Low Dissolved Oxygen Levels in the Stockton Deep Water Shipping Channel

Adverse Effects on Salmon and Steelhead and Potential Beneficial Effects of Raising Dissolved Oxygen Levels with the Aeration Facility

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Introduction

In 2008, the Department of Water Resources implemented the Stockton Deep Water Ship Channel Demonstration Dissolved Oxygen Aeration Facility Project. The project is designed to evaluate the effectiveness of using an aeration facility to increase dissolved oxygen levels in the Stockton Deep Water Ship Channel. The objective of the study is to maintain dissolved oxygen levels above the minimum recommended levels specified in the Water Quality Control Plan for the Sacramento River and San Joaquin River Basins (CVRWQCB 2009). The plan specifies water quality objectives for the San Joaquin River between Turner Cut and Stockton of 6.0 milligrams per liter (mg/L) for September 1 through November 30, and 5.0 mg/L the rest of the year. For a description of the aeration system, including background and status visit http://baydeltaoffice.water.ca.gov/sdb/af/index_af.cfm or contact the Department of Water Resources, Bay-Delta Office.

The purpose of this paper is to summarize historic findings of adverse effects of low dissolved oxygen levels on salmon and steelhead, and describe the potential benefits of raising dissolved oxygen levels for those species.

Background

The lower San Joaquin River flows north through Stockton and into the Sacramento-San Joaquin Delta, upstream of San Francisco Bay and the Pacific Ocean. The river connects the global economy to the Port of Stockton through a 78-mile long Deep Water Shipping Channel that was first dredged in the 1930s (Figure 1). The channel serves as a shipping corridor for cargo ships, but also as a migration corridor for anadromous fish. Fall-run Chinook salmon and steelhead navigate through the altered channel to the tributaries of the San Joaquin River where their life cycle began.

Chinook salmon that use the San Joaquin River basin exhibit a fall-run life history strategy (Yoshiyama and others 1998) which means adults migrate upstream from September – January, and juveniles migrate downstream and rear in the Delta March through June (Cuthbert and others 2010; Moyle 2002; Yoshiyama and others 1998). Steelhead adults are migrating into the San Joaquin River July through March, and juveniles migrate downstream and rear in the Delta November through July (NMFS 2009).

By 1963, resource agencies discovered that water quality issues in the lower San Joaquin River were affecting the annual migration of adult Chinook salmon. The problem was documented in a 1964 report titled “Problems of the Lower San Joaquin River Influencing the 1963 Salmon Run”, which summarized water quality issues associated with poor salmon returns, including low dissolved oxygen levels:

> “Dissolved oxygen sags in the lower San Joaquin River area are historically caused primarily by waste discharges – cannery wastes are suspected as the key problem

during the fall period. This problem is made more acute by the limited downstream flow in the San Joaquin River past Stockton."

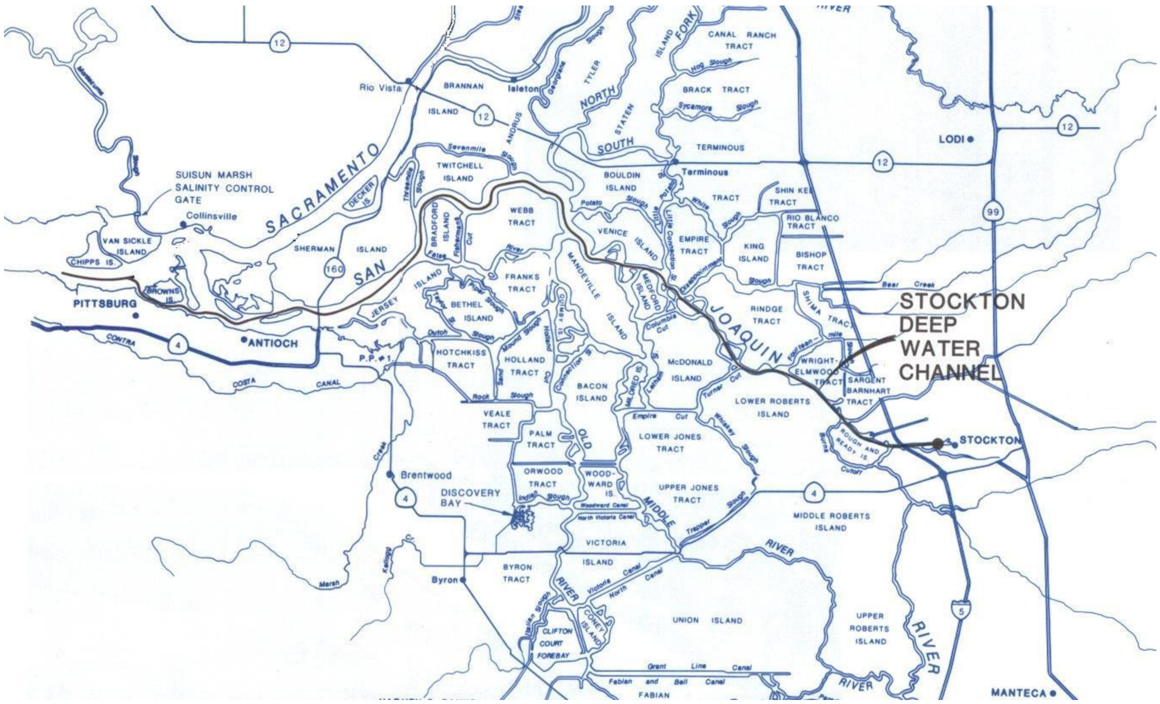


Figure 1. Stockton Deep Water Ship Channel in the South Delta

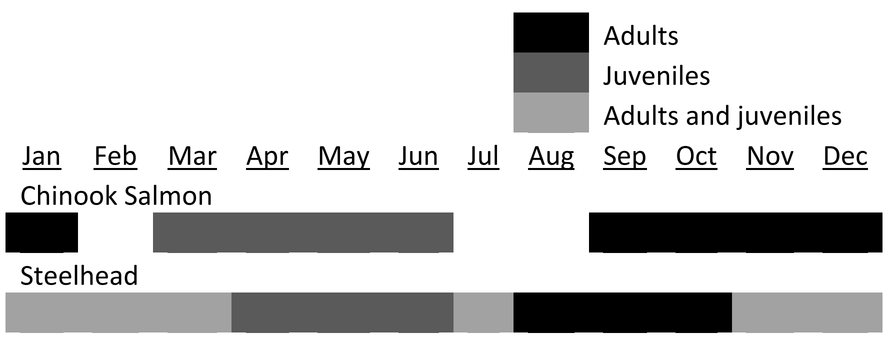


Figure 2. Possible salmon and steelhead occurrence in the Stockton Deep Water Ship Channel (Cuthbert and others 2010; NMFS 2009; Yoshiyama and others 1998)

As a result of poor water quality coinciding with collapse of the San Joaquin salmon run, resource agencies began water quality and biological monitoring. Department of Fish & Game (DFG) biologists monitored fish movement from 1964 through 1967 by releasing fish with sonic tags in the central part of the Delta. A goal of the study was to determine the reaction of salmon to low oxygen levels. The study was detailed in *Migrations of Adult King Salmon* *<u>Oncorhynchus tshawytscha</u>* *in the San Joaquin Delta as Demonstrated by the Use of Sonic Tags* (Hallock and others 1970). The study would serve as a foundation for setting dissolved oxygen criteria in the lower San Joaquin River. Some key passages from the 1970 report are:

> "From 1964 through 1967, salmon tagged with sonic tags were released in the central part of the Delta to determine their reaction to low oxygen levels and reversed flows. Electronic equipment enabled us to follow tags by boat and to record their movement past fixed points. Salmon avoided water with less than 5 [mg/L] dissolved oxygen by staying farther downstream until the oxygen block cleared."
>
> "In 1965, 1966, and 1967, dissolved oxygen concentration seems to have been the factor that controlled the movement of the first salmon past Stockton. In each year, no tagged fish appeared above Stockton until the lowest dissolved oxygen reading below Stockton had risen above 4.2 [mg/L], and in none of these three years did the first fish fail to appear by the time dissolved oxygen had increased to 5.0 [mg/L]."
>
> "Although the number of observations is relatively small, it would appear that a few fish will go through water containing a little less than 5.0 [mg/L] dissolved oxygen, but the bulk of the salmon will not migrate until the oxygen concentration is 5.0 [mg/L], or preferably more."
>
> "Less than 4.5 [mg/L] of oxygen should be regarded as a total or near total block and less than 5 [mg/L] as a partial block [to upstream migration]."

