Draft Technical Memorandum

Statistical Model of Dissolved Oxygen Concentration in the San Joaquin River Stockton Deepwater Channel at Rough and Ready Island, 1983-2001[1]

Submitted to the San Joaquin Dissolved Oxygen TMDL
Technical Advisory Committee

by

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Introduction

Dissolved oxygen concentration (DO) in the San Joaquin River Stockton Deepwater Channel ("ship channel") routinely declines below the 5 mg/L Basin Plan objective. Low DO conditions are most common during the summer and fall months, but can happen at any time of year (Jones & Stokes 1998). These conditions restrict the kinds of organisms that can inhabit the ship channel and delay the migration of fall run Chinook salmon to spawning grounds upstream (Hallock et al. 1970). Consequently, the San Joaquin River has been placed on the 303(d) list, thus triggering the need for a Total Maximum Daily Load (TMDL) report and the preparation of an implementation plan (Foe et al. 2002). This memorandum is intended to assist the development of this plan by providing a better understanding of the factors regulating DO in the ship channel.

Many factors affect DO in the ship channel. Among the most important are water temperature, flow, ammonia loading from Stockton's wastewater treatment facility (WWTF), algae produced in the ship channel itself (*in situ* algal production) and algae washed in from upstream. All of these factors can affect DO in more than one way and none operates in isolation.

Increasing temperature tends to reduce DO by reducing oxygen's solubility in water. At 10 C, for example, water is saturated with oxygen at a DO of 11 mg/L, whereas at 25 C, oxygen begins escaping to the atmosphere when DO is only 8 mg/L. Higher temperature also exponentially increases the rates of all chemical and biological processes that consume DO. To complicate matters further, increasing temperature also increases the rate of natural surface aeration, a process that supplies oxygen to the water from the atmosphere (Brown 2002).

The relationship between flow and DO is also complex. Increasing net flow reduces hydraulic residence time and thus the time available for oxygen-consuming processes to occur within the ship channel (Chen and Tsai 2001). Higher flow also increases mean velocity, thereby increasing natural aeration. Increasing flow, however, also increases the amount of artificial aeration required to achieve a unit increase in DO (Brown 2002). Higher flow may also increase the loading rate of algal biomass or other organic matter from upstream, thereby potentially reducing DO in the ship channel (Lee and Jones-Lee 2000). Moreover, within a certain range, increasing flow may merely displace the most DO-depleted zone of the ship channel a few miles or less downstream of its usual position near Rough and Ready Island (Hallock et al. 1970; Gowdy 2002).

Ammonia loading from Stockton's WWTF substantially increases the concentration of inorganic ammonia (NH_4-N) in the ship channel, especially under low flow conditions. *Nitrosomonas* bacteria oxidize the NH_4-N into nitrite while *Nitrobacter* oxidize the nitrite into nitrate (NO_3-N). The entire process, called nitrification, consumes some 4.5 lbs of oxygen for every pound of NH_4-N converted into NO_3-N and its rate increases exponentially with water temperature. There is little disagreement that nitrification of the City's effluent consumes DO in the ship channel, but it is not clear how important this process is compared to other factors, such as flow, *in situ* algal production and especially the influx of algal biomass from sources upstream.

The role of *in situ* algal production in regulating DO in the ship channel is also a subject of some debate. Field and bioassay-scale measurements indicate that *in situ* algal photosynthesis can add considerable amounts of oxygen to near-surface waters of the ship channel. Consequently, DO can be high during the day near the surface, but low near the bottom (Lehman 2001; Jones & Stokes 2002). This DO stratification of the water column is usually associated with a slight (<1 C) but measurable temperature difference between surface and bottom (Litton 2002) and is particularly marked in the more stagnant waters of the Turning Basin. In the Turning Basin, surface DO can approach saturation, while near-bottom DO can be <3 mg/L (Lehman 2001; Jones & Stokes 2002). In addition, biochemical oxygen demand (BOD), a bioassay-scale measure of oxygen-consuming material in a water sample, is not correlated with chlorophyll concentration (a measure of algal biomass) in the ship channel (Lehman 2000; Litton 2002) and one researcher has suggested that algae produced in the ship channel may actually consume more oxygen (through respiration and subsequent decomposition) than it generates through photosynthesis. Thus, according to this hypothesis, *in situ* algal production may on balance exert a negative effect on DO in the ship channel (Lehman 2001).

