Chapter 3. Particulate BOD may settle and contribute to SOD.

Particulate BOD Concentration

As described in Section 2.2.1.1, algae biomass represent significant source of BOD when they are suspended in the water column. However, if the algae biomass settle out of the water column they represent a source of SOD. Particulate NOM (i.e. detritus) in the water column that may exert BOD also represent a source of SOD if they settle out of the water column.

Iron and Sulfate Compounds

[To come.]

Residence Time

The effects of residence time on SOD are similar to those described for BOD in Section 2.2.1.1. A larger residence time may allow more of the particulate BOD to settle and contribute to SOD. The larger the residence time, the greater the DO decline from SOD may become.

Relationship between SOD and Other Primary Drivers

Residence time (see Section 2.2.3) affects SOD concentrations because particulate BOD, such as dead algae, that settle from the water column contribute to SOD (see Section 2.2.1).

Residence Time

Residence time is affected by flow volume and channel geometry. Generally, increasing flow volume decreases residence time by increasing flow velocity in the channel. Channel geometry (e.g., width, depth) determines residence time by affecting the velocity with which a given volume of water passes through a channel segment. The residence time can be calculated from the flow and volume:

$$\text{Time (days)} = 0.5 \times \text{Volume (af)} / \text{River Flow (cfs)}$$

Tidal flows increase the movement of water within the DWSC but do not change the average residence time of water. Particulate materials that settle to the sediments will have a larger residence time than those in the water (i.e. dissolved substances).

Secondary Drivers that Contribute to Residence Time

Flow Volume

Sources of flow include upstream releases from reservoirs; flow from tributaries (see Figure 2-X [to come]); groundwater discharge into the San Joaquin River; agricultural and other water returns; storm water runoff; and discharges from wastewater treatment plants and other urban and industrial sources. Diversions of water include agricultural, wetland, urban, and industrial water supply diversions (see Figure 2-X [to come]); groundwater aquifer recharge; and evaporation. Diversions of water from the San Joaquin River, particularly at the head of Old River, can remove a significant amount of San Joaquin River flow, especially in dry years with high Central Valley Project and State Water Project pumping (300001039, 300001278). Sources of flow and flow loss are described for each study area reach in Chapter 3.

Channel Geometry

The geometry of stream channels affects residence time by affecting flow velocity. With the exception of the DWSC in Reach 3, channel geometry in the study area is maintained primarily through natural fluvial geomorphic processes. The DWSC, however, was artificially created and is maintained through channel dredging. The geometry of the DWSC controls the flow of water through the DWSC and the tidal exchange and mixing within the DWSC (300000957). The San Joaquin River channel immediately above the DWSC is 10 to 15 feet deep and the channel within the DWSC is maintained to a depth of 35 to 40 feet (300001245). As described in Sections 2.2.1.1 and 2.2.2.1, residence time and tidal mixing influence the DO decline from BOD and SOD. Therefore, the geometry of the DWSC is a very important factor affecting the DWSC dissolved oxygen concentrations because it affects the residence times of oxygen demanding materials and tidal exchange and mixing (300000957).

Relationship between Residence Time and Other Primary Drivers

Residence time influences BOD and SOD concentrations by affecting the time available for oxygen demanding substances to exert an oxygen demand within a segment of river channel. Residence time also affects the amount of dissolved oxygen contributed through algal photosynthesis and reaeration.

Imported Dissolved Oxygen

Imported dissolved oxygen is dissolved oxygen that is contributed to the San Joaquin River in water from tributaries, return flows, and other flow sources. Imported dissolved oxygen contributes to the initial DO concentration of water flowing into each reach.

Reaeration

Reaeration is a natural (physical) process and is defined as the net flux of oxygen from the atmosphere to a body of water with a free surface (300001799). Reaeration acts to maintain the DO at saturation. With high algae biomass and photosynthesis, reaeration can reduce the DO to saturation.

The general mass balance equation for oxygen gas transfer from the atmosphere to a mixed volume of water exposed to the atmosphere is:

$$V * dC/dt = K_L * A * (C_s - C)$$

Where V = volume of water in contact with the surface (m^3)

A = area of water surface (m^2)

C = concentration of oxygen in water volume (mg/l)

Cs = saturated concentration of oxygen in water (mg/l)

KL = oxygen transfer velocity (m/day)

This relationship is often written as

$dC/dt = K_2 * (C_s - C)$

Where K_2 = reaeration coefficient (1/day). (300001088).

Reaeration increases with surface area, therefore reaeration is greater in the DWSC where the surface width is 600 feet. The oxygen transfer velocity is dependent on the turbulence of water near the water surface, which is generally estimated from the water velocity and depth (or other hydraulic parameters), as well as the wind speed. The water depth may influence the turbulence at the surface and is included in most regression equations used for estimating the transfer velocity. The rate of change in dissolved oxygen will always decrease as the mixed depth increases. (300001088).

When the DWSC is stratified, with a warmer layer isolated near the surface, the reaeration will also be limited to the surface. The surface mixed depth will be increased during periods of higher winds and at night from cooling. This will allow a larger fraction of the DWSC to be exposed to reaeration, and a greater mass of oxygen will be transferred to the DWSC during periods of higher wind speed. Stratification will limit the mixed depth that is exposed to surface reaeration. (300001088).

Secondary Drivers that Affect the Reaeration Rate

Secondary drivers that contribute to reaeration are shown in Table 2-2.

Water Temperature

The saturation dissolved oxygen concentration in water is affected by water temperature. As described under Section 2.2.1, increasing temperature tends to reduce dissolved oxygen concentrations by reducing oxygen's solubility in water. Stratification is more likely to occur during the afternoon of warm days (i.e. high solar radiation). Stratification can produce a shallow surface layer and limit reaeration of water below the surface layer.

Wind

Wind can increase reaeration by increasing turbulence, thus facilitating more oxygen exchange. The increase in turbulence can also increase mixing within the water column, allowing more of the water to be reaerated at the surface.

Residence Time

More reaeration is possible when the residence time is increased.

Relationship between Reaeration and Other Primary Drivers

Residence time affects reaeration by affecting the period of reaeration of the DWSC. BOD and SOD affect the rate of reaeration by reducing the existing concentration of dissolved oxygen in the water column. Photosynthesis by aquatic plants contributes to dissolved oxygen concentrations and, as dissolved oxygen concentrations provided by photosynthesis increase towards saturation levels, the rate of reaeration decreases (300001088).

Photosynthesis

Aquatic vascular plants, attached algae (periphytes), and free-floating algae (phytoplankton) produce oxygen through photosynthesis that contributes to dissolved oxygen concentrations in the water. The simplified chemical reaction that produces oxygen through photosynthesis (Tchobanoglous and Schroeder 1985) is:

$$CO_2 + H_2O + \text{Nutrients (in the presence of light)} \rightarrow CH_2O \text{ (new algal cells)} + O_2$$

Secondary Drivers that Support Photosynthesis

Secondary drivers that contribute to photosynthesis are shown in Table 2-2.

Imported Algal Biomass

Imported algal biomass is the algal biomass that is contributed to the San Joaquin River in water from tributaries, return flows, and other flow sources. Sources of imported algal biomass are described for each study area reach in Chapter 3.

Algal Biomass

Algae (phytoplankton) are the primary contributor of photosynthetically generated dissolved oxygen in the study area (300001245). Factors affecting algal biomass in the study area are described in Section 2.2.1.1. As algal biomass increases, the amount of oxygen produced by algae also increases. Studies conducted in the DWSC have shown that algal photosynthesis can add considerable amounts of oxygen to near-surface portion of the water column. As a result, dissolved oxygen concentrations can be high when photosynthesis is occurring during the day in the near surface waters of the DWSC, but low near the channel bottom (Lehman 2001; Jones & Stokes 2002; 3000001294).

Sunlight

Photosynthesis and subsequent production of oxygen requires the presence of sunlight (Tchobanoglous and Schroeder 1985). The amount of sunlight available for photosynthesis is determined by diurnal and seasonal variations in light intensity and by weather-related factors such as the presence and density of cloud cover. In some cases, the existence of vegetative cover from river banks can also affect the amount of sunlight reaching the water surface.

Turbidity

Once sunlight reaches the water surface, the clarity of the water determines the depth to which light travels down the water column. The portion of the water column receiving sufficient light for photosynthesis to occur is called the euphotic zone. Suspended particles in the water column can reduce the clarity of the water, decreasing the depth of the euphotic zone and decreasing the amount of sunlight reaching that zone.

Sources of turbidity in the study area include suspended soil particles resulting from erosion and other particulate matter entering the San Joaquin River from storm runoff and tributaries and other flow sources. In addition to turbidity, colored water released from managed wetlands in the Mud and Salt Slough watershed have been shown, at times, to contribute sufficient color to the San Joaquin River and DWSC to reduce light penetration sufficiently to affect the rate of algal photosynthesis (3000001245). Although algae in the San Joaquin River are mixed and grow at the average light level within the river, in the DWSC, the algae are not exposed to the surface lighted layer (euphotic zone) for enough of the day to grow well.

The amount of light that penetrates the water column affects algal growth and the rate of algal photosynthesis. Maximum rates of algal photosynthesis occur at 25-45% of the light intensity available at the DWSC water surface (300001005) (Figure 2-X [to come]). As the amount of suspended particulate material in the water column increases, the amount of light penetrating the water column decreases. Turbidity, therefore, affects the growth of algae by affecting the amount of light available for photosynthesis (300001005). Reductions in the availability of light associated with increasing turbidity can also reduce the lifespan of algae established in the affected water column (3000001773). Known potentially important sources of turbidity include suspended soil particles, particulate organic matter, discharges from wastewater treatment plants and other industrial sources, and pulses of colored water released from managed wetlands that enter the study area (300001245, 300001039).

Periods of the highest turbidity in the study area are likely experienced during February through May when flows are highest and materials are being flushed downstream. One study found that in 2001, turbidity values in the DWSC declined from June to October (300000940). Turbidity values in the San Joaquin River from Vernalis to Channel Point were similar to those measured in the DWSC and experienced a similar decline during the summer (300000940).

Water Temperature

Water temperature affects the rate that oxygen is generated through photosynthesis by affecting the growth rate of algae and other aquatic plants (see Section 2.2.1.1).

▪ Relationship between Photosynthesis and Other Primary Drivers

Residence time affects the amount of dissolved oxygen produced through photosynthesis by affecting algal biomass. Dissolved oxygen concentrations contributed through photosynthesis affects the amount of oxygen that can be dissolved through reaeration because, as dissolved oxygen concentrations provided by photosynthesis increase towards saturation levels, the rate of reaeration decreases (300001088). The maximum long-term DO concentration is the saturated DO concentration in the San Joaquin River or the DWSC.

Chapter 3
Reach-Specific Relationships Affecting Dissolved Oxygen in the Deep Water Ship Channel

Introduction

This chapter describes what is known about how the primary and secondary drivers that influence dissolved oxygen concentrations in each study area reach (Figure 1-2a) and how they may affect dissolved oxygen concentrations in each downstream reach. Uncertainties and data gaps are also described.

Reach 1 (Friant Dam to Vernalis)

The primary drivers affecting dissolved oxygen concentrations in Reach 1 (Figure 1-2a) are shown in Figure 3-1a.

Dissolved Oxygen and Oxygen Demanding Substances Contributed from Reach 1 to Reach 2

Sources, timing, and magnitude of oxygen demand (BOD and SOD) contributed from Reach 1 to Reach 2 and the contribution of substances from Reach 1 to Reach 2 that can generate oxygen demand in Reach 2 (e.g., algal nutrients) are not well understood. Dissolved oxygen concentrations in water entering Reach 2 from Reach 1 are summarized in Table 3-X (to come).

[Additional information to come.]

BOD Concentration

Secondary drivers affecting BOD concentration in Reach 1 are shown in Figure 3-2b.