Figures 3 – 8 seem to support DFG's conclusions. The figures show the overlap of the first two months of the 6.0 mg/L dissolved oxygen requirement and a portion of the salmon migration period in 2003 - 2008. When interpreting the figures, the reader should keep in mind the following information:

- The data for salmon come from a weir operated on the Stanislaus River which traps upstream migrants.
- The dissolved oxygen and water temperature data are daily average values collected in the Stockton Deep Water Ship Channel near Rough and Ready Island. The water quality instrument was fixed at a water depth of 1 meter.
- There are two dissolved oxygen lines on the graphs: one for the 5.0 mg/L level discussed by Hallock and others (1970), and one for the dissolved oxygen standard required by the Sacramento San Joaquin Basin Plan.

Figures 3 – 8 show that the beginning of the migration season for spawning fall-run Chinook coincides with elevated water temperatures and low dissolved oxygen levels. The biological effects of elevated water temperatures are compounded by low dissolved oxygen levels. As water temperature rises, the metabolic rates of salmon and steelhead increase, thus increasing their demand for oxygen (Ebersole and others 2001). Since the goal of this paper is to describe effects of low dissolved oxygen levels, it is best to separate low dissolved oxygen levels and high water temperatures. Therefore, if dissolved oxygen levels are suitable, but water temperature is above 70.0°F, a migration barrier may still exist. Portions of the graphs have been shaded to display periods when water temperature exceeds 70.0°F.

The graphs show that elevated water temperatures in the lower San Joaquin River are not a complete barrier for adult Chinook salmon. There may be several reasons for this. Hallock and others (1970) found that fewer salmon migrated upstream when water temperatures were above 70.0°F; indicating that 70.0°F can create a partial, rather than complete, migration barrier for salmonids in the Delta. Results from laboratory studies indicate that water temperatures ranging from 66.2-86.0°F cause obvious signs of thermal stress and significant disturbances in normal behavior in rainbow trout (Elliott 1981). But the appearance of thermal stress is affected by the period of exposure and acclimation temperature. Strange (2010) found that if adult Chinook salmon migration had not begun, temperatures above 73.4°F completely blocked migration; but if adults were already migrating upstream and temperatures increased to 73.4°F, the fish continued moving upstream without stopping.

The dissolved oxygen levels shown in Figures 3-8 are daily average values. Dissolved oxygen levels fluctuate over the course of a day (Figure 9). Even though the daily average dissolved oxygen level may be less than 6.0 mg/L there may be portions of the day when values are at or greater than 6.0 mg/L providing periods of time suitable for salmonid passage. Elevated dissolved oxygen levels in the Stockton Deep Water Ship Channel could alleviate some lethal effects from elevated water temperatures, and furthermore, it is more feasible to physically raise dissolved oxygen levels than it is to lower water temperatures.

Adverse Effects on Salmonids

This section reviews the potential adverse effects of low dissolved oxygen on Chinook salmon and steelhead as presented in the ICF International biological effects model. ICF International created the "Biological and Ecological Effects Model" under the guidance and support of the California Bay-Delta Authority, Ecosystem Restoration Program to examine adverse effects of low dissolved oxygen on fish. The model can be reviewed at the following web address: http://www.sjrdotmdl.org/concept_model/bio-effects_model/effects_home.htm or contact the Department of Water Resources Bay-Delta Office.

Potential adverse effects include direct effects as well as indirect effects. Some direct effects may occur immediately within the Stockton Deep Water Ship Channel such as mortality, reduced swimming performance, and altered behavior. Other effects such as reduced spawning success, reduced fertility, and impaired development may manifest when the fish have left the Delta.

Direct Adverse Effects

The direct adverse effects evaluated in this paper are behavioral or physiological responses of fish that occur as a result of exposure to low levels of dissolved oxygen.

Figure 3. 2003 Fall-Run Chinook Salmon Migration Timing and Dissolved Oxygen Content in the San Joaquin River

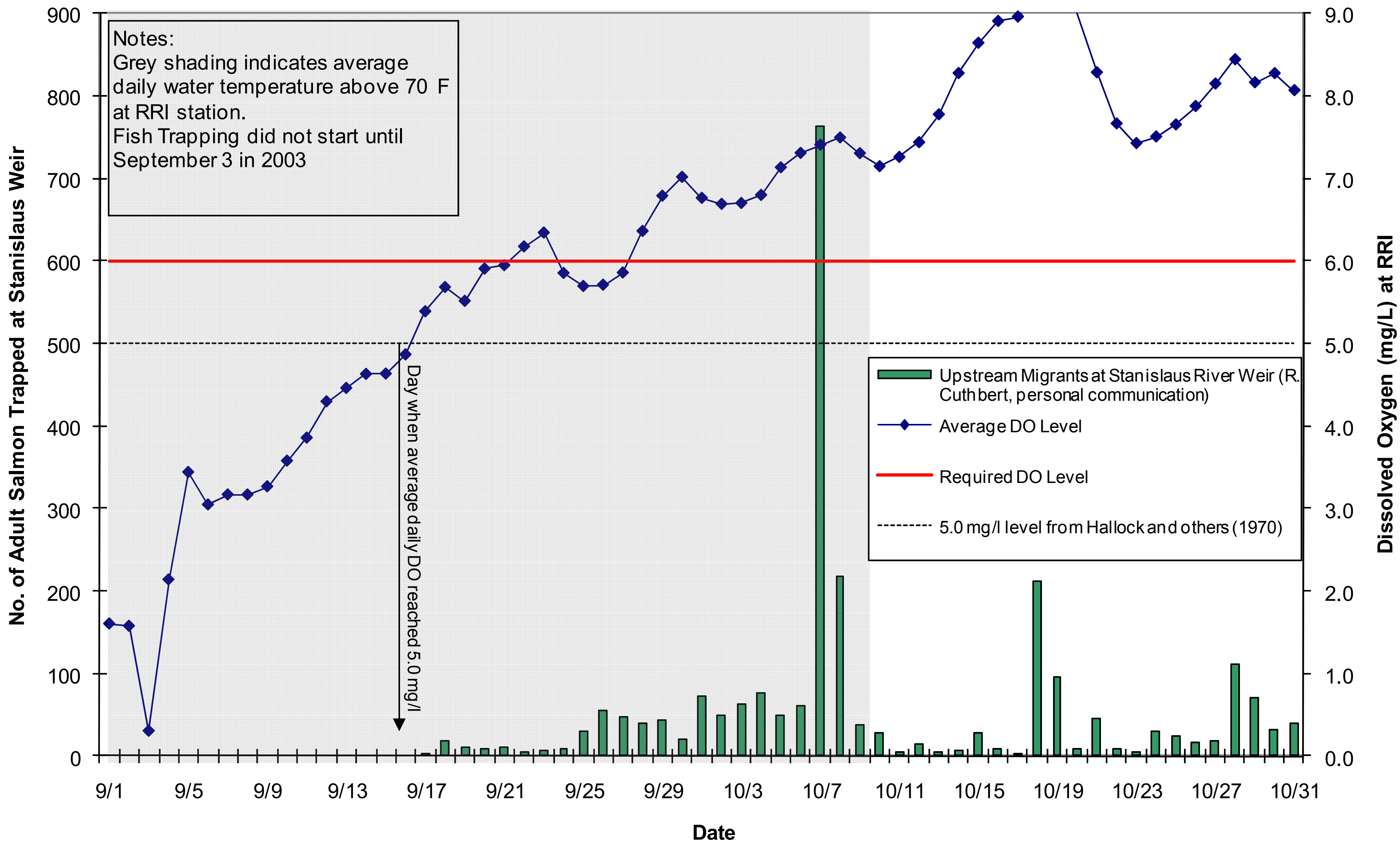
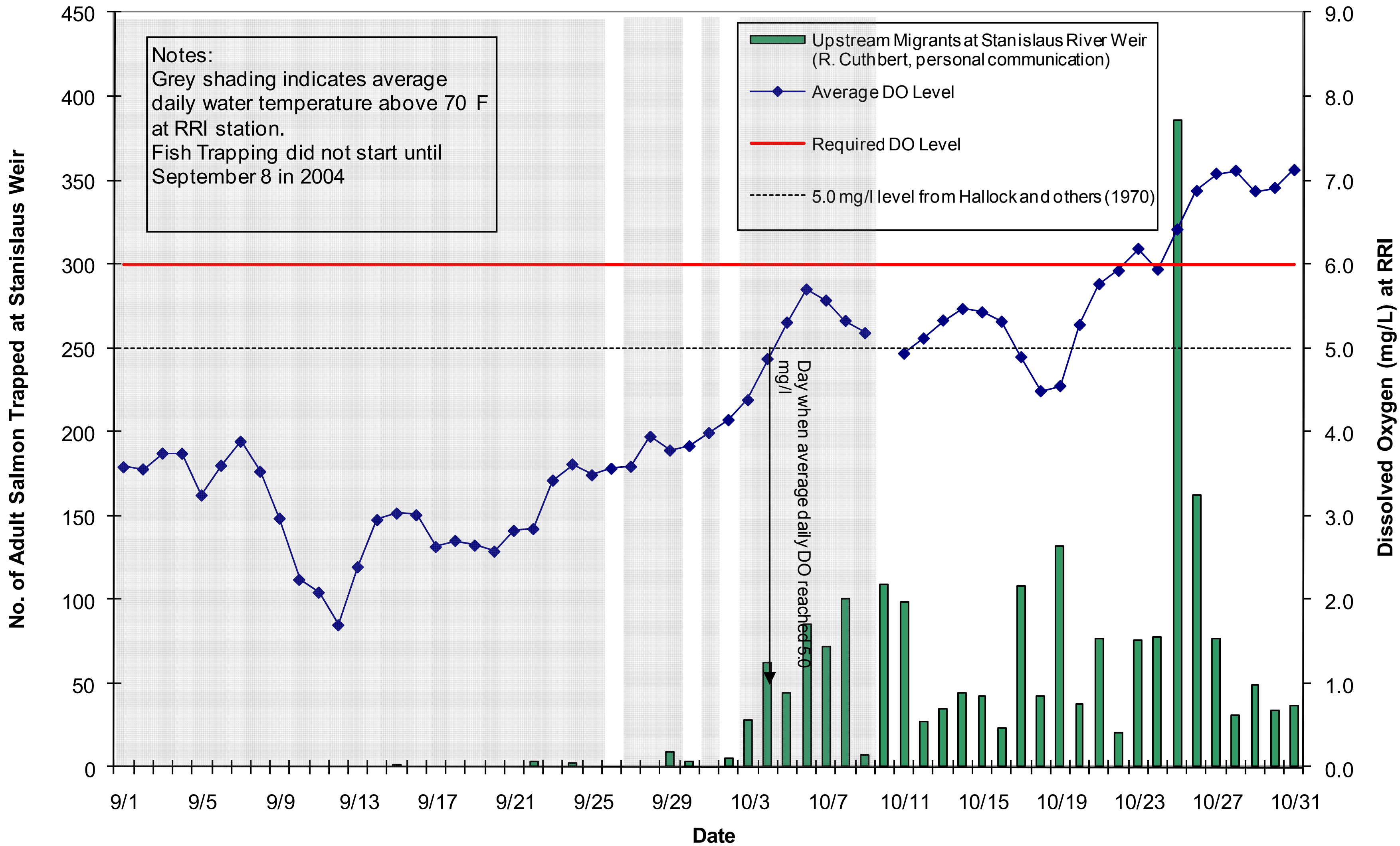