Unlike chlorophyll concentration (Chl) in the ship channel, Chl at Mossdale, Vernalis and other upstream sites bears a strong positive relationship with BOD (Foe et al. 2002). Algal biomass in this upstream reach is generally very “fresh” (has relatively low phaeopigments), but by the time it reaches the UVM station 15 miles downstream of Mossdale (Figure 1), it is already quite moribund (Litton 2002; Jones & Stokes 2002). When this not-so-fresh algal biomass enters the ship channel, some 60% of it quickly settles out and begins to decompose (Litton 2002). This process has long been thought to be the principle reason why DO is chronically low in the ship channel (McCarty 1968), but teasing out the effect of upstream Chl from flow and other factors has been difficult in part because upstream Chl and flow are negatively correlated (Foe et al. 2002).

Faced with the many complexities and uncertainties associated with DO dynamics in the ship channel and the need to renew its National Pollutant Discharge Elimination System (NPDES) permit, the City of Stockton commissioned Systech to develop a mechanistic water quality model of the ship channel (Schanz and Chen 1993). This link-node model represents the San Joaquin River from the Head of Old River to Columbia Cut as a series of 25 one-mile-long segments. The Systech model includes tidal flows and (given upstream concentrations, air temperature and other boundary conditions) simulates water transport and calculates mass balances for water temperature, DO, BOD, ammonia, nitrate, phosphorus, total and volatile suspended solids and chlorophyll. Thanks to funding from CALFED, the model has undergone considerable peer review and revision (Chen and Tsai 2001). With the exception of occasional episodes of extremely low DO, the revised model does a remarkably good job of simulating intra-annual variation in water temperature, DO and most other water quality constituents.

Calibration and validation of the Systech model applied in “hindcast mode” to a given year of data has improved understanding of the processes regulating DO in the ship channel and helped guide field studies. Equally important, however, has been the application of the model in “predictive mode” to evaluate specific management scenarios (Chen and Tsai 2001). Application of the model in this mode indicates, for example, that filling in the ship channel to its original depth of some 8 ft would eliminate the DO deficit (relative to the 5 mg/L objective) as long as net flow at Stockton were maintained at >1,000 cfs. Comparatively modest deficits would be expected at lower flows under this perhaps not-so-realistic solution to the DO problem. The "most realistic scenario" to emerge so far from the Systech modeling effort, however, would entail three major actions: (1) manage the river to ensure a net flow at Stockton of >1,000 cfs; (2) reduce the equivalent ultimate BOD (BOD_{eu}) loading from the WWTF by 25%; and (3) reduce the BOD_{eu} load from upstream by 25% (Chen and Tsai 2001). Just how realistic (and effective) this or any other set of proposed management actions is likely to be is one of the main questions the TMDL Steering Committee must address before it can develop a plan for solving the DO problem in the ship channel.

Statistical modeling of historical data provides yet another tool for improving scientific understanding of the DO problem and for weighing various management options for solving it. Unlike mechanistic modeling, however, which can be accomplished with very little field data (e.g., one year of data to calibrate and a second year to validate), the power of a statistical model depends largely on how many observations go into developing it. Fortunately, there are 19 years of continuous temperature, DO and other water quality data available for developing such a model for the ship channel.

The principle objectives this analysis were five-fold:

1. Summarize historical data on dissolved oxygen conditions in the ship channel using data from the continuous monitoring station at Rough and Ready Island (R&R) for 1983 through 2001;

2. Describe historical variation in temperature, flow conditions, and other factors regulating DO in ship channel;

3. Develop a statistical model to quantify historical variation in DO;

4. Use the statistical model to compare alternatives for improving DO conditions and;

5. Discuss some implications for future modeling, monitoring and management.

Methods

This analysis relies primarily on historical water quality data collected by the U.S. Bureau of Reclamation (USBR) and the California Department of Water Resources (DWR) under the Interagency Ecological Program (IEP) and other routine compliance monitoring efforts. The period of record extends from May 1983, when the continuous monitoring station at Rough and Ready Island (R&R) began operating, to December 2001. This station provides hourly measurements of air and water temperature, DO, pH and conductivity. Other water quality constituents required for this analysis, however, have been measured only once or twice a month since 1975. Consequently, unless otherwise indicated (e.g., Figure 3), the data from the continuous stations have been "dumbed down" to monthly averages. For 1999 through 2001, I also included upstream chlorophyll data collected by the City of Stockton, the Regional Board and UC-Davis.