Understanding of How Reach 1 BOD Concentrations may Affect Dissolved Oxygen Concentrations in the DWSC

One study found that wetlands, agricultural drainage, and wastewater treatment plants upstream of Vernalis contribute oxygen consuming materials that, in concert with other factors, cause the low dissolved oxygen in the DWSC (300001096). Some studies have found, however, that BOD concentrations in the San Joaquin River upstream of Vernalis may not be significantly affecting the dissolved oxygen concentrations in the DWSC. Differences in algal species carbon measured upstream of Vernalis and the species carbon measured downstream of Vernalis and in the DWSC indicate that algal species changed, decomposed, or were replaced as they moved downstream in the San Joaquin River (3000001054). These results also indicate that algal biomass upstream of Vernalis may not significantly affect the dissolved oxygen concentrations in the DWSC and that the majority of algae in the DWSC may be grown in the DWSC and not imported from upstream sources (3000001054). Other studies found that algal biomass contributed from Reach 1to the DWSC were poorly estimated by algal biomass measured at Vernalis (3000001005). Thus, other factors such as vertical settling, benthic and planktonic grazing, and agricultural diversions may be minimizing the effect of algae in the San Joaquin River upstream of Vernalis on dissolved oxygen concentrations in the DWSC (3000001005).

One study found that the DWSC received 6 times more $CBOD_5$ from river loads than from the Stockton RWCF (300001088), which may indicate that Reach 1 NOM sources are a source of oxygen demand affecting dissolved oxygen concentrations in the DWSC.

The ammonia load from upstream of the Stockton RWCF discharge (including the load from Reach 1) is only about 10 percent, but it could make a substantial contribution to oxygen demand in the DWSC if it increases during passage from Mossdale to downstream. The relative contribution of ammonia from Reach 1 to the dissolved ammonia concentration in the DWSC is strongly influenced by the ammonification rate in the DWSC (300000957, 300001245). However, the decay rate of the large upstream organic nitrogen (algal) load to dissolved ammonia is slow and most of the organic nitrogen is highly decomposed before reaching the DWSC (300001054). Agricultural drainage is an area of particular concern in determining the source and contribution level of ammonia to the amount of oxygen demand (300001245, 300001773). Some studies have found that NBOD transport from non-point sources in upstream areas is a large source of oxygen demand in the DWSC (300001054, 300001112).

At lower flows in the DWSC, the residence time increases and the relative contribution of Reach 1 NBOD loads increases (300001054). The increased residence time allows for more organic nitrogen (algae) to be converted to ammonia (300001054). In general, the Stockton RWCF discharged greater daily dissolved ammonia loads than upstream of Vernalis (300001914). However, the Reach 1 chlorophyll *a* loads strongly affected the relative contribution of the Stockton RWCF and Reach 1 to the dissolved ammonia loads in the DWSC (300001914). Thus, the importance of Reach 1 NBOD loads is dependent on algal loads upstream of Vernalis. At residence times of 10 days or greater, upstream of Vernalis NBOD loads will contribute more dissolved ammonia to the DWSC than the Stockton RWCF (300001054).

Flow volume contributed from Reach 1 can have two opposing effects. BOD concentrations transported downstream in Reach 1 flows may ultimately increase oxygen demand loads in the DWSC. Conversely, flows reaching the DWSC from Reach 1 contribute towards reducing the hydraulic residence time in the DWSC, which reduces the time during which the BOD concentrations transported from Reach 1 can be exerted in the DWSC. Diversions from the San Joaquin River, including those upstream of Vernalis, can remove large volumes of algal biomass and therefore minimize the potential effects of Reach 1 BOD concentrations on dissolved oxygen concentrations in the DWSC (3000001039).

Imported BOD Concentration

Some papers support that west-side streams and conveyances generally provide most of the algae inputs to the upper San Joaquin River (300001039). However, the westside tributaries of Los Banos Creek, Spanish Grant Drain, and Orestimba Creek are not significant contributors of algal biomass to the San Joaquin River (3000001245). Algal concentrations in the Tuolumne, Merced, and Stanislaus Rivers are low and are not likely important sources of imported BOD concentration (3000002003).

The largest inputs of algae to the San Joaquin River upstream of Vernalis are the San Joaquin River above Highway 165, and Mud and Salt Sloughs, which together account for 90 percent of the total chlorophyll *a* load immediately upstream of Vernalis (3000002003, 3000001245). These three inputs are important sources of algae because of long travel times to the DWSC, which allow for longer periods of algal growth in the San Joaquin River, and high algal concentrations (3000002003). It is believed that water drained from managed wetlands do not provide a substantial source of algal biomass to Mud Slough and, ultimately, the San Joaquin River during the summer months but do contribute greater algal biomass in September (3000001260). Results of one study indicated that most of the BOD from San Luis Drain is CBOD (300001260).

Salt Slough, Mud Slough and the Tuolumne and Stanislaus Rivers are the most significant tributary sources of dissolved organic carbon (3000001856). Harding Drain may be another substantial source of NOM to the San Joaquin River because most of its BOD is not derived from algae decomposition (300001245). The Turlock wastewater treatment plant may be contributing NOM to the Harding Drain (300001245).

Factors Affecting Imported BOD Concentration in Reach 1

Algal growth in Mud Slough, the three eastside rivers (3000002003), and in the San Luis Drain may be phosphorus limited (3000001260).

[Additional information to come.]

Relative Importance of Imported BOD Concentration to BOD Concentration in Reach 1

[To come.]

Algal Biomass

In general, algal biomass, as indicated by chlorophyll *a* concentrations, increase upstream of Vernalis in late May or early June and remain high until August. Beginning in August, the chlorophyll *a* concentrations begin to decline until October at which time the concentrations will remain generally low until the following spring (300002003). Phaeophytin *a* concentrations, an indication of dead algae, remain below the chlorophyll *a* concentrations for most of the year except during the largest algal blooms in the San Joaquin River (300002003). The total nitrogenous load from Reach 1 can exceed output from the Stockton RWCF, which is discharged into the San Joaquin River in Reach 2.

Flow from the eastside rivers, the Tuolumne, Merced, and Stanislaus Rivers, may be diluting algal concentrations in the San Joaquin River because algal concentrations in these flows are low (3000002003). These potential dilution effects are most noticeable when flows from these tributaries are increased to attract fish in October or for the Vernalis Adaptive Management Plan (VAMP) flows in the spring (3000002003).

One study found that the most significant sources of algal nutrients to the San Joaquin River upstream of Vernalis are the Tuolumne River, Harding Drain, and Mud Slough (3000001856). Some studies have found that the drainage from agricultural and managed wetlands can provide substantial quantities of nutrients that support algal growth in the San Joaquin River (3000001112). However, there are differing opinions on which type of drainage (agricultural or managed wetland) provides the greatest quantities of nutrient inputs to the San Joaquin River (3000001260, 3000001245).

Factors Affecting Algal-Related BOD Concentration in Reach 1

The limiting factor to algal growth in the San Joaquin River is light (3000002003, 3000001310) because nutrient concentrations are substantially greater than those concentrations that would limit algal growth (3000001245). In addition to turbidity, which affects available light, algal blooms upstream of Vernalis are controlled by nutrient inputs from erosion, stormwater runoff, agricultural inputs, the dairy industry, and other NPDES dischargers (3000001427). Predation by zooplankton and clams may also affect algal (phytoplankton) concentrations upstream of Vernalis (3000001245).

Relative Importance of Algal Biomass to BOD Concentration in Reach 1

The available information suggests that algal biomass is an important contributor to BOD concentrations in Reach 1.

NOM

Sources of carbonaceous and nitrogenous NOM to the San Joaquin River upstream of Vernalis include agricultural irrigation drainage, agricultural stormwater runoff, riparian vegetation, urban dry season runoff, urban wastewater drainage, and dairy and animal husbandry areas (300001880, 300001773).

Factors Affecting NOM-Related BOD Concentration in Reach 1

Important factors affecting NOM-related BOD concentrations in Reach 1 are not identified in the literature.

Relative Importance of NOM to BOD Concentrations in Reach 1

The relative importance of NOM to BOD concentrations in Reach 1 is not identified in the literature.

Ammonia Concentration

Point sources of ammonia to the San Joaquin River upstream of Vernalis include domestic wastewater discharges (300001773).

Factors Affecting Ammonia-Related BOD Concentrations in Reach 1

[To come.]

Relative Importance of Ammonia Concentration to BOD Concentration in Reach 1

[To come.]

Residence Time

[To come.]

Factors Affecting Residence Time in Reach 1

Factors affecting residence time in Reach 1 are described under Section 3.2.4.

Relative Importance of Residence Time to BOD Concentrations in Reach 1

[To come.]

Uncertainties

Uncertainties related to understanding how BOD concentrations in Reach 1 may affect dissolved oxygen concentrations in the DWSC include:

- sources and relative contribution of algal nutrients to algal biomass and BOD concentration in Reach 1;
- sources and effects of algal nutrients transported from Reach 1 on algal biomass and BOD concentrations in Reach 2;
- sources of algal biomass in Reach 1 (3000001997);
- sources and effects of turbidity on algal biomass (3000001245);
- sources of and relative contribution of NOM in Reach 1 to BOD concentrations;
- the effects of flow volume from Reach 1 on algal and NNC loads and dissolved oxygen concentrations in the DWSC (3000001179);
- sources, seasonality, and magnitude of algal biomass and NOM concentrations in Reach 1 that enter Reach 2;
- factors that affect BOD concentration in Reach 1; and
- the effect of BOD substances contributed from Reach 1 on BOD and SOD levels and dissolved oxygen concentrations in Reach 2.

Research to Address Uncertainties

Research needs identified in relevant literature are directed towards:

- improving the understanding of the link between algal sources in the upper San Joaquin River watershed and algal biomass entering the DWSC (3000001997);
- quantifying the NBOD loads, including ammonia, and algal nutrients entering the San Joaquin River upstream of Vernalis to determine the importance of Reach 1 NBOD concentrations on dissolved oxygen concentrations in the DWSC (300001773, 300001245, 300001112); and
- identifying and improving the understanding of the sources of nutrients, algae and BOD to Salt and Mud Sloughs, particularly potential inputs from agricultural drainage and managed wetlands (3000001260, 3000001468).

SOD Concentration

Secondary drivers affecting SOD concentration in Reach 1 are shown in Figure 3-3a.

Understanding of How Reach 1 SOD Concentrations may Affect Dissolved Oxygen Concentrations in the DWSC

[To come.]

Imported BOD and SOD Concentration

[To come.]

Factors Affecting Imported BOD and SOD Concentration in Reach 1

[To come.]

Relative Importance of Imported BOD and SOD Concentration to BOD Concentration in Reach 1

[To come.]

BOD Concentration

Algae and other BOD generating substances contribute to SOD concentration in Reach 1 when they settle out of the water column (see Sections 3.2.2.2 and 3.2.2.3).

Factors Affecting BOD Concentration on SOD Concentration in Reach 1

Factors affecting BOD concentrations in Reach 1 are described in Section 3.2.2.

Relative Importance of BOD Concentration on SOD Concentration in Reach 1

The relative importance of particulate BOD substances to SOD conentrations in Reach 1 is not identified in the literature.

Iron and Sulfate Compound Concentrations

[To come.]

Factors Affecting Iron and Sulfate Compound Concentrations on SOD Concentration in Reach 1

[To come.]

Relative Importance of Iron and Sulfate Compound Concentrations on SOD Concentration in Reach 1

The relative importance of iron and sulfate compound concentrations to SOD concentrations in Reach 1 are not identified in the literature.

Residence Time

[To come.]

Factors Affecting Residence Time in Reach 1

Factors affecting residence time in Reach 1 are described under Section 3.2.4.

Relative Importance of Residence Time to SOD Concentrations in Reach 1

[To come.]

Uncertainties

Uncertainties related to understanding how SOD concentrations in Reach 1 may affect dissolved oxygen concentrations in the DWSC include:

- the sources and relative contribution of BOD substances and iron and sulfate compound concentrations to SOD concentrations in Reach 1;
- BOD concentrations and iron and sulfate compound concentrations contributed from Reach 1 that contribute to SOD in Reaches 2 and 3; and
- contribution and importance of SOD concentration in Reach 1 to oxygen demand in Reach 2.