Figure 4. 2004 Fall-Run Chinook Salmon Migration Timing and Dissolved Oxygen Content in the San Joaquin River



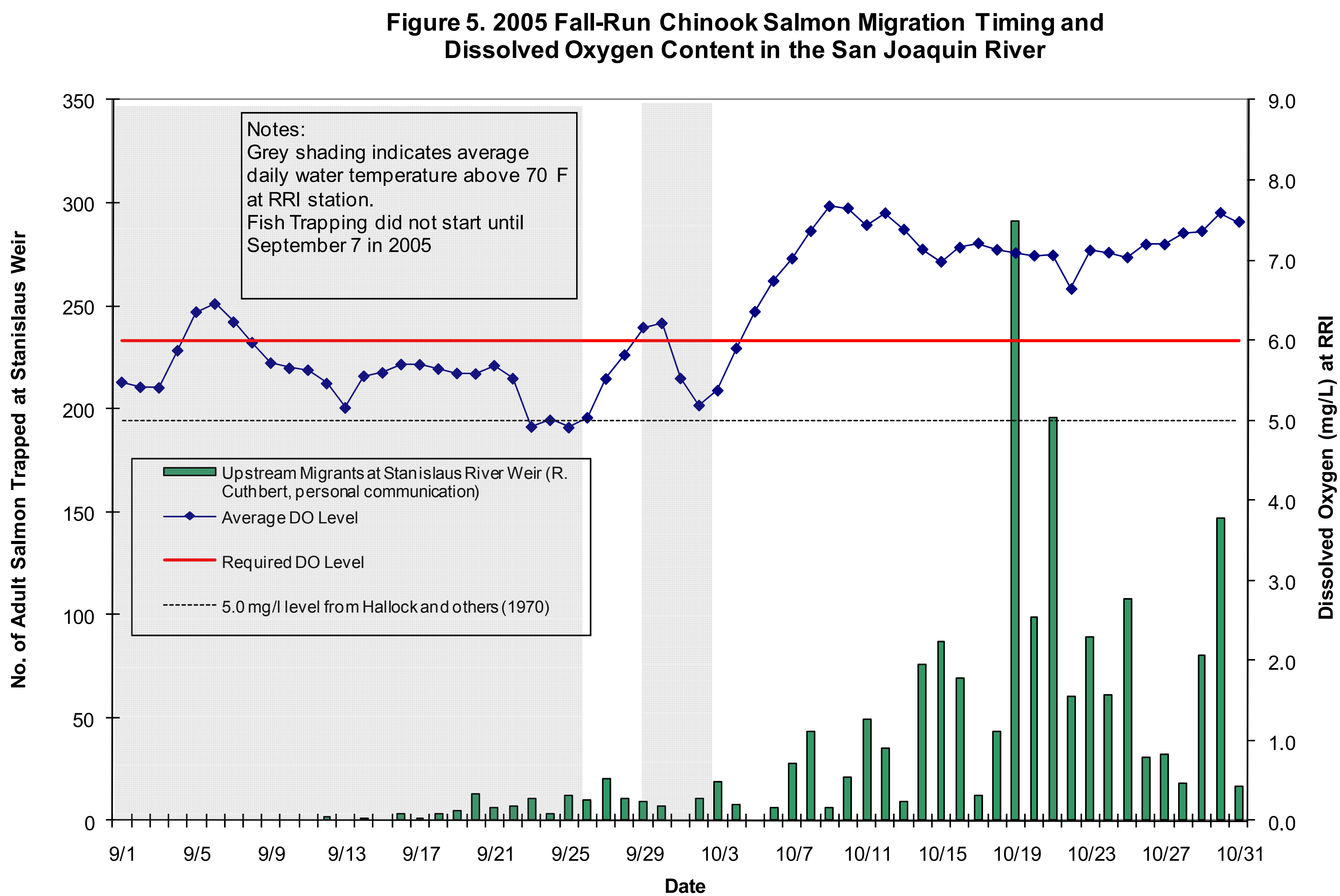


Figure 5. 2005 Fall-Run Chinook Salmon Migration Timing and
Dissolved Oxygen Content in the San Joaquin River
Notes:
Grey shading indicates average daily water temperature above 70 F at RRI station.
Fish Trapping did not start until September 7 in 2005
Upstream Migrants at Stanislaus River Weir (R. Cuthbert, personal communication)
Average DO Level
Required DO Level
5.0 mg/l level from Hallock and others (1970)
No. of Adult Salmon Trapped at Stanislaus Weir
Dissolved Oxygen (mg/L) at RRI
Date
350
300
250
200
150
100
50
0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
9/1
9/5
9/9
9/13
9/17
9/21
9/25
9/29
10/3
10/7
10/11
10/15
10/19
10/23
10/27
10/31

Figure 6. 2006 Fall-Run Chinook Salmon Migration Timing and Dissolved Oxygen Content in the San Joaquin River