Each of the conceptual variables described in the Introduction above had to be represented by real variables measured in the field ("indicator variables"). The indicator variables used in this analysis were defined as follows.

Dissolved Oxygen. The variable used in this analysis to represent dissolved oxygen conditions in the ship channel was the monthly arithmetic mean of the daily minimum DO recorded at the R&R continuous monitoring station (DO_{min}). The probe is placed about 7 feet below the surface in a water column that is roughly 40 ft deep and thus represents a near-surface measurement of DO. Hourly data for this station are available on the IEP web site (iep.water.ca.gov).

Water Temperature. Water temperature conditions were represented by the monthly arithmetic mean of the daily average water temperature recorded at the R&R continuous monitoring station (Temp). Hourly data are available on the IEP web site.

Hydraulic Conditions. Ideally, hydraulic conditions in the ship channel would be represented by the theoretical mean hydraulic residence time (i.e., total volume divided by net flow as estimated by UVM or other techniques). Net flow measurements from a U.S. Geological Survey tidal flow gage near the City of Stockton's effluent discharge site (Figure 1) have been available only sporadically since the gage was installed in 1997. It is known, however, that net flow at Stockton is directly proportional to discharge at Vernalis and nearly doubles when the Head of Old River Barrier (HORB) is in place (Jones & Stokes 2001). There is also evidence to suggest an inverse relationship with CVP-SWP export pumping. Consequently, in this analysis I used three variables to represent variation in average monthly hydraulic conditions in the ship channel: (1) monthly arithmetic mean of daily average discharge at Vernalis (Q_{vern}), (2) monthly arithmetic mean of daily average pumping at the CVP and SWP facilities (Q_{exp}), and (3) a binary indicator variable (HORB) that equals "1" when the barrier is in place for at least 15 days of the month or "0" otherwise. Daily discharge and export pumping data are from DAYFLOW available from the IEP web site. HORB operations data were obtained from Sandhu Amritpal, DWR Operations Compliance and Studies Section (asandhu@water.ca.gov).

Ammonia Loading. Ammonia-N loading to the ship channel from the City of Stockton's wastewater treatment facility was represented by the monthly average amount (in lbs/day) of ammonia-N discharged into the river just upstream of the ship channel. Assuming more or less constant channel morphometry, this loading value is directly proportional to the ammonia loading rate (lbs/acre/day) to the ship channel, so the terms may be used interchangeably. Monthly average NH_4-N loading (AmmLd) was calculated as the product of the flow-weighted mean effluent concentration of NH_4-N and the monthly average effluent discharge (cfs). These data were obtained from the City of Stockton.

***In situ* and Upstream Algal Biomass.** Suspended algal biomass in the ship channel was represented by the monthly arithmetic mean of chlorophyll concentration at the Buckley Cove station (P8, at Light 40) monitored by the IEP since 1975 (Chl_{ship}). Sestonic algal biomass in the mainstem of the San Joaquin River upstream of the ship channel was represented by the monthly arithmetic mean of chlorophyll concentration at Vernalis (Chl_{vern}). Sampling at Buckley Cove is done by boat using a pumped flow-through system that collects water at a depth of 3 ft. Sampling at Vernalis is done from a highway bridge by lowering a Van Dorn bottle with a rope. Vernalis samples are thus surface samples. For both sites, I used Chl uncorrected for phaeopigments.

Measurements at Mossdale, which is 15 miles closer to the ship channel reach than Vernalis, would have been slightly more representative of upstream algal biomass, but sampling there stopped after 1995. Given the importance of sample size in statistical modeling and the strong positive relationship between Chl at Vernalis and Chl at Mossdale (r=0.95, n=203), the use of Vernalis data was deemed appropriate.

The ratio of chlorophyll concentration corrected for phaeopigments to uncorrected chlorophyll concentration (Chl_c:Chl_u) provided an index of the average "health" or "age" (Litton 2002) of the suspended algal biomass. The higher this index, the higher the percentage of live-to-dead algae was assumed to be. Data on phytoplankton density (number of individuals/mL) and taxonomic composition (genus) were based on monthly grab samples collected at the same time as the water samples used to measure chlorophyll and other water quality constituents. There were no data for Vernalis, so I used Mossdale data to characterize the composition of upstream algal biomass. All data and metadata are available on the IEP website.