Research to Address Uncertainties

Research needs identified in relevant literature are directed towards determining if algae and organic detritus transported from Reach 1 to the DWSC during the winter and spring becomes SOD the following summer and fall (300001773) and to determining the sources of particulates in Reach 1 that become part of the DWSC SOD (300001773).

Residence Time

Secondary drivers affecting residence time in Reach 1 are shown in Figure 3-3b.

Understanding of How Reach 1 Residence Time may Affect Dissolved Oxygen Concentrations in the DWSC

Studies suggest that flow volume contributed from Reach 1 to the DWSC is an important factor affecting dissolved oxygen concentrations in the DWSC. Some results suggest that increasing San Joaquin River flow at Vernalis has a generally beneficial effect on dissolved oxygen conditions in the DWSC (300001294). When flows from Reach 1 entering Reach 2 at Vernalis decrease there is a subsequent decrease in dissolved oxygen concentrations in the San Joaquin River and therefore the DWSC (300001773). The diversions, particularly at the head of Old River, downstream of Vernalis are an important factor affecting the importance of flows upstream of Vernalis (300001773).

Flow Volume

Flow volume in Reach 1 is primarily governed by the timing and volume of flow contributed to the reach from tributaries and other sources and that is removed at diversions.

Sources of flow volume are shown in Figure 3-X (to come) and flow contributions are shown in Table 3-X (to come). Three eastside tributaries, the Merced, Tuolumne and Stanislaus Rivers, contribute 65 to 80 percent of the measured flow at Vernalis (300002003). Average daily flows in the San Joaquin River at Vernalis ranged from 1,638 cfs to 2,802 cfs in August 2000 and were around 1,300 cfs in October and November 2000, which is lower than usual (300001278, 300001138). San Joaquin River flows at Vernalis during June through November are much less variable than during the rest of the year (300001229). In 2002, the SJR flows at Vernalis were between 1,000 and 1,600 cfs from June through September and from 1,400 to 2,700 cfs during October and November (300001245).

Throughout most of the year the San Joaquin River gains water between the mouth of the Merced River and Vernalis, and groundwater inputs between Lander Avenue and Vernalis account for approximately 5 percent of the total flow in the San Joaquin River (300001039). Upstream of the Merced River/San Joaquin River confluence, the San Joaquin River mainly loses water to the adjacent groundwater aquifer (300001039). Irrigation return flows, which can enter the San Joaquin River either via surface water returns or groundwater accretions, are another source of flows to the San Joaquin River and can account for as much as 13 percent of the Reach 1 San Joaquin River flows (300001039).

Irrigation diversions from the San Joaquin River in June through August have a significant impact on the pattern of upstream to downstream loading rates, especially in the reach from Crows Landing to Maze Road (3000001229) (see Figure 3-X [to come]). Reach 1 diversions are summarized in Table 3-X [to come]. At times, upstream agricultural users divert up to 25 to 50 percent (1,000 to 2,000 cfs) of the San Joaquin River flow at Vernalis (300001245). Irrigation diversions are typically greatest during early to mid-summer and rapidly decline beginning in mid-August (300001039). Operation of south delta barriers also has the affect of increases flows past Vernalis and decreasing dissolved oxygen depletion in late summer and fall (300001278, 300001773).

[Additional information related to residence time to come.]

Factors Affecting Flow Volume in Reach 1

Factors affecting Reach 1 flow volume include timing and magnitude of annual precipitation and tributary reservoir releases (see Table 3-X [to come]) and timing and magnitude of water diversions (see Figure 3-X [to come] and Table 3-X [to come]).

Relative Importance of Flow Volume to Residence Time in Reach 1

Flow volume is the primary factor affecting residence time in Reach 1.

Channel Geometry

[To come.]

Factors Affecting Channel Geometry in Reach 1

[To come.]

Relative Importance of Channel Geometry to Residence Time in Reach 1

[To come.]

Uncertainties

[To come.]

Research to Address Uncertainties

[To come.]

Imported Dissolved Oxygen

[To come. This section will describe dissolved oxygen concentrations that are imported into Reach 1 from tributaries, return flows, and other sources.]

Reaeration

Secondary drivers affecting reaeration are shown in Figure 3-1b. Secondary drivers that support reaeration in Reach 1 are water temperature, wind, and residence time. The mechanisms through which wind affects reaeration rates are described in Section 2.2.5.1. Wind is a natural phenomenon that is not predictable or controllable and, as such, this secondary driver is not discussed further in this section. Seasonal dissolved oxygen concentrations of water in Reach 1 are shown in Table 3-X (to come). The proportion of dissolved oxygen concentrations that are derived from reaeration have not been identified.

Understanding of How Reaeration in Reach 1 may Affect Dissolved Oxygen Concentrations in the DWSC

The specific relationship between dissolved oxygen concentrations contributed through reaeration in Reach 1 and dissolved oxygen concentrations in the DWSC is not identified in the literature.

Water Temperature

Seasonal average water temperatures in Reach 1 at locations for which information is available are shown in Table 3-X (to come). Average temperatures of water contributed from Reach 1 to Reach 2 are shown in Table 3-X(to come).

Factors Affecting Water Temperature in Reach 1

Ambient air temperature, temperature of water entering Reach 1, and residence time are the primary factors affecting water temperature.

Relative Importance of Water Temperature to Reaeration in Reach 1

Water temperature is an important factor controlling reaeration rates because the amount of oxygen that can be dissolved in water is proportional to water temperature.

Residence Time

Flow volume and channel geometry affect reaeration rates in Reach 1 as described in Section 2.2.5.1. Sources, losses, and timing of flow in Reach 1 are described in Section 3.2.4.

Factors Affecting Residence Time in Reach 1

Factors affecting residence time in Reach 1 are described under Section 3.2.4.

Relative Importance of Residence Time to Reaeration in Reach 1

[To come.]

Uncertainties

Uncertainties related to understanding how reaeration rates in Reach 1 may affect dissolved oxygen concentrations in the DWSC include:

- effects of reaeration in Reach 1 on dissolved oxygen concentrations and oxygen demand in Reach 2.

Research to Address Uncertainties

No research needs related directly to reaeration in Reach 1 are identified in relevant literature.

Photosynthesis

Secondary drivers affecting photosynthesis are shown in Figure 3-2a. Factors affecting sunlight are described in Section 2.2.6.1. The amount of sunlight available for photosysnthesis is governed by factors that are generally not controllable and, therefore, this secondary driver is not discussed further in this section. The seasonal dissolved oxygen concentrations of water entering Reach 2 from Reach 1 are shown in Table 3-X (to come). The proportion of dissolved oxygen concentrations that are derived from photosynthesis have not been identified.

Understanding of How Photosynthesis in Reach 1 may Affect Dissolved Oxygen Concentrations in the DWSC

The specific relationship between dissolved oxygen concentrations contributed through photosynthesis in Reach 1 and dissolved oxygen concentrations in the DWSC is not identified in the literature.

Imported Algal Biomass

Potential sources of imported algal biomass are described in Section 3.2.2.2.

Factors Affecting Imported Algal Biomass in Reach 1

Factors affecting imported algal biomass are described in Section 3.2.2.2.

Relative Importance of Imported Algal Biomass on Photosynthesis in Reach 1

[To come.]

Algal Biomass

Algal biomass in Reach 1 is described in Section 3.2.2.3. As live algal biomass increases in Reach 1, the amount of oxygen produced through photosynthesis is expected to increase.

Factors Affecting Algal Biomass in Reach 1

Factors affecting algal biomass in Reach 1 are described in Section 3.2.2.3.

Relative Importance of Algal Biomass to Photosynthesis in Reach 1

The proportions of dissolved oxygen derived through photosynthesis from algae and other aquatic plants in Reach 1 has not been identified. Based information available for the study area, however, algae is probably the primary contributor of photosyntheically produced dissolved oxygen in Reach 1 (300001245).

Turbidity

[To come.]

Factors Affecting Turbidity in Reach 1

[To come.]

Relative Importance of Turbidity to Photosynthesis in Reach 1

[To come.]

Water Temperature

Seasonal average water temperatures in Reach 1 at locations for which information is available are shown in Table 3-X (to come). Average temperature of water contributed from Reach 1 to Reach 2 are shown in Table 3-X [to come].

Factors Affecting Water Temperature in Reach 1

Ambient air temperature, temperature of water entering Reach 1, and flow are the primary factors affecting water temperature.

Relative Importance of Water Temperature to Photosynthesis in Reach 1

[To come.]

Uncertainties

Uncertainties related to understanding how dissolved oxygen produced through photosynthesis in Reach 1 may affect dissolved oxygen concentrations in the DWSC include:

- effects of photosynthesis in Reach 1 on dissolved oxygen concentrations and oxygen demand in Reach 2; and

- sources and amounts of turbidity contributed from Reach 1 and its effects on dissolved oxygen produced through photosynthesis in Reaches 2 and 3.

Research to Address Uncertainties

No research needs related directly to photosynthesis in Reach 1 are identified in relevant literature.

Reach 2 (Vernalis to Channel Point)

The primary drivers affecting dissolved oxygen concentrations in Reach 2 (Figure 1-2a) are shown in Figure 3-4a.

Dissolved Oxygen and Oxygen Demanding Substances Contributed from Reach 2 to Reach 3

[To come.]

BOD Concentration

Secondary drivers affecting BOD concentration in Reach 2 are shown in Figure 3-5b.

Understanding of How Reach 2 BOD may Affect Dissolved Oxygen Concentrations in the DWSC

Diversions from Reach 2 can remove large volumes of algae biomass and therefore minimize the potential effects of algal biomass contributed from Reach 1 load on dissolved oxygen concentrations in the DWSC (3000001039). Consequently, when algal biomass from Reach 1is being diverted (primarily at Old River) the algal biomass generated in Reach 2 becomes much more important.

Studies suggest that additional information is needed to determine the importance of algal loads (CBOD loads) from Reach 2 on the dissolved oxygen concentrations in the DWSC. Although data suggests that algal loads in the DWSC are equally derived from growth in the DWSC and from sources upstream (3000001005, 3000001096), it is uncertain how much of the algal load entering the DWSC from the San Joaquin River is from algae grown between Vernalis and Channel Point and from algal inputs contributed from Reach 1. It has been observed that concentrations and loads of suspended materials, including algae, decrease between Vernalis and Channel Point (3000001054), which could indicate that Reach 1 CBOD loads are less important to DWSC dissolved oxygen concentrations than CBOD loads originated from Reach 2. This is supported by studies that found that algal species in Reach 2 are similar to those in the DWSC (3000001294) and that algal species carbon measured upstream of Vernalis is different from the species carbon measured downstream of Vernalis and in the DWSC (3000001054). One reason for the uncertainty about the importance of the Reach 2 CBOD loads is that the algal biomass dynamics in the San Joaquin River, including the potential settling and decay of algae and organic materials in Reach 2, are not well understood (3000001187, 3000001997).

Studies suggest that the Reach 2 NBOD loads may be a significant factor affecting the dissolved oxygen concentrations of the DWSC. A good indication that the RWCF is a significant source of NBOD is that when effluent from the RWCF contains high ammonia concentrations, the percentage of NBOD in the DWSC is higher (300001245, 300001005, 300001054, 300001112). The poor association between the organic nitrogen load from upstream and both dissolved ammonia concentration and NBOD was confirmed by correlation analysis and trend plots (300001054), and may support the significance of ammonia loads from the RWCF.

The ammonia load from upstream of the RWCF is only about 10 percent, but it could make a substantial contribution to oxygen demand if it increases during passage from Mossdale to downstream. However, one study indicates that the decay rate of the large upstream of Vernalis organic nitrogen load to dissolved ammonia is slow and most of the organic nitrogen highly decomposed before reaching the DWSC (300001054), thus ammonia loads from the RWCF may have a greater effect on the NBOD load in Reach 2. Thus, it is important to define the contribution of ammonia from upstream to measure its effect on low dissolved oxygen concentrations that violate the water quality objectives (300001245, 300001112). The San Joaquin Drainage Authority is conducting experiments to collect data to determine more accurately the liability of the soluble ammonia in this San Joaquin River reach and help determine the importance of NBOD loads from Reach 1 compared to NBOD loads from Reach 2 on DWSC dissolved oxygen concentrations. Understanding and predicting how fast ammonia is oxidized in this region is important to assigning the oxygen demand allocation between algal biomass and ammonia (300001385).