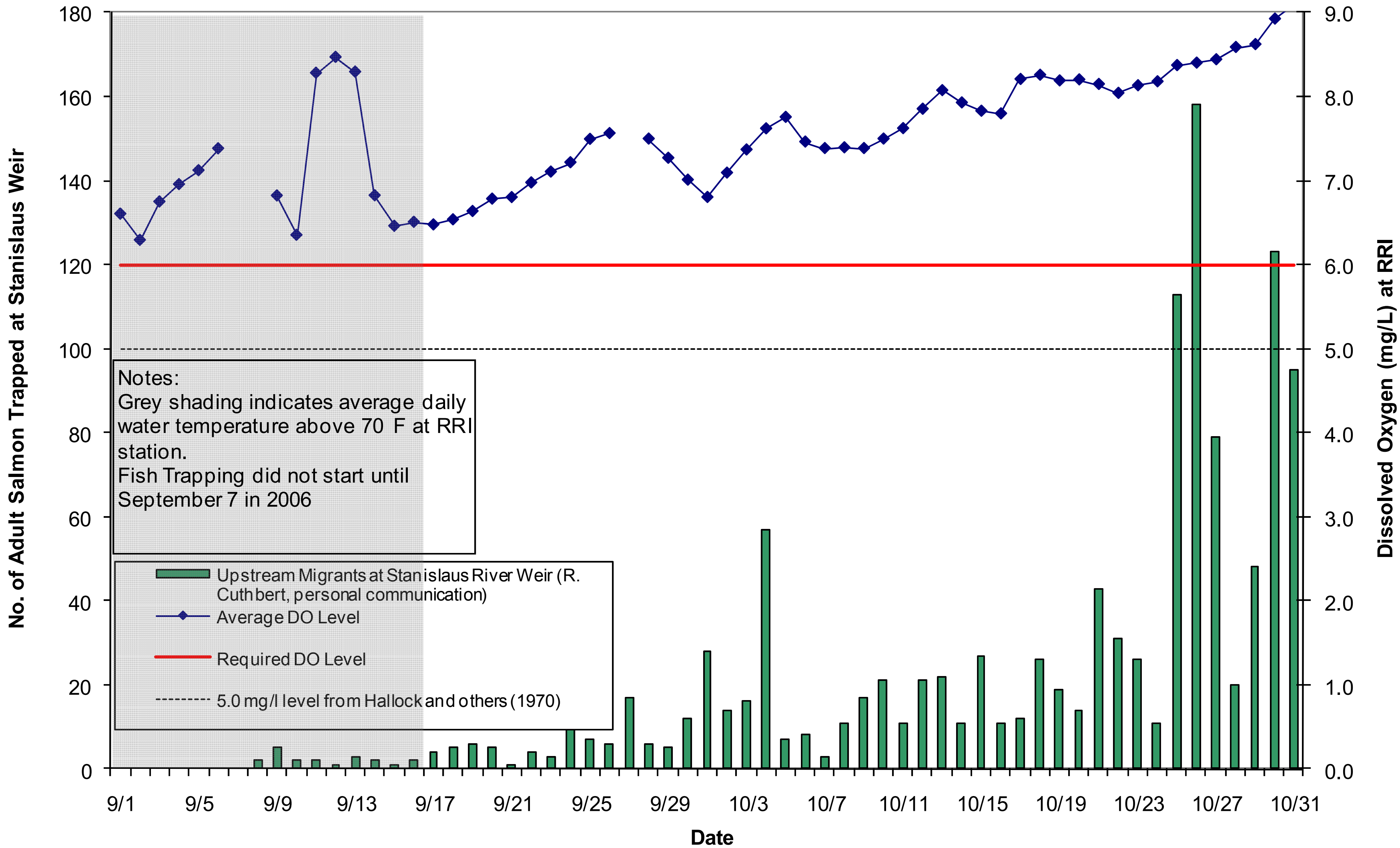


Figure 7. 2007 Fall-Run Chinook Salmon Migration Timing and Dissolved Oxygen Content in the San Joaquin River

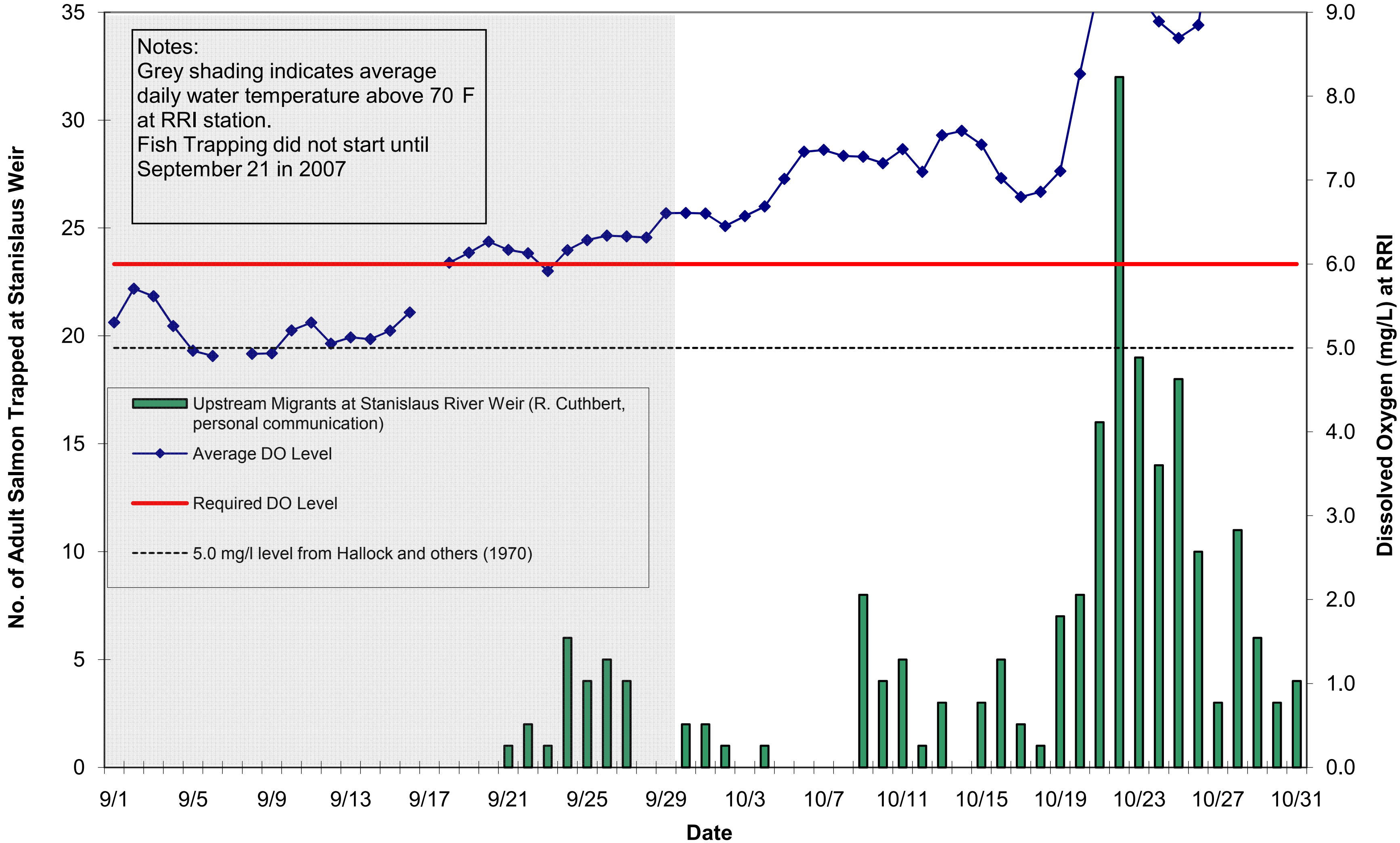


Figure 8. 2008 Fall-Run Chinook Salmon Migration Timing and Dissolved Oxygen Content in the San Joaquin River