Statistical Methods

With one exception, the data set used for this analysis consisted of monthly average values for the period May 1983 through December 2001. Some months had missing values for DO_{min} or for one or more of the independent variables, however, so the total number of observations used in this analysis was 206. For one analysis (frequency of DO <5 mg/L, Figure 3), I used the individual daily minimum DO values (rather than monthly averages) for the 1983-2001 period of record (n=5,619).

Summary statistics were presented as box-and-whisker plots, by month using all data. Thus, each "box" is based on 18 (Jan-Apr) or 19 values per month. These plots depict the interquartile range as a box bounded on top by the 75th percentile and on bottom by the 25th percentile values. The median is shown as a horizontal line and the arithmetic mean as a large dot within the box.

The upper and lower "whiskers" show the 90th and 10th percentile values, respectively, and extremes by dots outside the whiskers.

Relationships between variables were depicted with scatter plots and LOWESS (locally weighted sequential smoothing, Cleveland 1979) trend lines. Trend lines offer a model-free assessment of the approximate form of the relationship between two variables. Correlation coefficients were calculated using ranked values (Spearman r).

The statistical model was based on least squares multiple linear regression. For this analysis, some variables (Q_{vern}, Q_{exp}, Chl_{vern} and Chl_{ship}) were log_{10}-transformed to help stabilize variance. Interaction terms were assumed to be multiplicative. Because the data set was a time series, I had to determine if the model's residual error was serially autocorrelated. For this purpose, I used the Durbin-Watson test statistic (SAS Institute, Inc. 1989) and plots of residual error against time. Residual error (i.e., observed DO_{min} minus DO_{min} predicted by the statistical model) plots were also presented to confirm the assumption of homoscedasticity (homogeneity of variance). Ideally, the residual values on such plots should appear randomly scattered about the zero line (Zar 1974).

Comparison of Alternatives

The regression model was used to calculate monthly values of DO_{min} under six alternatives for reducing the DO deficit in the ship channel. To limit the comparisons to a reasonable number, all six alternatives assumed relatively high (i.e., 90th percentile) water temperature and high CVP-SWP exports for a given month. Each alternative thus represented different combinations of hydraulic conditions, ammonia loading to the ship channel, algal biomass in the ship channel, and algal biomass upstream.

Alternative "A" was the "No Action" alternative and assumed relatively low flow at Vernalis, high ammonia loading from the WWTF and relatively high chlorophyll concentration upstream. "Low" Q_{vern} was defined as the 10-year return flow for a given month (Jones & Stokes 2001). "High" AmmLd and Chl_{vern} were defined as the 90th percentile values for each month over the entire period of record (Table 1). To also assess the partial effects associated with installing or removing the barrier at the head of Old River and with variation in the abundance ("Low-Medium-High") of algae produced within the ship channel required six scenarios all together. "Low-Medium-High" monthly values of Chl_{ship} were also defined on the basis of summary statistics as the 10th, 50th (median) and 90th percentile values, respectively.

Alternative "B" was formulated to address the effect of imposing a 2 mg/L limit on the concentration of NH_4-N in the City of Stockton's WWTF effluent. Monthly average effluent discharge was assumed constant at 45 cfs, whereas flow at Vernalis was assumed to remain relatively low with Chl_{vern} relatively high. As in Alternative "A" and all other alternatives, six combinations of HORB operations and *in situ* algal biomass were compared.

Alternative "C" was formulated to address the question: "What if upstream algal biomass were reduced to half its historical average?" Flow at Vernalis was held low, while AmmLd was assumed to remain relatively high.

Alternative "D" addressed the flow-augmentation-only alternative by assuming relatively high flow at Vernalis, while keeping AmmLd and Chl_{vern} high. "Medium" Q_{vern} was defined as the 2-year (median) return flow as tabulated in Jones & Stokes (2001).

Alternative "E" represented the combined strategy of imposing a 2 mg/L NH_4-N effluent limit and cutting upstream Chl in half under relatively low flow conditions. Alternative "F" was formulated to represent the Systech alternative. It assumed a 25% reduction in median AmmLd, a 25% reduction in Chl_{vern}, and a net flow at Stockton of 1,000 cfs. A net flow of 1,000 cfs was assumed to prevail at Stockton if Q_{vern} was 1,200 cfs with the HORB in place or 2,200 cfs without the barrier (Jones & Stokes 2001).