San Joaquin River flows and diversions can have a substantial impact on the importance of NBOD loads in Reach 2 and the timing of the NBOD exertion. As river flows move from Vernalis downstream to the DWSC, the oxygen demand load changes and decays. At residence times of 10 days or less a larger fraction of the oxygen demand is exported from the DWSC before it can exert its full potential. At 30 day or greater residence times most of the CBOD and NBOD is exerted within the DWSC (300001773, 300001245). Consequently, Reach 1 NBOD loads will contribute more dissolved ammonia to the DWSC and therefore be more significant than the Stockton RWCF at residence times of 10 days or greater (300001054). Higher river flows allow for more dilution of the discharge from RWCF and less time for decay (300000957, 3000001245). Thus the water diversions at Old River, which reduce flows through the DWSC and result in high ammonia loads, may substantially influence the dissolved oxygen depletion problem (300001245, 300001773).

Imported BOD Concentration

BOD concentrations and concentrations of BOD substances that are contributed from Reach 1 to Reach 2 are presented in Table 3-X [to come].

Factors Affecting Imported BOD Concentration in Reach 2

[To come.]

Relative Importance of Imported BOD Concentration to BOD Concentration in Reach 2

[To come.]

Algal Biomass

Algal biomass in this reach is dependent on algae produced within Reach 2 and algal biomass contributed from Reach 1. Some studies have found that tributaries to Reach 1 strongly influence the chlorophyll *a* (algal) concentrations within Reach 2 (3000002003). One study found that algal loads discharged into Reach 1 from Mud and Salt Sloughs continue to develop in the San Joaquin River such that 1 lb of algal oxygen demand in the San Joaquin River downstream of the sloughs results in 8 lbs of oxygen demand in Reach 2 (3000001245). In general it appears that algal loads (based on chlorophyll *a* concentrations) in Reach 2 are larger than those in Reach 1 (300002003). The primary sources of nutrients supporting algal growth in Reach 2 are the Stockton RWCF and the upstream agricultural discharges and drainage (3000001112).

The Stockton RWCF is a source of CBOD loads to Reach 2 of the San Joaquin River (300001476). Approximately half of the BOD discharged by the RWCF is CBOD (300001187). As indicated by measurements of VSS and CBOD in the Stockton RWCF effluent, most of the CBOD is from VSS (i.e. particulates) (300001062). Because the Stockton RWCF uses oxidation ponds (with a 30-day residence time) as their secondary treatment, all of the VSS that passes through the Stockton RWCF's air flotation treatment and sand filters is derived from algae growing in the oxidation ponds (300001062). Therefore, most of the measured CBOD loads from the Stockton RWCF are algal-derived. CBOD concentrations from the Stockton RWCF and the San Joaquin River are generally highest from June through September (300000957, 300001062). One study found that during August 1999 the Stockton RWCF discharged 3,000 lbs/day of CBOD (300001773). Another study found that CBOD loads from the Stockton RWCF varied with the discharge flow and ranged from 500 to 2,500 lbs/day in 2001 (300000940). The average CBOD load during June through October 2001 was approximately 800 lbs/day (300000940).

In general, algal loads, as indicated by chlorophyll *a* concentrations, increase between Vernalis and Channel Point in late May or early June and remain high until August (see Table 3-X [to come]). Beginning in August, the chlorophyll *a* concentrations begin to decline until October at which time the concentrations will remain generally low until the following spring (3000002003). Phaeophytin concentrations, an indication of dead algae, remain below the chlorophyll concentrations for most of the year except during the largest algal blooms in the San Joaquin River (3000002003).

Factors Affecting Algal-Related BOD in Reach 2

The limiting factor to algal growth in the San Joaquin River is light (3000002003, 3000001310) because nutrient concentrations are substantially greater than those concentrations that would limit algal growth (3000001245). Other factors affecting algal-related BOD in Reach 2 include algal and algal nutrient load contributed from Reach 1, discharge of algae from the Stockton RWCF and diversions. One study found that CBOD loads from the Stockton RWCF varied with the RWCF discharge flow (300000940). Diversions from Reach 2, including from Old River, can also remove large volumes of algal biomass (3000001039).

Studies have indicated that Reach 1 chlorophyll *a* loads can strongly affect the relative contribution of the Stockton RWCF and Reach 1 to the dissolved ammonia loads in the DWSC (300001914). Therefore, the importance of Reach 2 NBOD loads is dependent on algal loads upstream of Vernalis.

Relative Importance of Algal Biomass to BOD Concentration in Reach 2

The available information suggests that algal biomass is an important contributor to BOD concentrations in Reach 2.

NOM

Sources of NOM in Reach 2 include organic nitrogen compounds discharged from the Stockton RWCF (300001476) and from NOM contributed from Reach 1.

Factors Affecting NOM-Related BOD Concentration in Reach 2

[To come.]

Relative Importance of NOM to BOD Concentrations in Reach 2

The relative importance of NOM to BOD concentrations in Reach 2 is not identified in the literature.

Ammonia Concentration

The Stockton RWCF is a source of ammonia to Reach 2 (300001476). Studies have indicated that, in general, the Stockton RWCF discharges greater daily dissolved ammonia loads into Reach 2 than is contributed by Reach 1 (300001914). Approximately half of the BOD discharged by the RWCF is NBOD (300001187). NBOD concentrations from the Stockton RWCF and the San Joaquin River are generally highest from June through September (300000957, 300001062). One study found that during August 1999 the Stockton RWCF discharged 2,400 lbs/day of NBOD (300001773).

Factors Affecting Ammonia-Related BOD Concentrations in Reach 2

[To come.]

Relative Importance of Ammonia Concentration to BOD Concentration in Reach 2

[To come.]

Residence Time

High concentrations of BOD from the Stockton RWCF effluent are diluted by San Joaquin River flows before entering the DWSC (300000957, 300001062). When flows are low, ammonia concentrations are intensified. Seasonal increases in ammonia concentrations have been widely reported (30001245, 300001112, 300001005, 300001054).

One study suggests that when river flows are 300 cfs or less, the effects of the Stockton RWCF discharge are far more significant than when flows are above 800 cfs or greater (300001245) because the lower flows provide less dilution of the discharge (300000957). As river flows move from Vernalis downstream to the DWSC, the oxygen demand load changes and decays. At residence times of 10 days or less a larger fraction of the oxygen demand is exported from the DWSC before it can exert its full potential. At 30 day or greater residence times most of the CBOD is exerted within the DWSC (300001773, 300001245). Higher river flows allow for more dilution of the discharge from RWCF and less time for decay (300000957, 3000001245).

Factors Affecting Residence Time in Reach 2

Factors affecting residence time in Reach 2 are described under Section 3.3.4.

Relative Importance of Residence Time to BOD Concentrations in Reach 2

The available information suggests that residence time is an important contributor to BOD concentrations in Reach 2.

Uncertainties

Uncertainties related to understanding how BOD concentrations in Reach in Reach 2 may affect dissolved oxygen concentrations in the DWSC include:

- sources and relative contribution of algal nutrients to algal biomass and BOD concentration in Reach 2;
- sources, relative importance, and effects of algal nutrients transported from Reach 2 on algal biomass and BOD concentrations in Reach 3;
- the relative importance of imported algal biomass and algal biomass generated in Reach 2 on BOD concentration in Reach 2;
- sources and effects of turbidity on algal biomass;
- sources of and relative contribution of NOM in Reach 2 to BOD concentrations;
- sources, seasonality, and magnitude of algal biomass and NOM concentrations in Reach 2 that enter Reach 3;
- relative importance of ammonia, algal biomass, and NOM on BOD concentrations in Reach 2;
- algal mass dynamics, including the potential settling and decay of algae and organic materials in Reach 2 (3000001187, 3000001997).
- factors that affect BOD concentration in Reach 2; and
- the effect of BOD substances contributed from Reach 2 on BOD and SOD levels and dissolved oxygen concentrations in Reach 3.

Research to Address Uncertainties

Research needs identified in relevant literature are directed towards:

- obtaining a better understanding of the rates of reactions involving organic nitrogen and the seasonal patterns of NBOD discharges from the Stockton RWCF;
- obtaining a better understanding of flows on effluent ammonia discharges (300001254, 300001112).;
- determining the effect of nitrification rates on the oxidation of ammonia and the conditions controlling nitrification (300001245);
- determining why The ammonification and nitrification of large upstream loads do not mask the effects of small dissolved ammonia loads from the RWCF, but do not (300001245, 300001112); and
- analyzing the Stockton RWCF discharge records to construct a multi-year time series of flow and discharge concentrations of several key variables including nitrogen species (not only ammonia, but also organic nitrogen), $CBOD_u$ and dissolved oxygen to accurately characterize the seasonal trends of ammonia discharge from the RWCF (300001112).

SOD Concentration

Secondary drivers affecting SOD concentration in Reach 2 are shown in Figure 3-6a.

Understanding of How Reach 2 SOD may Affect Dissolved Oxygen Concentrations in the DWSC

The significance of Reach 2 sources of SOD is affected by the quantity of other sources of SOD, namely BOD from Reach 1 and algae grown in the DWSC. The SOD exerted in the DWSC is also likely greater during ebb flows because during flood tides the San Joaquin River flows are reduced or reversed and the loading of settling particles into the DWSC is therefore reduced (300001252). One study found that CBOD loads (and therefore potential SOD loads to the DWSC) from the Stockton RWCF varied with the RWCF discharge flow (300000940). Results of another study indicated that that oxygen demands from the RWCF and SOD are less important than the oxygen demand in the San Joaquin River (300001112).

Imported BOD and SOD Concentration

[To come.]

Factors Affecting Imported BOD and SOD Concentration to SOD Concentration in Reach 2

[To come.]

Relative Importance of Imported BOD and SOD Concentration to SOD Concentration in Reach 2

[To come.]

BOD Concentration

BOD generating substances contribute to SOD concentration in Reach 2 when they settle out of the water column. During the summer and fall of 2001, approximately 88 percent of the total solids in the Stockton RWCF discharge were organic materials that could contribute to SOD or BOD (300000940). Approximately half of the measured BOD in the discharge was in particulate form during the summer and fall of 2001 (300001021). Thus, the Stockton RWCF discharge may be an important source of SOD in Reach 2.

Factors Affecting BOD Concentration on SOD Concentration in Reach 2

Factors affecting BOD concentrations in Reach 2 are described in Section 3.3.2.

Relative Importance of Particulate BOD Concentration on SOD Concentration in Reach 2

[To come.]

Iron and Sulfate Compound Concentrations

[To come.]

Factors Affecting Iron and Sulfate Compound Concentrations on SOD Concentration in Reach 2

[To come.]

Relative Importance of Iron and Sulfate Compound Concentrations on SOD on SOD Concentration in Reach 2

The relative importance of iron and sulfate compound concentrations to SOD concentrations in Reach 2 are not identified in the literature.

Residence Time

[To come.]

Factors Affecting Residence Time in Reach 2

Factors affecting residence time in Reach 2 are described under Section 3.3.4.

Relative Importance of Residence Time to SOD Concentrations in Reach 2

[To come.]

Uncertainties

Uncertainties related to understanding how SOD concentrations in Reach 2 may affect dissolved oxygen concentrations in the DWSC include:

- the sources and relative contribution of BOD substances and iron and sulfate compound concentrations on SOD in Reach 2;
- quantities and relative importance of particulate SOD and resuspended sediments in the San Joaquin River between Vernalis and Channel Point (300001773);
- BOD concentrations and iron and sulfate compound concentrations contributed from Reach 2 that contribute to SOD concentrations in Reach 3; and

2. contribution and importance of SOD concentrations in Reach 2 on oxygen demand in Reach 3.

Research to Address Uncertainties

Research needs identified in relevant literature are directed towards:

- determining the importance of SOD inputs in Reach 2 on the dissolved oxygen concentrations in the DWSC and

Residence Time

Secondary drivers affecting residence time in Reach 2 are shown in Figure 3-6b.