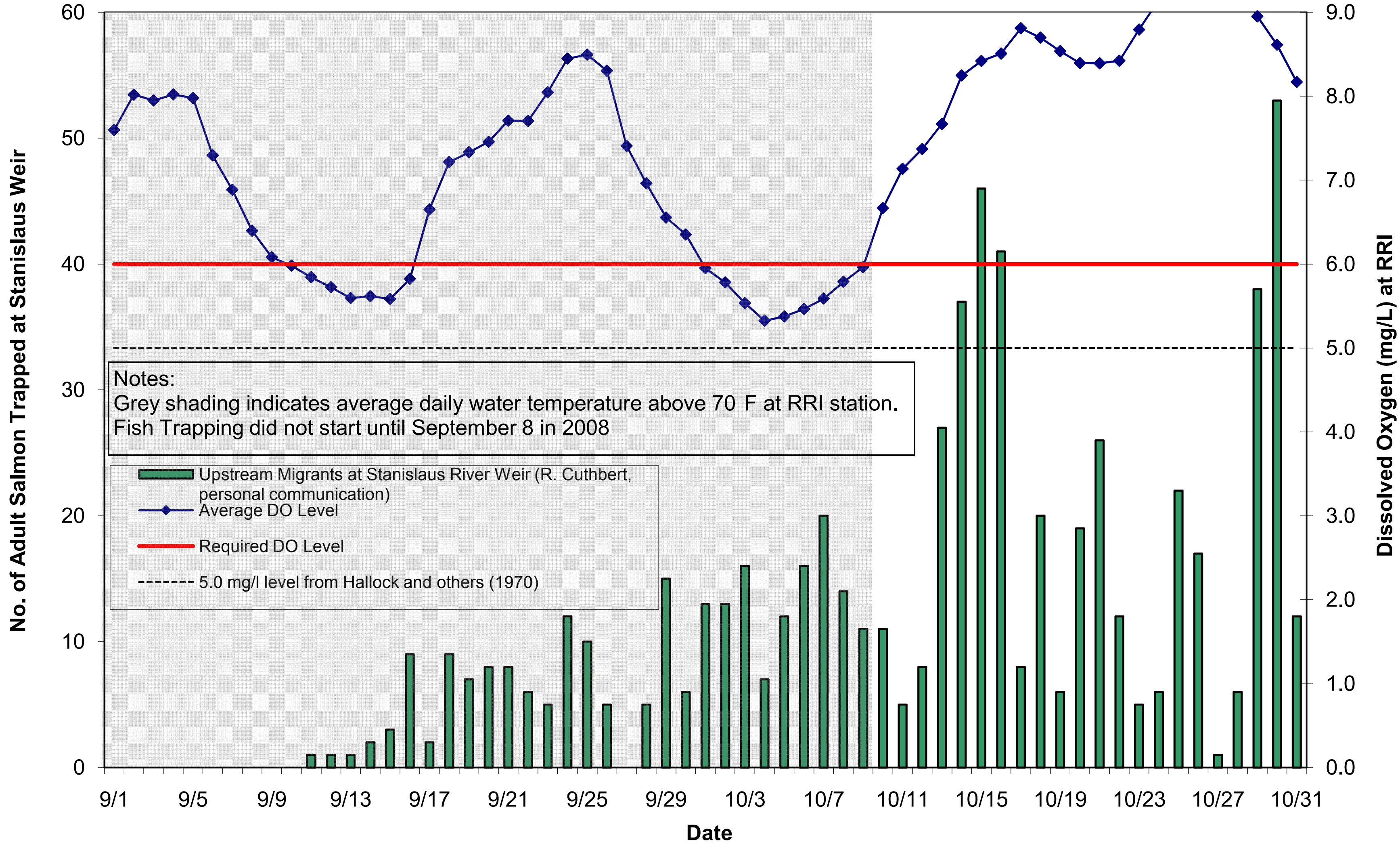
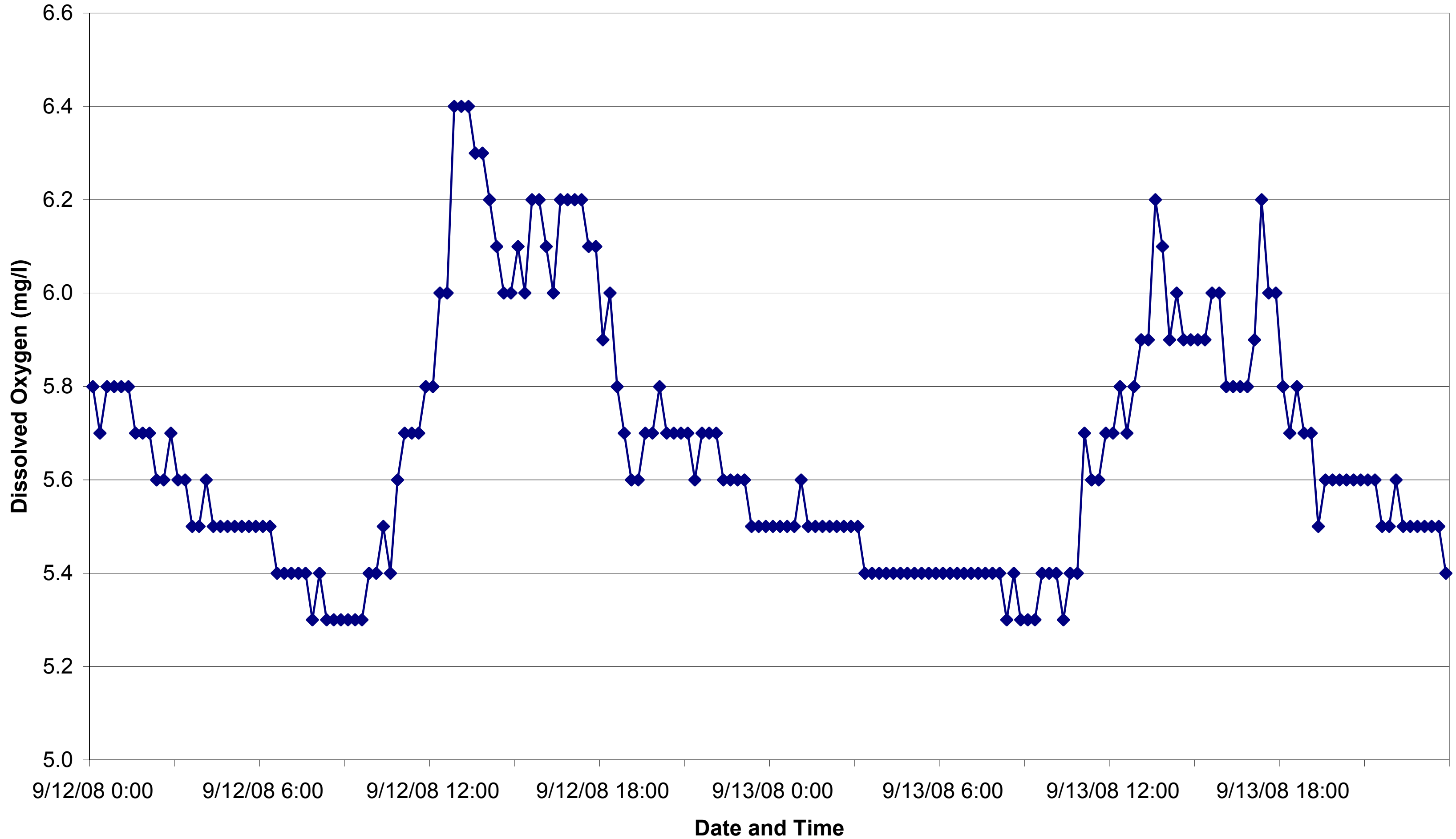


Figure 9. Dissolved Oxygen Levels at Rough and Ready Island Station Over Two Days in September 2008



Direct effects include mortality, reduced swimming performance, reduced growth, impaired development, reduced spawning success, reduced fecundity and fertility, and altered behavior.

Mortality

Low dissolved oxygen concentrations can kill fish. For salmonids, the upper limit of the lethal range is about 3 mg/L. As dissolved oxygen drops to 2.0 – 2.5 mg/L, mortality becomes high (Hicks 2000). The rate of mortality is affected by water temperature and length of exposure. Generally, as water temperature increases, fish require a higher concentration of dissolved oxygen. As long as temperature stays below 68°F, salmonids should survive dissolved oxygen levels of 3 – 4 mg/L (Hicks 2000). However, in this range other adverse effects occur.

Because salmonids are migratory, they would more likely avoid low dissolved oxygen levels rather than expose themselves for long periods of time. In the Stockton Deep Water Ship Channel, avoidance would require upstream migrants to either stage downstream of the dissolved oxygen sag until concentrations improved, or migrate into other Delta channels (Hallock and others 1970).

Reduced Swimming Performance

Low dissolved oxygen affects fish swimming performance and as a result inhibits feeding, predator avoidance, and negotiating swift currents. Swimming performance is classified into three speeds: salmonids are capable of swimming at *sustained speeds* for longer than 200 minutes without tiring, at *prolonged speeds* for 20 seconds up to 200 minutes, and at *burst speeds* for less than 20 seconds. Salmonids generally swim at sustained speeds during migration. Laboratory studies indicate that the sustained swimming performance of salmonids is hindered at 6.5 to 7.0 mg/L. Chinook salmon juveniles were tested at various dissolved oxygen concentrations and exhibited a 10% reduction in swimming speed at 7 mg/L and a 38% reduction at 3 mg/L (Davis and others 1963).

While low dissolved oxygen can hinder salmonid swimming performance in a laboratory setting, the magnitude of the effect in the Stockton Deep Water Ship Channel depends on the life stage and the length of exposure. Adults migrating upstream may avoid low dissolved oxygen concentrations by waiting for better conditions, by navigating to other channels, or just continuing on their migration (Strange 2010). Juveniles migrating downstream are more likely to move during higher flows when there is consequently higher dissolved oxygen levels. However, the end of the migration season for juvenile salmonids can coincide with low dissolved oxygen periods in the Stockton Deep Water Ship Channel (Figure 10), therefore there is potential for a portion of the juvenile Chinook salmon and steelhead population to be affected by reduced swimming performance.