For each alternative, the model was used to predict the average monthly DO deficit relative to 5 mg/L. Monthly deficits were multiplied by the estimated value of monthly average net flow in the ship channel (Q_{net}) and the resulting products summed (and mulitplied by 5.4*30) to provide an index of the cumulative deficit for the year (lbs/year). For comparative purposes, Q_{net} was assumed to equal 50% of Q_{vern} when the HORB was not in place and equal to Q_{vern} when the HORB was installed. For the Systech alternative, Qnet was held constant at 1,000 cfs. The cumulative annual deficit was used for purposes of comparison as an index of the total amount of artificial aeration that would be required annually to meet a 5 mg/L objective.

Dissolved Oxygen

Over the 1983-2001 period of record (n=206 months), DO_{min} at R&R ranged from 1.5 mg/L to 10.3 mg/L, averaging 6.2 mg/L overall (Table 2). Percent saturation spanned a similarly broad range (16 - 94%), averaging some 63% overall (Table 2).

Intra-annual variation in DO_{min} followed a fairly consistent pattern. Although the minimum DO on any given day could be low (<5 mg/L) during any month of the year, DO_{min} was typically >5 mg/L from late fall through late spring (November through May). During this period, median DO_{min} remained well below saturation, however (Figure 2). By contrast, during the summer months (June-August), DO_{min} remained relatively low. By October, DO_{min} began to return to its winter levels (Figure 2).

The percentage of days with minimum DO <5mg/L ranged from 5% in November to 54% in July. Month-to-month variation in the frequency with which the 5 mg/L objective was violated thus varied inversely with the median of DO_{min} over the period of record (Figure 3). During the three month period when the DO objective is raised to 6 mg/L, the frequency of violations increased 1.7- (September), 1.8- (October) and 5.6-fold (November).

Water Temperature

Average water temperature at the R&R continuous monitoring station (Temp) ranged from 7 to 27 C with an average of 18 C overall (Table 2). Monthly variation in Temp followed a pattern characteristic of most north temperate rivers, with warmer temperatures during the second half of the year than during the first half (Figure 4).

A scatter plot of DO_{min} as a function of Temp suggested a strong inverse relationship. The LOWESS trend line indicated that this inverse relationship was most marked at Temp >18 C (Figure 5). Nevertheless, the DO_{min}-Temp relationship at >18 C nearly paralleled the decline in saturation concentration with increasing Temp. By contrast, the slope of the trend line at Temp <18 C was nearly flat compared to the slope of the saturation concentration-temperature line. These results suggested that DO_{min} was adversely affected by one or more processes over the full range of temperature conditions and not just at high temperatures.

Hydraulic Conditions

Monthly mean flow at Vernalis was highly variable over the period of record ranging from 447 to 35,057 cfs. The overall average was 4,416 cfs with a coefficient of variation (CV) of ±132% (Table 2). Flow at Vernalis was typically higher and more variable during the winter months than during summer, when median Q_{vern} was <2,000 cfs (Figure 6). Export pumping also ranged widely (1,316 - 11,648 cfs), but was much less variable than Q_{vern} averaging a comparatively steady (CV=42%) 6,685 cfs overall (Table 2). Median values of Q_{exp} thus tended to hover more closely around its overall mean than Q_{vern}. Pumping was comparatively low during May, the peak of the salmon smolt outmigration season, but comparatively high during July through September, when algal production in the river is usually at its highest (Figure 7).

From May 1983 to December 2001, the Head of Old River Barrier was in place for >15 days in 30 out of the 206 months (15%). The barrier was in mostly during the months of September (n=6), October (n=8) and November (n=9), to help provide fall attraction flows and improve water quality conditions in the ship channel during the salmon migration season, but was also in place during April (n=2) and May (n=5) as part of the VAMP experiment.

A scatter plot suggested that increasing flow at Vernalis had a generally beneficial effect on DO conditions in the ship channel (Figure 8). The correlation coefficient (r) between DO_{min} and Q_{vern} was indeed positive (r=0.57) and highly significant (p<0.0001). The LOWESS trend line indicated that this positive relationship was weak, however, at Q_{vern} <2,000 cfs and >4,000 cfs. By contrast, at intermediate flows, DO_{min} increased rapidly with Q_{vern} (Figure 8).