Understanding of How Reach 2 Residence Time may Affect Dissolved Oxygen Concentrations in the DWSC

Increasing flow at Vernalis is thought to generally have a beneficial effect on dissolved oxygen conditions in the DWSC (300001294). Low San Joaquin River flows between Vernalis and Channel Point and their associated low dissolved oxygen concentrations in the DWSC are primarily controlled by the amount of San Joaquin River water that is diverted into the Old River Channel (300001773).

Citations support that flow in the Vernalis to Channel Point reach affects dissolved oxygen concentrations in the DWSC. Diversion of San Joaquin River flow down Old River has a significant effect on the magnitude and duration of dissolved oxygen depletion below the Water Quality Objectives (WQOs) in the DWSC during both the summer and fall. This diversion of San Joaquin River flow into the South Delta may be related to low dissolved oxygen problems in the DWSC (300001773). Another indication of the importance of the Old River diversion is that the maximum travel time for San Joaquin River flows between Channel Point and Turner Cut would be 8 days if the diversion did not exist (300001245).

Flow Volume

Flow volume in Reach 2 is primarily governed by the timing and volume of flow contributed from Reach 1, French Camp Slough, and Walker Slough from Reach 1, tributaries and other sources and that is removed at diversions. Discharges from the Stockton RWCF also contribute flow to Reach 2 (300001773, 300001914, 300001245, 300001468). Sources of flow volume and diversions are shown in Figure 3-X (to come) and flow contributions and diverted flow volumes are shown in Table 3-X (to come).

The hydraulic travel times between Mossdale, located approximately 15 miles upstream of Channel Point, and Channel Point are generally between one to two days at San Joaquin River flows greater than approximately 750 cfs (300001245). At San Joaquin River flows of 100 cfs or less, the hydraulic travel times range from approximately 10 to 15 days (300001245).

Operation of south delta barriers increases Reach 2 flows and decreases dissolved oxygen depletion in late summer and fall (300001278, 300001773). Water is diverted from Reach 2 by both state and federal pumps and Old River (300001096, 300002003). In 2002, the Old River diversion removed 30 to 96 percent of the lowest monthly San Joaquin River flow at Vernalis (300001245). The Old River diversion has the greatest impact on San Joaquin River flows during the summer and early fall before the Head of Old River Barrier is installed in the fall to increase San Joaquin River flows for fish (300000940).

Factors Affecting Flow Volume in Reach 2

Reach 2 flows are affected by flow volume received from Reach 1, diversions, operation of the south delta barriers, and pumping at state and federal pumps (300001245, 300001039, 300001237, 300001278, 300001773, 300002003).

Relative Importance of Flow Volume to Residence Time in Reach 2

The availabe information suggests that flow volume is an important factor affecting residence time in Reach 2.

Channel Geometry

[To come.]

Factors Affecting Channel Geometry in Reach 2

[To come.]

Relative Importance of Channel Geometry to Residence Time in Reach 2

[To come.]

Uncertainties

[To come.]

Research to Address Uncertainties

[To come.]

Imported Dissolved Oxygen
[To come. This section will describe dissolved oxygen concentrations that are imported into Reach 2 from Reach 1, tributaries, return flows, and other sources.]

Reaeration
Secondary drivers affecting reaeration are shown in Figure 3-4b. Secondary drivers that support reaeration in Reach 2 are water temperature, wind, and residence time. The mechanisms through which wind affects reaeration rates are described in Section 2.2.5.1. Wind is a natural phenomenon that is not predictable or controllable and, as such, this secondary driver is not discussed further in this section. Seasonal dissolved oxygen concentrations of water in Reach 2 are shown in Table 3-X (to come). The proportion of dissolved oxygen concentrations that are derived from reaeration have not been identified

Understanding of How Reaeration in Reach 2 may Affect Dissolved Oxygen Concentrations in the DWSC

The specific relationship between dissolved oxygen concentrations contributed through reaeration in Reach 2 and dissolved oxygen concentrations in the DWSC has not been identified.

Water Temperature

Seasonal average water temperatures in Reach 2 at locations for which information is available are shown in Table 3-X (to come). Average temperature of water contributed from Reach 2 to Reach 3 are shown in Table 3-X (to come).

Factors Affecting Water Temperature in Reach 2

Ambient air temperature, temperature of water entering Reach 2, and residence time are the primary factors affecting water temperature.

Relative Importance of Water Temperature to Reaeration in Reach 2

Water temperature is a primary factor controlling reaeration rates because the amount of oxygen that can be dissolved in water is proportional to water temperature.

Residence Time

Flow volume and channel geometry affect reaeration rates in Reach 2 as described in Section 2.2.5.1. Sources, losses, and timing of flow in Reach 1 are described in Section 3.3.4.

Factors Affecting Residence Time in Reach 2

Factors affecting residence time in Reach 2 are described under Section 3.3.4.

Relative Importance of Residence Time to Reaeration in Reach 2

[To come.]

Uncertainties

Uncertainties related to understanding how reaeration rates in Reach 1 may affect dissolved oxygen concentrations in the DWSC include:

- effects of reaeration in Reach 2 on dissolved oxygen concentrations and oxygen demand in Reach 3.

Research to Address Uncertainties

No research needs related directly to reaeration in Reach 2 are identified in relevant literature.

Photosynthesis

Secondary drivers affecting photosynthesis are shown in Figure 3-5a. Factors affecting sunlight are described in Section 2.2.6.1. The amount of sunlight available for photosysnthesis is governed by factors that are generally not controllable and, therefore, this secondary driver is not discussed further in this section. The seasonal dissolved oxygen concentrations of water entering Reach 3 from Reach 2 are shown in Table 3-X (to come). The proportion of dissolved oxygen concentrations that are derived from photosynthesis have not been identified.

Understanding of How Photosynthesis in Reach 2 may Affect Dissolved Oxygen Concentrations in the DWSC

The specific relationship between dissolved oxygen concentrations contributed through photosynthesis in Reach 2 and dissolved oxygen concentrations in the DWSC is not identified in the literature.

Imported Algal Biomass

Potential sources of imported algal biomass are described in Section 3.3.2.2.

Factors Affecting Imported Algal Biomass in Reach 2

Factors affecting imported algal biomass are described in Section 3.3.2.2.

Relative Importance of Imported Algal Biomass on Photosynthesis in Reach 2

[To come.]

Algal Biomass

Algal biomass in Reach 2 is described in Section 3.2.3.3. As live algal biomass increases in Reach 2, the amount of oxygen produced through photosynthesis is expected to increase.

Factors Affecting Algal Biomass

Factors affecting algal biomass in Reach 2 are described in Section 3.2.3.3.

Relative Importance of Algal Biomass to Photosynthesis

The proportions of dissolved oxygen derived through photosynthesis from algae and other aquatic plants in Reach 2 has not been identified. Based information available for the study area, however, algae is probably the primary contributor of photosyntheically produced dissolved oxygen in Reach 1 (300001245).

Turbidity

[To come.]

Factors Affecting Turbidity in Reach 2

[To come.]

Relative Importance of Turbidity to Photosynthesis in Reach 2

[To come.]

Water Temperature

Seasonal average water temperatures in Reach 2 at locations for which information is available are shown in Table 3-X (to come). Average temperature of water contributed from Reach 2 to Reach 3 are shown in Table 3-X [to come].

Factors Affecting Water Temperature in Reach 2

Ambient air temperature, temperature of water entering Reach 1, and flow are the primary factors affecting water temperature.

Relative Importance of Water Temperature to Photosynthesis in Reach 2

[To come.]

Uncertainties

Uncertainties related to understanding how dissolved oxygen produced through photosynthesis in Reach 2 may affect dissolved oxygen concentrations in the DWSC include:

- effects of photosynthesis in Reach 2 on dissolved oxygen concentrations and oxygen demand in Reach 3; and

- sources and amounts of turbidity contributed from Reach 2 and its effects on dissolved oxygen produced through photosynthesis in Reach 3.

Research to Address Uncertainties

No research needs related directly to photosynthesis in Reach 2 are identified in relevant literature.

Reach 3 (DWSC From Channel Point to Disappointment Slough)

The primary drivers affecting dissolved oxygen concentrations in Reach 3 (Figure 1-2a) are shown in Figure 3-7a.

Dissolved Oxygen and Oxygen Demanding Substances Contributed from Reach 3 to Downstream

[To come.]

BOD Concentration

Secondary drivers affecting BOD concentration in Reach 1 are shown in Figure 3-8b.

Understanding of How BOD Concentrations may Affect Dissolved Oxygen Concentrations in the DWSC

BOD has been postulated as being the cause of dissolved oxygen concentrations in the DWSC falling below the water quality objective (300001245). Studies suggest that additional information is required to determine the importance of CBOD loads in the DWSC on the DWSC dissolved oxygen concentrations. It has been suggested that algal loads and the importance of upstream sources of algal loads (and therefore CBOD loads) can vary significantly year to year (300001039). Some sources believe that recent algal-related oxygen demands in the DWSC are less important than they were in the 1970s (300001005). In addition, other studies suggest that CBOD loads in the DWSC are less important than NBOD loads in the DWSC (300001005) and that that most of the oxygen demand in the DWSC is caused by NBOD (300001245, 300001054). The large contribution of NBOD to oxygen demand in the Deep Water Ship Channel was identified as early as the late 1960s (McCarty 1969) (30001054). A study found that the 10-day CBOD was small compared to the total BOD in the DWSC and that the DWSC's total BOD was not correlated with CBOD (300001005). In addition, CBOD loads did not vary with the seasonal changes in the total BOD (300001914). However, the lower San Joaquin River dissolved oxygen model simulated that CBOD in the DWSC during 1999, 2000, and 2001 was 3,000 kg/d, which is nearly double the simulated NBOD of 1,600 kg/d (300001096).

Ammonia inputs from Reach 2 and the decomposition of algae produced in the DWSC and imported from Reach 2 are sources of NBOD in the DWSC. During August and September 1999, at least 60 percent of the NBOD loads in the DWSC were found to be from the San Joaquin River (300000999). The percentage of total BOD provided by NBOD varies by season, but is consistent the observed seasonal changes in total BOD (300001914). The relative contribution of the RWCF and upstream ammonia load to the dissolved ammonia concentration in the DWSC is strongly influenced by the ammonification rate. The rate of ammonia nitrification declines as water temperature lowers. Consequently, NBOD concentrations are less during the winter. The lower the temperature, the lower the rate of nitrification and the amount of ammonia in the DWSC and, at extremely low temperatures, nitrification will cease almost entirely (300000957, 300001245).

Imported BOD Concentration

Concentrations of BOD contributed to Reach 3 from Reach 2 are presented in Table 3-X [to come].

Factors Affecting Imported BOD Concentration in Reach 3

[To come.]

Relative Importance of Imported BOD Concentration to BOD Concentration in Reach 3

The available information suggests that BOD concentrations contributed from Reach 2 are a primary factor affecting dissolved oxygen concentrations in Reach 2.

Algal Biomass

Algal loads in the DWSC may be equally derived from growth in the DWSC and from sources upstream (300001005, 300001096). An additional source of algae to the DWSC is the Turning Basin (300000999). Nutrients in the DWSC are an order of magnitude above limiting levels for algal growth (300001054) and are derived from wastewater and agricultural runoff (3000001112). Thus, substantial algal productivity may occur within the DWSC (300000940). Based on phaeophytin and chlorophyll *a* concentrations, some sources indicate that most of the algae entering the DWSC from the San Joaquin River at Channel Point is already decaying (300000999). Immediately after entering the DWSC, approximately 60 percent of the phaeophytin (300001245) and 60 percent of the chlorophyll *a* (300001559) settles out of the water column and begins to decompose.

Algae may be an important source of oxygen demand in the DWSC. In fall 1999, the algae contributed between 10 and 100 percent of the oxygen deficit in the DWSC (300000999). The high concentrations of phaeophytin relative to chlorophyll *a* concentrations in the DWSC and its tributaries suggests that decaying algal biomass contributes significantly to oxygen demand in the DWSC (300000999).