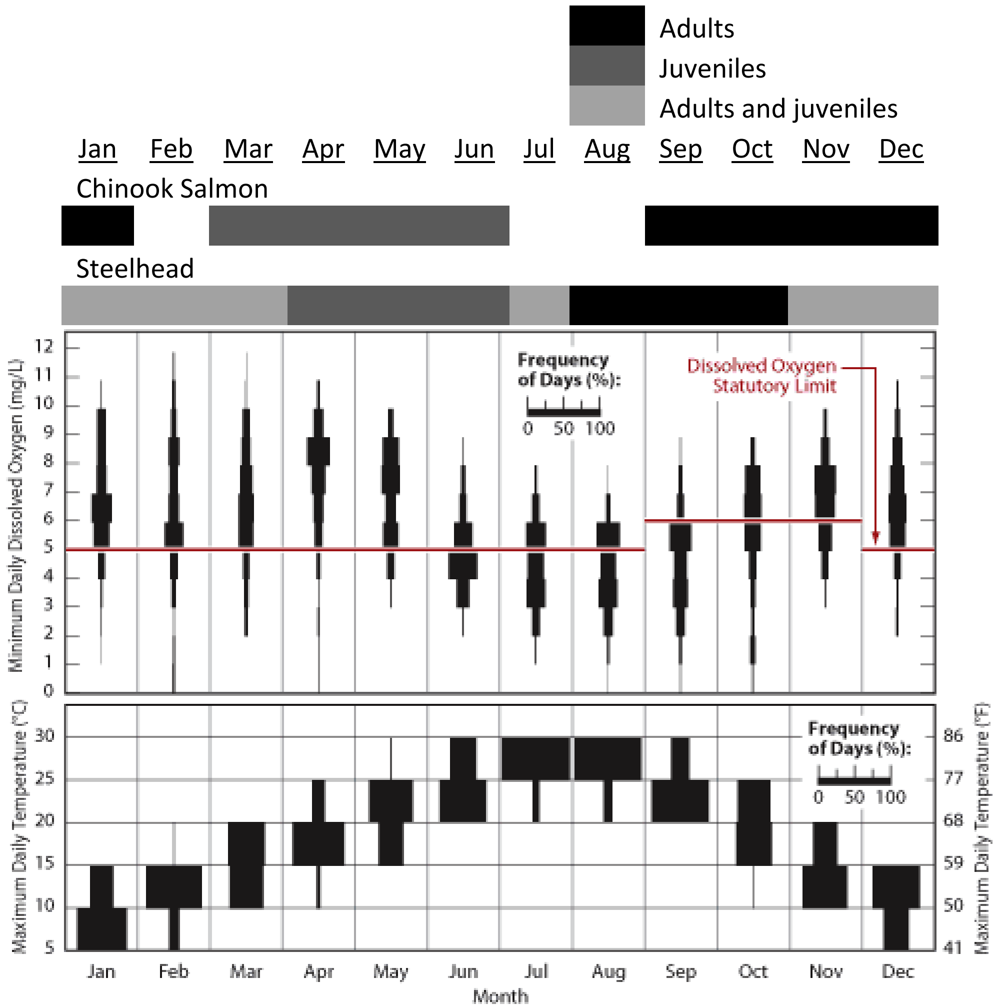


Figure 10. Overlap of low dissolved oxygen levels, elevated water temperatures, and potential salmonid occurrence in the Stockton Deep Water Ship Channel (from http://www.sjrdotmdl.org/concept_model/bio-effects_model/lifestage.htm; Cuthbert and others 2010; NMFS 2009; Yoshiyama and others 1998)

Reduced Growth

Fish grow slower when exposed to low dissolved oxygen concentrations frequently or for an extended period of time because fish will conserve energy and spend less time actively feeding (Breitburg 2000; Kramer 1987; Brett 1979; Doudoroff and Shumway 1970). When fish feed in low dissolved oxygen concentrations, the rate at which food is converted to growth is less efficient (Breitburg 2000).

In a laboratory setting, the minimum dissolved oxygen concentration at which trout will grow optimally is 4-5 mg/L (Itazawa 1971). Another study showed that growth rates of trout were reduced by 25% at a 4 mg/L and 14% at 5 mg/L. The same test showed Chinook salmon are slightly more affected by low dissolved oxygen, where Chinook juveniles displayed 29% and 16% reduction at 4 mg/L and 5 mg/L respectively. Both tests were conducted with unlimited feeding opportunities at 59°F (JRB Associates 1984).

Reduced growth rates would be a consideration only for juvenile salmonids in the Stockton Deep Water Ship Channel. Some steelhead and Chinook juveniles wait until June to migrate out through the Delta, and their migration may overlap with low dissolved oxygen periods in the Stockton Deep Water Ship Channel (Figure 10). However, most juveniles are likely to move downstream when flows are higher in the late winter and spring. It is not expected that this overlap would result in a population level effect since only a small portion of the juvenile salmonids encounter low dissolved oxygen and do so only for a limited amount of time.

Impaired Development

Fish require a minimum dissolved oxygen level to perform necessary functions and activities, and as dissolved oxygen levels drop below required levels fish embryos and larvae exhibit reduced growth, retarded development, deformities, and death (Chapman 1986). The effects of low dissolved oxygen specifically related to development of Chinook salmon and steelhead are not well understood. Rather, effects of low dissolved oxygen combined with increased temperatures have been studied, and these effects are assumed to be similar to low dissolved oxygen alone.

Before entering the marine environment, juvenile Chinook salmon and steelhead must undergo a transformation from a freshwater-dwelling fish (a *parr*) to a saltwater-dwelling fish (a *smolt*). This "smoltification" process requires sufficient dissolved oxygen and suitable water temperature, and if these conditions are not met smolting can be delayed to the point of causing fish to be ill-equipped for saltwater life or to even revert back to the parr stage (Hoar 1988 in Myrick and Cech 2001) and be unable to survive in saltwater.

It is important to reiterate that low dissolved oxygen in the absence of elevated water temperatures has not been studied. However, water temperature in the Stockton Deep Water Ship Channel often reaches 59°F during April – June (Figure 10), which is known to impair steelhead smolt development (Adams at al. 1973 and 1975 in Myrick and Cech 2001). This timing coincides with the end of the juvenile migration period for steelhead and Chinook salmon. More importantly, smolt migration coincides strongly with high flows. High flows lead to higher dissolved oxygen and are more likely to occur in winter and spring and as a result, the majority of smolts should move out when dissolved oxygen levels are up. Nevertheless, smolts that do not migrate earlier in the season are likely to be affected by higher water temperatures and reduced dissolved oxygen.

Reduced Spawning Success

Starting in August and September, adult steelhead and Chinook salmon migrate through the Delta and into San Joaquin River tributaries. The timing of their migration is part of a life-history strategy that allows eggs and juveniles to grow in tributaries when conditions are most suitable. For the purposes of this section, "Spawning Success" is defined as adult salmonids migrating into San Joaquin tributaries during a time period which affords juveniles sufficient time for rearing.

Low dissolved oxygen in the Stockton Deep Water Ship Channel can directly affect spawning success by blocking fish from migrating into San Joaquin River tributaries. Adults may avoid the low dissolved oxygen areas by waiting for better conditions or by migrating into different watersheds (Mokelumne River and Sacramento River). Adults that wait for better conditions will use more energy staging below the Stockton Deep Water Ship Channel. Since adult Chinook salmon do not feed after entering fresh water, the energy used for additional migration time reduces the amount of energy available for gonad development and spawning. Adults that stray into other watersheds may spawn successfully, but the offspring of strays are not likely to contribute to the San Joaquin River population when they return as adults.

Low dissolved oxygen has the potential to affect adult Chinook salmon and steelhead. Hallock and others (1970) found that Chinook salmon are delayed in their migration until dissolved oxygen rises to 5.0 mg/L in the Stockton Deep Water Ship Channel. Low dissolved oxygen periods coincide with the early part of the fall-run Chinook salmon and steelhead migration (Figure 10). The most evident effect of this overlap is a delay in migration. Evidence also shows that fall-run salmon are straying into other rivers to complete their life cycle (Hallock and others 1970; Moyle 2002).

Reduced Fecundity and Fertility

Spawning Chinook salmon and steelhead allocate stored energy to gonad development. As dissolved oxygen and water temperature become more ideal, gonads develop more effectively and egg production and viability increase. If salmon or steelhead migration is delayed because of low dissolved oxygen levels then less energy is allocated to gonad development. While there are no data that show a direct relationship between low dissolved oxygen and decreased fecundity, the potential for this relationship can be inferred from what is known about fish bioenergetics.