Export pumping (Q_{exp}) bore little relationship to DO_{min} until pumping exceeded about 8,000 cfs (Figure 9). At these higher-than-average export rates, DO_{min} declined with Q_{exp}. Thus, in contrast to Q_{vern}, the overall correlation between DO_{min} and Q_{exp} was negative and comparatively weak, though still highly significant (Table 3).

Neither flow-related factor was strongly correlated with water temperature in the ship channel (Figure 10). There was essentially no relationship with Q_{exp} (p=0.56) and only a weak negative correlation between Temp and Q_{vern} (Table 3).

Ammonia Loading

Average monthly NH_4-N loading to the ship channel from the City of Stockton's waste treatment ponds (AmmLd) ranged from 0 to 7,593 lbs/day, with an overall average of 1,971 lbs/day (Table 2). Lower-than-average loading typically occurred during April through August, whereas relatively high loading rates prevailed during the fall and winter months (Figure 11). Variability in loading (as evidenced by the length of the interquartile range) was highest during the fall months, especially October and November. Inter- and intra-annual variation in AmmLd was due mostly to variation in the concentration of NH_4-N in the effluent rather than in the effluent discharge, which typically averaged between 30 and 40 cfs.

Average monthly NH_4-N concentration in the ship channel ranged from 0.02 to 2.4 mg/L averaging 0.36 mg/L (n=195). This average value was 3.6-times higher than the average concentration in the San Joaquin River at Vernalis over the same period. Intra-annual variation in NH_4-N concentration in the ship channel paralleled the month-to-month pattern observed in ammonia loading from the treatment facility (Figure 12). Indeed, there was a strong positive correlation (r=0.57, p<0.0001, n=195) between NH_4-N loading to the ship channel and NH_4-N concentration in the ship channel (Figure 13). Collectively, these results indicated that a substantial percentage of the "extra" NH_4-N in the ship channel originated from the City of Stockton WWTF.

A scatter plot of DO_{min} against AmmLd suggested that ammonia loading had no effect on dissolved oxygen conditions in the ship channel, an initial impression supported by the nearly flat LOWESS trend line (Figure 14). A regression-tree analysis performed by Marc Vayssieres at DWR indicated, however, that AmmLd may have exerted a negative effect on DO_{min}, but only at relatively low flow and high water temperature. His analysis suggested a Q_{vern} threshold value of 3,241 cfs and a Temp threshold value of 21 C (Marc Vayssieres, pers. comm.). Plotting only the observations that met these criteria supported the hypothesis that AmmLd did indeed exert a negative effect on DO_{min} under warm, low flow conditions (Figure 14).

As one might have deduced from the general pattern of intra-annual variation in AmmLd (Figure 11), there was a negative correlation between AmmLd and average water temperature in the ship channel (Table 3). The LOWESS trend line suggested that this inverse relationship was stronger at Temp <18 C (the average for 1983-2001) than at higher Temp (Figure 15). By contrast, AmmLd was only weakly correlated with flow at Vernalis (Table 3) or with export pumping (Figure 16).

In situ Algal Biomass

Monthly average chlorophyll concentration in the ship channel at Buckley Cove (Chl_{ship}) ranged from 1.4 to 58 ug/L averaging 10.5 ug/L overall (Table 2). The health ("age") index spanned an order of magnitude (0.1 - 1.0), but averaged 0.54. Month-to-month variation in median Chl_{ship} suggested two peaks, one in spring and a second in the fall (Figure 17). Overall, however, the variation in Chl_{ship} was comparatively low (CV=76%). The health index seemed to follow a similar intra-annual pattern (Figure 18) and was also comparatively stable (CV=28%).

Some 58 taxa of algae were recorded at Buckley Cove on at least five occasions over the period of record. The most common, however, were diatoms (*Cyclotella, Melosira, Navicula, Nitzschia, Skeletonema, Synedra, Thallasiosira*) and green algae (*Ankistrodesmus, Chlamydomonas, Scenedesmus*). *Cryptomonas* and unidentified flagellates were also very common. Among the diatoms, *Cyclotella* was usually the most abundant, whereas among the greens, *Chlamydomonas* and other flagellated forms were usually most abundant. Monthly average abundance of *Cyclotella* in the ship channel peaked in April and May, declined to lower levels during summer and then peaked a second time during September with an abrupt drop in abundance thereafter (Figure 19). *Chalmydomonas* abundance also had two peaks, the first during February-March and the second during September-October.