One study found that at least 60 percent of the CBOD loads in the DWSC were from the San Joaquin River during August and September 1999 (300000999). Others have found that 30-50 percent of the total BOD in the DWSC was CBOD in 2000 and 2001 (300001914). In the DWSC, the primary cause of CBOD is the decomposition of organic matter (300001054).

Algae is also a potentially significant source of NBOD (300001302, 300001245, 30001054). Particulate organic matter (e.g., phytoplankton) comprise the largest fraction of BOD in the DWSC. Plankton respiration results from nitrification, which consumes oxygen. Large quantities of organic matter have been measured in the San Joaquin River as it enters the DWSC (300001302, 300001245, 30001054), which may indicate that algal biomass from upstream may be the primary source of NBOD in the DWSC rather than from algae produced within the DWSC.

Factors Affecting Algal-Related BOD Concentration in Reach 3

The primary limiting factor to algae growth in the DWSC is light (3000001005, 300000940, 3000001054, and 3000001096**)**. Light is the primary limiting factor of algal growth in the DWSC because required nutrients (nitrogen, phosphorus, silica) for algal growth are an order of magnitude above limiting levels (3000001054). The photic zone in the DWSC is generally restricted to a depth of 2 meters below the water surface because of high sediment suspension and turbidity (3000001005). Within this limited photic zone, the algae receive only approximately 20 percent of the surface irradiance (3000001005, 3000001054). Algae concentrations in the DWSC are also related to the settling rates (3000000957).

Relative Importance of Algal Biomass to BOD Concentration in Reach 3

The relative importance of algal growth to BOD concentrations in Reach 3 is not fully known but one study suggests that algal growth may be the most important factor affecting CBOD in Reach 3. In the DWSC, the primary cause of CBOD is the decomposition of organic matter (300001054). Algal growth, however, may be less important to concentrations of NBOD because NBOD is closely correlated to dissolved ammonia concentrations in the DWSC. Ammonia discharges from the Stockton RWCF in Reach 2 can substantially affect NBOD concentrations in the DWSC (300001245, 300001005, 300001054, 300001112). However, the importance of algal-related BOD may be affected by the composition of the algal biomass. One study suggests that live phytoplankton biomass decompose more quickly and account for more of the short-term BOD than more oxidized detrital or organic matter (300001914).

NOM

Sources of NOM in Reach 3 include inputs from the Turning Basin (300000999) and from Reach 2. One study found that approximately 65 percent of the NOM in the DWSC in August and September 1999 was derived from the upper San Joaquin River (300000999).

Factors Affecting NOM-Related BOD Concentration in Reach 3

Important factors affecting NOM-related BOD concentrations in Reach 1 are not identified in the literature.

Relative Importance of NOM to BOD Concentrations in Reach 1

The relative importance of NOM to BOD concentrations in Reach 1 is not identified in the literature.

Ammonia Concentration

NBOD concentrations are correlated to dissolved ammonia concentrations in the DWSC. Ammonia discharges from the Stockton RWCF into the San Joaquin River in Reach 2 can substantially affect NBOD concentrations in the DWSC (300001245, 300001005, 300001054, 300001112).

[Additional information to come.]

Factors Affecting Ammonia-Related BOD Concentrations in Reach 3

[To come.]

Relative Importance of Ammonia Concentration to BOD Concentration in Reach 3

[To come.]

Residence Time

At residence times of 10 days or less a larger fraction of the oxygen demand is exported from the DWSC before it can exert its full potential. At 30 day or greater residence times most of the CBOD is exerted within the DWSC (300001773, 300001245). Longer residence times also increases NBOD concentrations by providing greater time for the ammonification of organic nitrogen. Travel time of organic nitrogen from upstream to the DWSC varies depending on the time of year. During periods of high flow through the DWSC, there is not time for all organic nitrogen compounds to be ammonified and nitrified to nitrate before leaving the DWSC (300001245, 300001054).

Factors Affecting Residence Time in Reach 3

Factors affecting residence time in Reach 3 are described under Section 3.4.4.

Relative Importance of Residence Time to BOD Concentrations in Reach 3

The available information suggests that residence time is an important factor affecting BOD concentrations in Reach 3.

Uncertainties

Uncertainties related to understanding how CBOD loads generated in Reach 3 may contribute to low dissolved oxygen concentrations in the DWSC include:

- the relative importance of algal biomass contributed to Reach 3 from upstream sources to algal production within Reach 3 on dissolved oxygen concentrations;
- sources of and relative contribution of NOM and ammonia in Reach 3 to BOD concentrations;
- sources, seasonality, and magnitude of algal and NOM loads in Reach 2 that enter Reach 3;

- factors that affect BOD concentrations in Reach 3; and
- how the composition of the algal load to Reach 3 may affect the importance of algal-related BOD concentrations (300001914).

Research to Address Uncertainties

Research needs identified in relevant literature are directed towards:

- quantifying algal loads to the DWSC and the importance of upstream sources of algal loads (300001039);
- understanding the mechanisms by which carbonaceous and nitrogenous compounds are oxidized in the DWSC (300002060);
- quantifying BOD loads in stormwater runoff entering Reach 3 (300001245); and
- determining the importance of NBOD concentrations on dissolved oxygen concentrations in the DWSC. understanding the mechanisms by which nitrogenous compounds are oxidized in the DWSC (300002060); and

SOD Concentration

Secondary drivers affecting SOD concentration in Reach 3 are shown in Figure 3-9a.

Understanding of How SOD Concentrations may Affect Dissolved Oxygen Concentrations in the DWSC

SOD sources in the DWSC include particulate BOD and algae that settle from the water column to the bottom of the DWSC. The chemical oxidation reactions that occur when reduced forms of iron and sulfur come into contact with dissolved oxygen also act as sources of SOD. Sediments suspended in the water column as well as deposited or bedded sediments can exert an SOD (300001096). Thus, near-bottom waters in the DWSC, which tend to have higher concentrations of suspended sediments and are nearest to the bedded SOD, generally have lower dissolved oxygen concentrations than waters at the water surface or at mid-depth (300001245). In the DWSC between Channel Point and Turner Cut, SOD contributed approximately 2,000 lbs/day of oxygen demand (BOD_u) to the total BOD_u during the summer and fall of 2001 (300001245). The quantity of SOD in the DWSC decreases with distance downstream indicating that particulates in the water column continue to settle out as the water flows downstream (300001302). Although SOD is accepted as a dissolved oxygen sink in the DWSC, it is generally not considered a significant factor affecting dissolved oxygen concentrations in the

DWSC (300001302, 300001773, 300001096, 300001112) and has been estimated to contribute less than 10 percent of the overall DWSC oxygen demand (300001302).

In general, citations support that SOD influences dissolved oxygen concentrations in the DWSC (300001088, 300001245, 300001427, 300001054, 300001302, 300001690). However, there are differing opinions about the importance of SOD as a sink for dissolved oxygen in the DWSC. SOD is not considered a substantial sink of dissolved oxygen within the mainstem of the DWSC (300001302, 300001773, 300001096, 300001112). The major sinks were algae respiration and the decay of CBOD and volatile suspended solids (300001096). Contrary to the hypothesis that SOD is not a major sink of dissolved oxygen, the Chen and Tsai (1997) model suggests that SOD is a principal factor controlling DWSC dissolved oxygen concentrations (300001427). In addition, it has been found that SOD can remove 1,800 kilograms per day (kg/d) of dissolved oxygen from the DWSC, which is greater than the dissolved oxygen removed by NBOD (1,600 kg/d) and the 1,500 kg/d of dissolved oxygen input into the DWSC via photosynthesis (300001096).

Imported BOD and SOD Concentration

[To come.]

Factors Affecting Imported BOD and SOD Concentration in Reach 3

[To come.]

Relative Importance of Imported BOD and SOD Concentration to BOD Concentration in Reach 3

[To come.]

BOD Concentration

[To come.]

Factors Affecting BOD Concentration on SOD Concentration in Reach 3

Factors affecting BOD concentrations in Reach 3 are described in Section 3.4.2.

Additional factors that affect SOD concentrations related to BOD concentrations are factors that affect sediment resuspension and the quantity of particulates that settle to the bottom of the DWSC. Bedded sediments in the DWSC can be resuspended by tidal or river currents, organisms, stirring of the sediments, ship traffic, as well as biochemical reactions that occur in sediments that lead to gas formation, which stirs the sediments as the gas bubbles rise through the sediments (300001773). The quantity of particulates that settle to the bottom of the DWSC would be expected to increase with increasing inputs of particulate BOD (including algae) to the DWSC from the San Joaquin River. The particulate fraction of BOD in the DWSC has a greater effect on SOD than dissolved BOD because the particulate BOD is more likely to settle out of the water and contribute to SOD (300000940, 300001021). In addition, the particulate fraction of BOD likely has a longer residence time than dissolved BOD (300000940). Another potential factor affecting the settling and resuspension of sediments and SOD is the geometry of the DWSC (300001112).

Relative Importance of BOD Concentration on SOD Concentration in Reach 1

One study indicates that the relative importance of BOD concentrations to SOD concentrations compared to the importance of iron and sulfate compound concentrations is unknown (300001773).

Iron and Sulfate Compound Concentrations

[To come.]

Factors Affecting Iron and Sulfate Compound Concentrations on SOD Concentration in Reach 3

[To come.]

Relative Importance of Iron and Sulfate Compound Concentrations on SOD Concentration in Reach 3

One study indicates that the relative importance of iron and sulfate compound concentrations to SOD concentrations compared to the importance BOD concentrations of is unknown (300001773).

Residence Time

The quantity of SOD exerted in the DWSC varies depending on the tides. In general, higher tidal velocities can lead to an increased SOD in the near-bottom waters of the DWSC because they support the suspension of bedded sediments and hinder the settling of suspended sediments (300001245, 300001302). Water velocities in the DWSC during ebb tides, when the tidal flow is moving downstream, have been found to be approximately 25 to 30 percent higher than during flood tides, which indicates that more sediment resuspension likely occurs at the bottom of the DWSC during ebb flows (300001302). The SOD exerted in the DWSC is also likely greater during ebb flows because during flood tides the San Joaquin River flows are reduced or reversed and the loading of settling particles into the DWSC is therefore reduced (300001252). In addition, the SOD during ebb tides is likely higher than during flood tides because the sediment deposition rates are generally highest during ebb tides (300001252, 300001302).

Factors Affecting Residence Time in Reach 3

Factors affecting flow in Reach 3 are described under Section 3.4.4.

Relative Importance of Residence Time to SOD Concentrations in Reach 3

[To come.]

Uncertainties

Uncertainties related to understanding how SOD concentrations may affect dissolved oxygen concentrations in the DWSC include:

- importance of SOD on dissolved oxygen concentrations in the DWSC;
- sources, seasonality, and magnitude of BOD concentrations in Reach 2 that enter Reach 3 and contribute to SOD;
- factors that affect SOD concentrations in Reach 3; and
- the relative importance of iron and sulfate compound and particulate BOD concentrations to SOD in Reach 3.

Research to Address Uncertainties

Research needs identified in relevant literature are directed towards:

- quantifying algal load to the DWSC and the importance of upstream sources of algal loads to CBOD/NBOD loads (300001039) and ultimately SOD;

- identifying the relative significance of the BOD as a cause of SOD versus the chemical oxygen demand (iron and sulfate compounds) (300001773).

Residence Time
Secondary drivers affecting residence time in Reach 1 are shown in Figure 3-9b.