As with “Spawning Success,” this factor is more likely to affect Chinook salmon than steelhead. This effect on Chinook salmon could be significant based on the overlap between run-timing and low dissolved oxygen periods.

Altered Behavior

This section examines the relationship between low dissolved oxygen and its effect on fish behavior. For the purposes of this section, “Altered Behavior” is defined as a change in behavior that reduces oxygen demand or increases oxygen uptake. Altered behavior can take different forms, including severe reduction in activity, surface breathing, or avoiding low dissolved oxygen areas. These behaviors help fish lessen the adverse effect of exposure to low dissolved oxygen, but the behaviors can expose fish to other risks such as predation, disease, and starvation.

There are many studies that demonstrate that trout alter their behavior to increase survival when exposed to low dissolved oxygen. Behavioral data are less available for salmon but the physiology between salmon and trout is similar enough for comparison. At dissolved oxygen concentrations of 3.0 mg/L trout have been observed surfacing constantly, but rarely do so at 5.0 mg/L (Dean and Richardson 1999). This behavior, known as surface breathing, is used by fish to increase oxygen intake from the water. Juvenile trout have been observed in isolated pools where dissolved oxygen was less than 3.5 mg/L, but they swam near the surface of the pool where they could maximize oxygen uptake (Erman and Leidy 1975 in McCullough 1999). In general, research data show that juvenile trout behavior is altered at dissolved oxygen levels lower than 5.0 mg/L.

NMFS (2009) examined dissolved oxygen data from 2000 – 2005. They reported that dissolved oxygen levels less than 5.0 mg/L occurred in all migratory months for San Joaquin River salmonids over those five years. Peak adult steelhead migration occurs in December and January; and peak juvenile steelhead migration occurs in April and May (NMFS 2009). Dissolved oxygen levels in the Stockton Deep Water Ship Channel are typically higher during those months, but readings below 5.0 mg/L do occur.

As discussed earlier, Chinook salmon can alter their behavior when encountering low dissolved oxygen by avoiding the Stockton Deep Water Ship Channel. However, the adverse effects associated with Chinook salmon altered behavior are potentially significant because they can result in increased straying or increased migration time. As described earlier, the cost of increased migration time is having less energy to allocate to gonad development and spawning.

Indirect Adverse Effects

Indirect effects are a result of direct effects. The direct effects described in this paper are behavioral or physiological responses of fish that encounter low dissolved oxygen. Some of the responses include reduced activity, poor swimming performance, slow growth, or altered migration pattern. All of these responses can help fish to survive encounters with low dissolved oxygen, but also increase their susceptibility to other indirect effects. Potential indirect effects include increased susceptibility to predation, parasites or pathogens, and contaminants.

Increased Susceptibility to Predation

Large size and strong swimming ability help fish avoid predation. Exposure to low dissolved oxygen can result in slow growth and poor swimming ability, which can lead to an increased chance of predation. Passage barriers, such as a dissolved oxygen block, can extend the migration period and increase the amount of time that fish are exposed to predators. For example, sea-lions have become a normal presence in the Delta and have been observed feeding on adult salmon (NMFS 1997).

No studies have been published on the link between low dissolved oxygen and increased susceptibility to predation, but decreased swimming performance could lead to a higher chance of being taken as prey. Decreased swimming ability is probably less significant for juvenile steelhead since their peak migration is in April and May when dissolved oxygen levels in the Stockton Deep Water Ship Channel are typically higher. However, the end of the juvenile salmonid migration period coincides with low dissolved oxygen episodes in the Stockton Deep Water Ship Channel, so they could be more susceptible to predation if their swimming ability is reduced.

Adult salmonids have the greatest potential to be affected by increased predation while their migration is delayed in the fall. The magnitude of sea lion predation has not been quantified (NMFS 1997)

Increased Susceptibility to Parasites/Pathogens

Fish are continuously exposed to pathogens and parasites in their natural environment, and infection by parasites and pathogens can lead to reduced reproduction and/or pre-spawn mortality. Good water quality and a healthy immune system can defend fish from being infected by a pathogen or parasite, and poor environmental conditions increase the susceptibility of fish to parasites and disease. This effect has only been investigated in artificial environments (hatchery or laboratory setting) because of the difficulty in isolating multiple stressors in a natural environment. Fish hatcheries provide ample evidence of the effects of poor conditions on fish health, where low dissolved oxygen concentrations in the hatchery lead to increases in infectious diseases (Wedemeyer 1970; Wedemeyer and Wood 1974 in Karna 2003).

Juvenile and adult steelhead are less likely to encounter low dissolved oxygen periods because of the timing of their peak migration. As a result, they should be less susceptible to parasites and pathogens. Adult Chinook are likely to wait out low dissolved oxygen periods or to seek out different rivers for spawning, therefore adult Chinook salmon are less prone to an increased susceptibility of disease due to indirect effects of low dissolved oxygen concentrations. Juvenile Chinook salmon that wait until June are most likely to experience an increased susceptibility to infection by a pathogen or parasite because their migration through the Stockton Deep Water Ship Channel can overlap with low dissolved oxygen levels. However, the significance of this factor is unclear because of limited understanding of the effects of pathogens on Chinook salmon and the effect of multiple stressors on fish in their natural environment.

Increased Susceptibility to Contaminants

Contaminants introduced into waterways from runoff can be toxic to fish, and the ability of fish to tolerate contaminants is lessened as dissolved oxygen drops (Meehan 1991; Palawski and others 1985; Richards and Rago 1999). In low dissolved oxygen conditions fish need to increase their respiratory effort in an attempt to get more oxygen. As the fish draw more water through their gills they also expose themselves to more contaminants. Therefore, the effect of contaminants could be exacerbated by increased respiration (Lloyd 1961 in Chapman 1986).

Chinook salmon and steelhead are continuously exposed to contaminants as they migrate in and out of the Delta. If water quality is good they have a better tolerance of contaminants, but as Chinook salmon and steelhead become exposed to lower dissolved oxygen levels their ability to tolerate contaminants without negative effects decreases.

Beneficial Effects on Salmonids from Raising Dissolved Oxygen Levels

Raising dissolved oxygen levels through artificial means such as an aeration facility or other means should reduce the adverse effects associated with low dissolved oxygen levels in the Stockton Deep Water Ship Channel. The adverse effects described previously were evaluated based on low dissolved oxygen periods and their correlation with the timing of Chinook salmon and steelhead migration and rearing in the Delta and San Joaquin River. The effects for adult Chinook salmon and steelhead include: reduced spawning success, reduced fecundity and fertility, altered behavior (migration delays), and increased susceptibility to predation. Effects for adult steelhead may be somewhat less since their peak migration period occurs in December and January. The effects for juvenile salmonids include reduced swimming performance, impaired development, and increased susceptibility to parasites, pathogens, and contaminants.

Chinook salmon and steelhead travel long distances between variable environments and as a result are subjected to varying adverse elements. If poor conditions in the Stockton Deep Water Ship Channel are improved, it is possible that a benefit to salmon and steelhead populations will be evident. However, salmonids are also subject to many other potentially adverse factors, so it is possible that any benefit will be masked by the effects of other stressors. Therefore, beneficial effects on salmonid populations will be presented in a conjectural manner.

Direct Beneficial Effects

The following section describes direct beneficial effects that may occur if dissolved oxygen levels in the Stockton Deep Water Ship Channel are maintained above the regulatory minimum. Direct beneficial effects are considered behavioral or physiological responses of fish that occur as a result of exposure to dissolved oxygen levels above the regulatory minimum.

Swimming Performance

The end of the migration season for juvenile Chinook salmon and steelhead overlaps with low dissolved oxygen periods in the Stockton Deep Water Ship Channel. Because of this overlap there is potential for part of the juvenile salmonid population to be affected by reduced swimming performance during low dissolved oxygen periods, making it more difficult for them to feed and avoid predators. Juvenile salmonids would benefit from increased swimming performance if dissolved oxygen levels were higher in the Stockton Deep Water Ship Channel, but dissolved oxygen levels would have to be higher than 6.5 mg/L for juveniles to benefit from their full swimming potential (Davis and others 1963 in Hicks 2000). The San Joaquin River Basin Plan objective during this period is 5 mg/L.

Nevertheless, juveniles should be able to feed more, which would potentially lead to increased growth, and be more adept at avoiding predators. Increased growth and improved predator avoidance would both result in increased survival of juveniles.