Chl_{ship} was not significantly correlated with DO_{min} ($p=0.09$) as was evidenced by the scatter plot and LOWESS trend line (Figure 20). A plot of Chl_{ship} against monthly average water temperature in the ship channel suggested a peak at about 20 C (Figure 21), but Chl_{ship} was only weakly correlated with Temp (Table 3). Similarly, there was no systematic relationship between Chl_{ship} and either flow at Vernalis or monthly average exports at the CVP-SWP facilities (Figure 22). A plot of Chl_{ship} against AmmLd also indicated no intercorrelation between these two factors (Figure 23).

Upstream Algal Biomass

Monthly average chlorophyll concentration in the San Joaquin River at Vernalis (Chl_{vern}) ranged from 1.6 to 389 ug/L averaging 32 ug/L overall; about 3-times higher than in the ship channel

(Table 2). The health ("age") index ranged from 0.18 to 0.91 averaging 0.63. Suspended algae were thus on average more abundant and healthier upstream in the river than in the ship channel.

Month-to-month variation in median Chl_{vern} suggested a modest pulse in April and a much larger sustained pulse during the summer months (Figure 24). This more unimodal pattern differed markedly from the bimodal, spring-fall-pulse pattern observed in the ship channel (Figure 17). Given its 3-fold higher average value, Chl_{vern} was much more variable (CV=138%) than Chl_{ship} (CV=76%). The health index was generally above average during spring and summer with below average values prevailing during November through February (Figure 25).

The most commonly recorded taxa at Mossdale were the same as in the ship channel. Similarly, among the diatoms *Cyclotella* was by far the most abundant, whereas among the greens, *Chlamydomonas* and other flagellated forms were usually most abundant. Unlike the ship channel, however, where the abundance of *Cyclotella* and *Chlamydomonas* were comparable at all times of the year (Figure 19), *Cyclotella* was typically an order of magnitude more abundant than *Chlamydomonas* at Mossdale, except during the winter months (Figure 26).

Monthly average abundance of *Cyclotella* at Mossdale displayed a bell-shaped curve that (like Chl_{vern}) generally peaked in July. This mid-summer peak was not evident in the in the ship channel (Figure 27). By contrast, the general pattern of intra-annual variation in the abundance of *Chalmydomonas* at Mossdale was similar to the bimodal pattern documented for the ship channel. The spring peak at Mossdale occurred about a month later than in the ship channel, however, and both peaks were about twice as high at Mossdale (Figure 28).

In contrast to Chl_{ship}, which by itself bore no significant correlation with minimum DO in the ship channel (DO_{min}), there was a highly significant negative correlation ($r=-0.67$, $p<0.0001$) between DO_{min} and monthly average chlorophyll concentration in the San Joaquin River at Vernalis (Chl_{vern}). This inverse relationship between DO_{min} and upstream algal biomass was clearly evidenced by the steep downward slope of the LOWESS trend line (Figure 29).

Given the seasonal pattern of *Cyclotella* abundance at Mossdale (Figure 27), it was not surprising that Chl_{vern} was positively correlated with water temperature in the ship channel (Table 3). The slope of the trend line as Temp increased from 20 to 25 C suggested a 6 ug/L increase in Chl_{vern} per unit increase in Temp (Figure 30). By contrast, Chl_{vern} was negatively correlated ($r=-0.49$, $p<0.0001$) with average flow at Vernalis (Figure 31). Such negative correlations are often observed at river sites where *Cyclotella* or other euplanktonic algae (algae that grow only while suspended in the water column) are the most common form of suspended algae and indicate a classic dilution effect (Smith and Alexander 1983). By contrast, there was no intercorrelation between Chl_{vern} and Q_{exp} (Figure 31). Similarly, variation in ammonia loading to the ship channel was independent of variation in average chlorophyll concentration at Vernalis some 52 miles upstream (Figure 32).

Statistical Model

All of the factors hypothesized to have an effect on DO in the ship channel were highly significant variables in the multiple regression analysis. Addition of two interaction terms, one for the interaction between the partial effects of ammonia loading and flow at Vernalis and a second for the interaction between Q_{vern} and Chl_{vern}, significantly reduced residual error of the model ($p<0.02$). The resulting model was highly significant ($F=68.3$, $p<0.0001$, $n=206$) and explained some 74% of the variance in DO_{min} with a standard error of 0.88 mg/L or ±14% (Table 4).