Understanding of How Residence Time may Affect Dissolved Oxygen Concentrations in the DWSC

Citations support that flow does contribute to dissolved oxygen in the DWSC Reach. Flow has been identified as one of the main factors affecting dissolved oxygen levels (300001427, 300001245, 300001112, 300001138, 300001146, 300001278, 300001294, 300001328, 300001484, 300001609, 300001666, 300001773, 300001807, 300001914, 300001922, 300001948, 300002003, 300002045). San Joaquin River flow that enters the DWSC has two opposing effects: increasing oxygen demand loads into the DWSC, and reducing the hydraulic residence time in the critical reach of the DWSC. It has been found that when San Joaquin River flows through the DWSC are above 2,000 cfs there are few dissolved oxygen depletion problems that result in violations of the dissolved oxygen water quality objectives (300001245, 300001088, 300001294, 300001328, 300001468, 300001484, 300001526, 300001559, 300001773, 300001807, 300002003). Under these low flow conditions the dissolved oxygen concentrations in the DWSC can decline to 1 or 2 mg/L (300001245, 300001773). A dissolved oxygen sag has been known to develop in the DWSC from Columbia Cut to Fourteen Mile Slough during low flow periods and, historically, the greatest oxygen deficits have been measured within the first 3 miles of the DWSC, downstream from the Port of Stockton (300001328, 300002045). The magnitude of flows entering the DWSC from the San Joaquin River can affect the location of the dissolved oxygen sag. During water year 1998, which had average daily flows at Vernalis ranging from approximately 4,500 to 6,500 cfs from August through October, the dissolved oxygen sag occurred between Columbia Cut and Fourteen Mile Slough and downstream of its historical location in the Rough and Ready Island area (300001328).

There are also citations that do not support that flow contributes to dissolved oxygen in the DWSC Reach. Despite exceptionally high San Joaquin River inflows into the eastern DWSC of 2,000 cfs, a dissolved oxygen depression occurred in the central channel from Columbia Cut to

Fourteen Mile Slough in August and early September 1998 (300001138, 300001146, 300001328). There were also times when San Joaquin River flows into the DWSC were below 1,000 cfs and the DWSC dissolved oxygen concentrations were not depleted below the WQO (300001773). Some results have indicated that nitrification exerted a greater effect on dissolved oxygen in the DWSC than flow or upstream algal biomass (300001294). It has also been speculated that reducing flows into the DWSC will not reduce the input of oxygen demanding materials because the DWSC is not a completely mixed system (300001468). Model results from the Statistical Model of Dissolved Oxygen Concentration in the San Joaquin River Stockton Deepwater Channel at Rough and Ready Island (300001294) also indicated that increasing flow would have less of a beneficial effect on dissolved oxygen than previously hypothesized.

Other citations suggest that additional study is required to determine the relationship between flows in the DWSC and dissolved oxygen concentrations in the DWSC. Because there are several factors that interact with dissolved oxygen in the San Joaquin River, it is difficult to observe any direct effects of flow on dissolved oxygen concentrations in the DWSC (300001427). Particularly, separating the effects of chlorophyll *a* from flow has been difficult (300001294). When San Joaquin River flows are between 500 and 1,500 cfs there is not a readily discernable relationship between those flows and dissolved oxygen depletion in the DWSC. Despite the generalized relationship between San Joaquin River flow and dissolved oxygen depletion in the DWSC presented by the Chen and Tsai (2002) model, DWSC monitoring data raises questions about the reliability of the Chen model results (300001468).

Flow Volume

The primary flow input to the DWSC is the San Joaquin River's flows, which enter the DWSC at Channel Point. Therefore, flows in the DWSC are strongly affected by diversions and flow inputs that affect San Joaquin River flows upstream of Channel Point. It is generally accepted that flows in the DWSC are a significant factor that affects the dissolved oxygen concentrations in the DWSC. San Joaquin River flow that enters the DWSC has two opposing effects: increasing oxygen demand loads into the DWSC, and reducing the hydraulic residence time in the critical reach of the DWSC. It has been found that when San Joaquin River flows through the DWSC are above 2,000 cfs there are few dissolved oxygen depletion problems that result in violations of the dissolved oxygen water quality objectives (300001245, 300001088, 300001294, 300001328, 300001468, 300001484, 300001526, 300001559, 300001773, 300001807, 300002003). Flow from the Sacramento River is also thought to be an important factor in reducing dissolved oxygen depletion within the DWSC because of its dilution of the San Joaquin River flow in the vicinity of Disappointment Slough/Columbia Cut (300001773).

The average tidal stage range in the DWSC is approximately 3 feet from high tide to low tide each day (300000957). This tidal stage results in a tidal flow at the USGS Stockton UVM station, at the Rough and Ready Island monitoring station and at Turner Cut of 2,500, 5,100, and 7,800 cfs, respectively (300000957). The tidal excursions at these three locations are, respectively, 2.8, 1.25, and 2 miles (300000957). Thus, water from the DWSC generally will move upstream into the San Joaquin River during flood tides. However, it is known that if San Joaquin River flows entering the DWSC are greater than the average tidal flows in the DWSC (i.e approximately 5,100 cfs) then the tidal flows will not move upstream (300000957).

Tidal flow in the DWSC can affect the location of the dissolved oxygen sag and mixing of the water column. During flood tides when the tidal flow is negative, the dissolved oxygen sag in the DWSC typically occurs farther upstream in the DWSC than during ebb tides. Tidal fluctuations and the resultant greater water column mixing can contribute to the elimination of dissolved oxygen sags (300001138). At DWSC flows less than 500 cfs, downstream tidal exchange with Sacramento River flows may increase dissolved oxygen concentrations in the DWSC upstream of Turner Cut (300000957). A relatively homogenous vertical dissolved oxygen profile can be created during flood or ebb tides, when the flow of water in the channel may permit mixing of the water column (300001252). However, during the summer months, warm air temperatures may cause the surface layer of the DWSC to become isolated from the mixing and allow algal growth in the afternoon that creates high dissolved oxygen concentrations at the water surface. Tidal flow has also been shown to have a strong influence on lateral dispersion in the DWSC (300001484).

Factors Affecting Flow Volume in Reach 3

[To come.]

Relative Importance of Flow Volume to Residence Time in Reach 3

[To come.]

Channel Geometry

[To come.]

Factors Affecting Channel Geometry in Reach 3

[To come.]

Relative Importance of Channel Geometry to Residence Time in Reach 3

[To come.]

Uncertainties

Uncertainties related to understanding how residence time may affect low dissolved oxygen concentrations in the DWSC include:

- the synergistic effects of various volumes, locations, and timing of flow and diversions and tides on dissolved oxygen levels in the DWSC (300001260, 300000940), and

- the daily relationship between flow and oxygen demand loads and dissolved oxygen deficits in the DWSC (300001245).

Research to Address Uncertainties

Research needs identified in relevant literature are directed towards:

- determining the relationship between flows in the DWSC and dissolved oxygen concentrations in the DWSC (300001427, 300001773), and

- determining the effects of chlorophyll *a* from effects of flow on dissolved oxygen concentrations (300001294).

Imported Dissolved Oxygen

[To come. This section will describe dissolved oxygen concentrations that are imported into Reach 3 from Reach 2, sloughs, return flows, and other sources.]

Reaeration

Secondary drivers affecting flow are shown in Figure 3-7b. Secondary drivers that support reaeration in Reach 3 are water temperature, wind, and residence time. The mechanisms through which wind affects reaeration rates are described in Section 2.2.5.1. Wind is a natural phenomenon that is not predictable or controllable and, as such, this secondary driver is not discussed further in this section. Seasonal dissolved oxygen concentrations of water in Reach 3 are shown in Table 3-X (to come). The proportion of dissolved oxygen concentrations that are derived from reaeration have not been identified.

Understanding of How Reaeration may Affect Dissolved Oxygen Concentrations in the DWSC

Reaeration will supply about 18 pounds of oxygen/acre/day based on an assumed DWSC reaeration transfer distance of 0.5 m/day and a dissolved oxygen deficit of 4 mg/l. There are about 250 acres of water surface area between Channel Point and Rough & Ready Island station, so the reaeration in this portion of the DWSC would be about 4,500 lbs/day. The dissolved oxygen concentration increase from one day of reaeration would be about 0.25 mg/l (i.e., 0.06 * 4 mg/l). This is only a moderate reaeration term compared with the Stockton RWCF and San Joaquin River loads of BOD. In addition to natural reaeration, the U.S. Army Corps of Engineers operates a mechanical reaeration device in Reach 3 at Channel Point that has a potential of adding about 2,000 lb/day of dissolved oxygen to the DWSC (300001245).

Results of two studies found that the amount of oxygen contributed from reaeration during the summers of 1999-2001 ranged from about 4,500 -5,500 lb/day (300001088, 300001773). Widening and deepening of DWSC has decreased the water surface area-to-water depth ratio, decreasing the natural reaeration efficiency of the channel compared to the pre-modified channel conditions (300002060). Stratification in the water column has also been cited as factor that can limit natural reaeration because it reduces the depth of the water column that is subject to mixing and exposure to the atmosphere (300001088).

Water Temperature

Seasonal average water temperatures in Reach 3 at locations for which information is available are shown in Table 3-X (to come). Average temperature of water contributed from Reach 2 to Reach 3 are shown in Table 3-X (to come).

Factors Affecting Water Temperature in Reach 3

Ambient air temperature, temperature of water entering Reach 3, and residence time are the primary factors affecting water temperature.

Relative Importance of Water Temperature to Reaeration in Reach 2

Water temperature is a primary factor controlling reaeration rates because the amount of oxygen that can be dissolved in water is proportional to water temperature.

Residence Time

Flow volume and channel geometry affect reaeration rates in Reach 3 as described in Section 2.2.5.1. Sources, losses, and timing of flow in Reach 3 are described in Section 3.4.4.

Factors Affecting Residence Time in Reach 3

Factors affecting flow in Reach 3 are described under Section 3.4.4.

Relative Importance of Residence Time to Reaeration in Reach 3

[To come.]

Uncertainties

Uncertainties related to understanding how reaeration may affect dissolved oxygen concentrations in the DWSC include:

- effects of channel geometry on reaeration and dissolved oxygen concentrations;
- causes of vertical stratification in the water column and effects on reaeration and dissolved oxygen concentrations;
- the significance of reaeration to dissolved oxygen concentrations throughout the year; and
- the oxygen transfer velocity of the DWSC.

Research to Address Uncertainties

[To come.]

Photosynthesis

Secondary drivers affecting photosynthesis are shown in Figure 3-8a. Factors affecting sunlight are described in Section 2.2.6.1. The amount of sunlight available for photosysnthesis is governed by factors that are generally not controllable and, therefore, this secondary driver is not discussed further in this section. The seasonal dissolved oxygen concentrations of water exiting Reach 3 are shown in Table 3-X (to come). The proportion of dissolved oxygen concentrations that are derived from photosynthesis have not been identified.

Understanding of How Photosynthesis may Affect Dissolved Oxygen in the DWSC

The specific relationship between dissolved oxygen concentrations contributed through photosynthesis in Reach 3 and dissolved oxygen concentrations in the DWSC has not been identified.

The euphotic zone of the DWSC, the portion of the water column receiving at least 1 percent of the surface irradiance, extends to approximately 2 meters below the water surface (300001005). Because light is required for photosynthesis and algal growth, algae can only grow in the DWSC up to a depth of 2 meters. Maximum specific production rates of algae in the DWSC during in-situ incubation experiments ranged from approximately 2 to 40 µg of oxygen/µg chlorophyll *a*/hr and generally declined from August through November (300001005). In in-situ incubation experiments, maximum specific production rates of approximately 20 µg of oxygen/µg chlorophyll *a*/hr generally occurred at light intensities ranging from 25 and 45 percent of the surface irradiance (300001005). However, the average surface light intensity within the DWSC euphotic zone is only 18 percent thereby indicating that algal growth in the DWSC is less than 25 percent of its maximum and affected by the suspended material in the DWSC (300001005).

[Additional information to come.]

Imported Algal Biomass

[To come.]

Factors Affecting Imported Algal Biomass in Reach 3

[To come.]

Relative Importance of Imported Algal Biomass on Photosynthesis in Reach 3

[To come.]

Algal Biomass

Algal biomass in Reach 3 is described in Section 3.4.2.3. As live algal biomass increases in Reach 3, the amount of oxygen produced through photosynthesis is expected to increase.

Factors Affecting Algal Biomass in Reach 3

Factors affecting algal biomass in Reach 3 are described in Section 3.4.2.3. Relative Importance of Algal Biomass to Photosynthesis in Reach 3

Algal biomass is the primary contributer of photosyntheically produced dissolved oxygen in Reach 3.