This effect would be difficult to quantify. First, there are few historical data on growth and survival rates of juvenile salmonids from the San Joaquin River. Furthermore, trapping would have to occur downstream of the Stockton Deep Water Ship Channel and fish that were collected would need to be identified as San Joaquin River fish before any comparison to historical data could be made. It would be more likely to identify an increase in numbers of returning adults, but there are too many other variables involved to be able to link improved recruitment to success of the aeration facility.

Development

Increased dissolved oxygen levels in the Stockton Deep Water Ship Channel would provide one component of the requirements for smolts to develop unimpaired. However, water temperatures will remain the same, and high temperatures can impair smolt development. Juveniles that migrate early in the season are exposed to higher flows and higher dissolved oxygen levels, both of which promote good development. The main benefit of increased dissolved oxygen levels in the Stockton Deep Water Ship Channel would be to the juveniles that migrate later in the season. However, even though these juveniles may experience higher dissolved oxygen levels, if they encounter water temperatures of 59°F or higher, then they will still suffer some level of impaired development into smolts.

Therefore, when water temperature in the Stockton Deep Water Ship Channel is at or below 59°F, juvenile salmonids will benefit from increased dissolved oxygen and have a higher likelihood of developing into smolts.

Spawning Success

The direct benefit of increased dissolved oxygen levels in the Stockton Deep Water Ship Channel to upstream migrants is the ability to access spawning grounds early in their migration season. Salmon initiate their upstream migration based on environmental cues, following a strategy that allows their offspring to benefit from suitable flow conditions in winter and spring. This timing also affords juveniles time to develop and then abandon natal grounds before flows and water temperature become unsuitable in the summer. If salmon were able to arrive at spawning grounds on their natural schedule, it could perpetuate an increase in salmon production in the San Joaquin River system.

If dissolved oxygen conditions were maintained above the regulatory minimum in the Stockton Deep Water Ship Channel, we would expect an increase in the amount of salmonids that successfully spawn in the San Joaquin River system. Assuming all other environmental requirements are met, an increase in successful spawners could lead to an increase in production of juveniles, which in turn could result in an increase of smolts and a corresponding increase in numbers of return spawners. This increased production is largely assumed and could not be attributed solely to meeting regulatory criteria in the Stockton Deep Water Ship Channel. Rather, the assumed effect is intended to illustrate the benefits that could occur if dissolved oxygen requirements were met in combination with all other environmental requirements.

Fecundity and Fertility

Spawning Chinook salmon allocate stored energy to gonad development. They do not feed at all once they have begun their upstream migration, therefore no new energy sources are acquired from that point forward. If dissolved oxygen regulatory criteria are met in the Stockton Deep Water Ship Channel, salmon would not have to extend their migration period and would be able to allocate more energy to egg production and fertility. Furthermore, studies of fish bioenergetics infer a direct relationship between high dissolved oxygen levels and increased fecundity.

The magnitude of this benefit is probably not of the same order as the benefit of increased spawning success. However, as with spawning success, the benefit of increased fecundity and fertility could perpetuate increases in production at other life stages.

Behavior

The “Adverse Effects” section describes altered behavior as “avoidance” for adult salmonids. Adult salmonids avoid low dissolved oxygen periods by waiting for better conditions or migrating into other river systems with more suitable conditions. If dissolved oxygen regulatory criteria were met, we would expect adults to stop avoiding the area and enter the San Joaquin River system without delay.

The adverse effects of avoidance were described as exposing salmonids to increased stressors which affect spawning success and fecundity. The benefit of meeting dissolved oxygen regulatory criteria would lessen the number of stressors encountered by adults, and increase the likelihood of San Joaquin River fish returning to the San Joaquin River to spawn.

Indirect Beneficial Effects

Indirect effects are the result of direct effects. The direct effects described in the “Adverse Effects” section are behavioral or physiological responses of fish that encounter low levels of dissolved oxygen. Direct beneficial effects are based on responses of fish that encounter dissolved oxygen levels above the regulatory minimum. There are also beneficial indirect effects which occur from the behavioral or physiological response to increased levels of dissolved oxygen. Potential indirect effects include reduced susceptibility to predation, parasites or pathogens, and contaminants. Beneficial effects are only presented if an adverse effect was established for Chinook salmon or steelhead in the “Adverse Effects” section.

Susceptibility to Predation

The “Adverse Effects” section described extended migration time as the cause of increased predation in adults. If the dissolved oxygen block was removed, adults would not have to wait for ideal conditions and could avoid an increase in exposure to predation.

Juvenile salmonids could indirectly benefit from higher dissolved oxygen levels, as well. The end of the juvenile salmonid migration season coincides with low periods of dissolved oxygen. If dissolved oxygen conditions were improved, this segment of the Chinook salmon and steelhead populations would benefit from increased swimming performance and thus be more adept at predator avoidance.

Susceptibility to Parasites/Pathogens

Juveniles that wait until late in their migration season are most susceptible to an increase in disease because of their overlap with low dissolved oxygen periods. Therefore, there may be an indirect benefit regarding resistance to parasites or pathogens if dissolved oxygen remains above the regulatory minimum throughout the juvenile migration season. Good water quality and a healthy immune system can defend fish from being infected by a pathogen or parasite. However, there are multiple stressors in the natural environment and the link between dissolved oxygen and susceptibility to parasites has only been studied in artificial settings.

Susceptibility to Contaminants

If water quality, including dissolved oxygen, remains good then juvenile salmonids will have a greater ability to tolerate contaminants that would otherwise be toxic.

Summary

Chinook salmon and steelhead populations of the San Joaquin River have undergone drastic decreases in population levels. In the 1950s the average San Joaquin River Chinook fall-run population was typically 40,000 spawners, but since the 1960s, the average return is closer to 15,000 spawners and in some years less than 1,000 spawners have made their way in to the San Joaquin River and its tributaries (CDFG 2007). In the 1960’s, a Department of Fish and Game study documented the effects of low dissolved oxygen levels on adult salmon. The study was a foundation for setting dissolved oxygen criteria in the lower San Joaquin River.

The *Water Quality Control Plan for the Sacramento River and San Joaquin River Basins* sets water quality objectives for the San Joaquin River between Turner Cut and Stockton of 6.0 mg/L for September 1 through November 30, and 5.0 mg/L the rest of the year. The Stockton Deep Water Ship Channel Demonstration Dissolved Oxygen Aeration Facility Project is evaluating the effectiveness of using an aeration facility to increase dissolved oxygen levels in the Stockton Deep Water Ship Channel with the goal of maintaining dissolved oxygen levels above the minimum recommended levels specified in the plan.

Available data indicate that low dissolved oxygen that would impact salmonids is most likely to occur in September and October during the upstream migration period, and during June in the downstream migration period. This makes Chinook salmon more likely to be exposed to low dissolved oxygen levels than steelhead since peak migration for steelhead occurs outside of those months.

Hallock and others (1970) documented low dissolved oxygen areas in the Delta blocking adult Chinook salmon from migrating upstream into the San Joaquin River. When adult salmonids encounter low dissolved oxygen areas multiple adverse effects can occur including altered behavior (migration delays), reduced spawning success and fecundity, and increased susceptibility to predation.

Juvenile salmonids may be exposed to low dissolved oxygen periods during the end of their downstream migration period (primarily in June). Low dissolved oxygen levels can lead to decreased swimming performance, reduced growth, impaired development and increased susceptibility to predation, parasites/pathogens and contaminants.

If the aeration facility is successful at increasing dissolved oxygen levels in the Stockton Deep Water Ship Channel, there could be several beneficial effects. For adult salmonids, these benefits include a shorter migration time, better predator avoidance, more energy expenditure devoted to gonad development and earlier arrival to spawning grounds. For juvenile salmonids, benefits of increased dissolved oxygen include better predator avoidance, less impaired development, and less susceptibility to parasites, pathogens and contaminants.

It will be very difficult to demonstrate and isolate the beneficial effects of the aeration facility for Chinook salmon and steelhead in a field study. Any study will be influenced by other stressors (like warm water temperatures) that anadromous fish encounter throughout their life history. The most easily testable effect is altered behavior (or effects on migration). It is equally difficult to determine differences in fish populations before and after construction of the Stockton Deep Water Ship Channel because the earliest reliable San Joaquin River fisheries data only extend back to the 1930s, when the first deepening of the channel was completed. Without baseline data to compare with current fisheries data and a way to isolate other stressors in the system, drawing population level conclusions becomes difficult. However, we could compare recent data to future data and establish trends in Chinook salmon and steelhead populations and run-timing. If populations increase and fish begin to arrive in the San Joaquin River earlier, we can infer that low dissolved oxygen is no longer a considerable stressor in the Stockton Deep Water Ship Channel.

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