Turbidity

One study found that turbidity sufficiently reduced light penetration in the water column of the DWSC to reduce the influence of the rate of algal production on dissolved oxygen concentrations. High concentrations of suspended sediment restricted the euphotic zone to the upper 2 m of the DWSC (3000001054). Causes of dissolved oxygen crashes in the DWSC have not yet been determined, but it has been hypothesized that one potential cause may be related to pulses of high turbidy entering the DWSC that result in a subsequent reduction in algal photosynthesis (3000001468).

Factors Affecting Turbidity in Reach 3

[To come.]

Relative Importance of Turbidity to Photosynthesis in Reach 3

[To come.]

Water Temperature

Seasonal average water temperatures in Reach 3 at locations for which information is available are shown in Table 3-X (to come).

Factors Affecting Water Temperature in Reach 3

Ambient air temperature, temperature of water entering Reach 3, and residence time are the primary factors affecting water temperature.

Relative Importance of Water Temperature to Photosynthesis in Reach 3

[To come.]

Uncertainties

Uncertainties related to understanding how rates of photosynthesis in Reach 3 may contribute to low dissolved oxygen concentrations in the DWSC include:

- the contribution of in situ algal photosynthesis to dissolved oxygen concentrations in the DWSC (3000001054)

Research to Address Uncertainties

No research needs related directly to photosynthesis in Reach 3 are identified in relevant literature.

Chapter 4

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[Note to Reviewers: the bar code number indicated at the beginning of each reference corresponds to the bar code number citations indicated in the text of Chapters 1 through 3.]

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Chapter 5
Glossary of Terms and Units of Measure

Terms

303(d) List – Under Section 303(d) of the 1972 Clean Water Act, states, territories and authorized tribes are required to develop a list of water quality limited segments of water bodies subject to the Clean Water Act. These waters on the list do not meet water quality standards, even after minimum required levels of pollution control technology have been installed at point sources of pollution. The law requires that jurisdictions establish priority rankings for water bodies on the lists and develop action plans, called Total Maximum Daily Loads (TMDL), to improve water quality and restore of the water body to serve beneficial uses.

Algal Load – The amount of algae in a fixed volume of water. Live algal load is typically estimated using measurements of chlorophyll *a* and detrital algal load is typically estimated using measurements of phaeophytin pigment.

Ammonification - a biochemical process that converts organic nitrogen to ammonia (NH_3) or ammonium ($NH4^+$). This process is carried out by ammonifying bacteria.

Ammonifying Bacteria – bacteria in the river which convert organic nitrogen (nitrogen contained in organic chemicals within living or dead organic materials) to ammonia.

Basin Plan – A plan adopted by the Regional Water Quality Control Board that sets standards for a variety of constituents of water quality. The Water Quality Control Plan for the Sacramento River and San Joaquin River Basins contains standards for dissolved oxygen levels in the San Joaquin River. The long-term failure to attain these standards has led to inclusion of the Stockton Deep Water Ship Channel portion of the San Joaquin River to the 303(d) list of impaired water bodies for dissolved oxygen.

Biological Oxygen Demand or Biochemical Oxygen Demand (BOD) – Some living organisms in a water body utilize oxygen dissolved in the surrounding water for metabolism. BOD is a measure of the amount of dissolved oxygen that would be used by the organisms contained in a given volume of water. For the purposes of this conceptual model, BOD consists of two components, carbonaceous BOD and nitrogenous BOD. BOD levels are attained using laboratory tests.

BOD_5, BOD_{10} – BOD is measured using a laboratory test that lasts a certain number of days. Estimates of BOD based on tests lasting 5 days are denoted as BOD_5 and results based on tests lasting 10 days are denoted as BOD_{10}.

Carbonaceous Biological (or Biochemical) Oxygen Demand (CBOD) – organic chemicals are subject to biochemical decay and chemical conversion by bacteria. Organic matter and dead organisms in aquatic environments are degraded by bacteria using biochemical processes that remove dissolved oxygen from the surrounding water.

Deep Water Ship Channel (DWSC) – the portion of the San Joaquin River that has been altered by dredging to maintain a fixed depth of 35 feet and a fixed width of at least 250 feet to accommodate ship traffic for the Port of Stockton. The DWSC begins at Channel Point in Stockton and extends into San Francisco Bay.

Direction – in the Driver-Linkage-Outcome form of a conceptual model, direction is an attribute of a linkage that indicates whether increased input from a driver leads to increases (positive) or decreases (negative) in levels of an outcome.

Dissolved Oxygen – Oxygen molecules (O_2) dissolved in the water. Water has a capacity to hold dissolved oxygen that increases with pressure (thus deeper water can hold more oxygen) and temperature (colder water can hold more oxygen). The availability of dissolved oxygen is important for fish that "breathe" the dissolved oxygen through their gills, and for other aquatic species that require oxygen to live.

Dissolved Oxygen Depletion – reductions in the level of dissolved oxygen in the water body that occur when those factors reducing oxygen levels outweigh those factors increasing oxygen levels.

Driver – in the Driver-Linkage-Outcome form of a conceptual model, a factor known to influence an outcome through a linkage mechanism. For example, the rate of photosynthesis is a driver for dissolved oxygen, because the rate of photosynthesis of organisms in the water body directly affects the amount of dissolved oxygen. See also Primary Driver and Secondary Driver.

Euphotic Zone – The range of water depths in a water column that provide optimal conditions for aquatic plant growth. The range is different for different species.

Flow – the movement of water. Defined as the volume of water passing a point on the river in a given period of time. Often measured in cubic feet per second (cfs). Flow rates in the San Joaquin River are determined by the operation of upstream dams, natural hydrology, diversions from the river and its tributaries, return flows from agricultural and urban uses, and interactions between the river and adjacent groundwater basins.

Impairment – Inability for a body of water to provide for a beneficial use (e.g. drinking water, irrigation water, recreation, habitat) due to either excess quantities of a harmful water quality constituent (e.g. heavy metals, pesticides) or insufficient levels of a beneficial one (e.g. dissolved oxygen).

Importance - in the Driver-Linkage-Outcome form of a conceptual model, importance is an attribute of a linkage that indicates how much influence a driver has on the outcome. Importance is usually denoted in relative terms.

Linkage - in the Driver-Linkage-Outcome form of a conceptual model, the known or hypothesized mechanism by which the driver influences the outcome. For example, in the conceptual model for dissolved oxygen in the DWSC, CBOD is a primary driver. The linkage or mechanism that connects CBOD levels with dissolved oxygen levels is the biochemical pathways that break down CBOD and consume oxygen, decreasing dissolved oxygen levels. Linkages also have attributes associated with them, including direction, importance, and certainty. See also Primary Driver, Secondary Driver, importance, and uncertainty.

Net Flow – in an estuary, river flows are complicated by the juxtaposition of tidal flow cycles on top of the river flows. For instance, water in the tidally influenced section of the San Joaquin River has a net flow towards the ocean, but water actually moves back and forth with the tides. Net flow is the flow of the river with the tidal cycles removed.

Nitrification – a chemical or biochemical process that converts nitrogen in the form of ammonia (NH_3) to oxidized forms such as nitrites (NO_2) and nitrates (NO_3^-). In water, this process uses dissolved oxygen (O_2) from the water column and thus contributes to the depletion of dissolved oxygen levels.

Nitrifying Bacteria – bacteria in aquatic systems which convert ammonia to nitrites or nitrates, depleting dissolved oxygen in the process.

Nitrogenous Biological Oxygen Demand (NBOD) – A quantitative measure of the amount of oxygen required for the biological oxidation of nitrogenous material, such as ammonia nitrogen and organic nitrogen. NBOD is usually calculated by subtracting CBOD from total BOD.

Non-Algal Organic Matter (NOM) – sources of organic matter in the water other than algae.

Outcome – in the Driver-Linkage-Outcome form of a conceptual model, the desired end state of management actions, or the variable being measured. For example, in the conceptual model for dissolved oxygen in the DWSC, dissolved oxygen level is the outcome. See also Driver and linkage.

Oxidation Reaction – one half of a chemical reaction in which electrons are transferred from one substance to another (often called a redox reaction). The oxidation half involves the substance losing an electron. All oxidation reactions are paired with reduction reactions in which a substance gains and electron. Oxygen (O_2) is a strongly oxidizing substance.

Photosynthesis – a biochemical process carried out by plants by which light is converted to chemical energy stored in sugars. In the process carbon dioxide (CO_2), water, and light are used and sugars and oxygen (O_2) are generated.

Primary Driver - a factor known to influence the principle outcome through a linkage mechanism. For example, in the conceptual model for dissolved oxygen in the DWSC, dissolved oxygen levels are the primary outcome, and the rate of photosynthesis is a primary driver, because the rate of photosynthesis of organisms in the water body directly affects the amount of dissolved oxygen. See also Driver and Secondary Driver.

Reaeration –Oxygen in the atmosphere exchanges with dissolved oxygen in the surface layer of water bodies. When water bodies have low levels of dissolved oxygen, the exchange tends to favor the movement towards the water and is called reaeration. The amount of reaeration depends on the amount of water surface area in contact with the atmosphere. Higher flows can lead to turbulence which increases the surface area of the water and increases reaeration.

Reduction Reaction – one half of a chemical reaction in which electrons are transferred from one substance to another (often called a redox reaction). The reduction half involves the substance gaining an electron. All reduction reactions are paired with oxidation reactions in which a substance loses and electron.

Residence Time –the amount of time that a molecule of water remains in a water body prior to exiting. Residence time is a measure of the amount of net flow in a river or lake.

Secondary Driver - a factor known to influence the outcome through an indirect linkage mechanism involving a primary driver. For example, in the conceptual model for dissolved oxygen in the DWSC, sunlight is a secondary driver, because it influences dissolved oxygen levels indirectly by influencing the rate of photosynthesis which, in turn, influences dissolved oxygen levels. See also Driver and Primary Driver.

Sediment Oxygen Demand (SOD) – the rate of oxygen consumption exerted by the bottom sediment on the overlying water. SOD is generated both by the oxidation of inorganic compounds such as iron and sulfur contained in sediments and by the decay of organic materials in the sediments.

Total Maximum Daily Load (TMDL) - the maximum amount of pollution that a waterbody can assimilate without violating state water quality standards. In this process, the state identifies the particular pollutant(s) causing the water not to meet standards. The process involved in developing a TMDL, in simplified form, involves
prioritizing waters that do not meet standards for TMDL development, establishing TMDLs (set the amount of pollutant that needs to be reduced and assign responsibilities) for priority waters to meet state water quality standards, developing strategies for reducing water pollution and assess progress made during implementation of the strategy.

Turbidity - a condition in water caused by the presence of suspended matter, resulting in the scattering and absorption of light. Turbidity limits the penetration of light into the water column, limiting the growth of organisms dependent on photosynthesis.

Uncertainty - in the Driver-Linkage-Outcome form of a conceptual model, uncertainty is an attribute of a linkage that indicates how well the relationship between the driver and the outcome is understood. Two types of uncertainty can be considered, that associated with a lack of scientific understanding of the mechanism, and that associated with changes in the importance of a mechanism over time. Uncertainty is usually denoted in relative terms.

Units of Measure

Acre-Foot – unit of measure for water volume. The amount of water which would cover an acre of land to a depth of one foot. Equal to 325,851 gallons.

cfs – cubic feet per second. Unit of measure of the rate of flow of water.

lb/day – pounds per day. Unit of measure for the rate of addition of a substance to a water body. Used to measure the addition of oxygen to water.

mg/l – milligrams per liter. Unit of measure of concentration, for instance of a contaminant in water. One grams is equal to 1,000 milligrams. This is equal to 1 part per million.

:g/l – micrograms per liter. Unit of measure of concentration, for instance of a constituent in water. One gram is equal to 1,000,000 micrograms. Used to measure very small concentrations. This is equivalent to 1 part per billion.

:S/cm – microsiemens per centimeter. A measure of the electro-conductivity of water, which is an indirect measure of the concentration of the salinity of the water. Also measured in :mhos per centimeter.