The Durbin-Watson *d* statistic indicated that the model's residual error (i.e., the observed DO_{min} value minus the DO_{min} value predicted by the model) was not serially autocorrelated ($d=1.23$, 1st order auto-r=0.38, n=206). This hypothesis was supported by a residual plot against observation number sorted to form a time series (i.e., observation 1=May 1983, 2=June 1983, 3=July 1983...206=December 2001). This plot showed that the residual values were scattered randomly about the zero line (Figure 33). Moreover, the LOWESS trend line was essentially flat. Collectively, these results indicated that the multiple regression model estimates of error variance were unbiased and that the model was thus suitable for hypothesis testing.

A plot of residual values against the predicted values of DO_{min} calculated from the model revealed no systematic pattern of variation (Figure 34). This result indicated that the model did not suffer from heterogeneity of variance. Residual plots for water temperature (Figure 35), average flow at Vernalis (Figure 36) and all the other independent variables used in the multiple regression model (Figures 37 - 42) displayed the same shot-gun-like pattern of scattered data points and an essentially flat LOWESS trend line. These results confirmed the validity of the homogeneity of variance assumption and the appropriateness of a least-squares linear regression model for this data set. Consequently, the model could be used as a tool for comparing alternative solutions to the DO problem in the ship channel.

Comparison of Alternatives

The multiple regression model was used to predict DO deficits for each month under the 36 alternative-scenario combinations defined in Table 1 (Table 5). Comparisons among and within alternatives revealed a number of differences. These differences included the magnitude of the annual cumulative DO deficit (CDOD), the timing of the greatest monthly DO deficit, the effect of opening or closing the HORB, and the effect of *in situ* algal production.

Not surprisingly, the "No Action" alternative, which represented low flow conditions exacerbated by high ammonia loading and high upstream algal biomass (Table 1), had the highest CDOD values. Averaged over all six scenarios, the CDOD for "Alternative A" was 990,675 lbs/year (Table 5). This result indicated that under these "do-nothing-worst-case" conditions, a minimum of about one million pounds of oxygen per year would have to be artificially injected into the ship channel to meet a year-round 5 mg/L DO objective.

Among the "do something" alternatives, "Alternative D" had the next highest CDOD value (Figure 43). This alternative was formulated to provide information about how the system would respond if it were managed to ensure that flows at Vernalis were maintained at their median monthly levels (Table 1 in Jones & Stokes 2001) while allowing AmmLd and Chl_{vern} to remain high. Under these circumstances, the model indicated that nearly 800,000 lbs/year of artificial oxygenation would be required to ensure that DO in the ship channel would not decline to <5 mg/L.

Reducing upstream chlorophyll to half its historical average ("Alternative C") performed slightly better than "Alternative D," but still resulted in a substantial annual deficit. Under this alternative, Q_{vern} would remain low while AmmLd would stay high. On average, the results of the model indicated that this alternative would require about 600,000 lbs of artificial oxygenation each year; a 40% improvement over the "No Action" alternative (Figure 34).

"Alternative B," which imposed a 2 mg/L NH_4-N effluent limit on the City of Stockton's wastewater treatment facility, had among the lowest CDOD values. This alternative, which allowed Q_{vern} to remain low and Chl_{vern} to remain high, had an average CDOD of about 280,000 lbs/year; substantially lower than the averages for alternatives "C" and "D" (Figure 43). This result indicated that nitrification exerted a greater effect on DO conditions in the ship channel than flow or upstream algal biomass.

In contrast to alternatives "B," "C" and "D," which changed only one factor (flow, Chl_{vern} and AmmLd, respectively) as a way to improve DO conditions in the ship channel, the "Systech Alternative" ("Alternative F") required some change in all three factors at once. In effect, this alternative called for a net flow at Stockton of 1,000 cfs and modest (25%) cuts in ammonia loading and upstream algal biomass (Chen and Tsai 2001). Applying the statistical model to these conditions indicated that the average CDOD would be reduced to 183,600 lbs/year; a substantial improvement over the single-action alternatives and a 5.4-fold improvement over the "No Action" alternative (Figure 43). Moreover, the "Systech Alternative" was the only one to yield a scenario under which no artificial oxygenation would be necessary to meet the 5 mg/L objective (Table 5).

Of the six alternatives evaluated, "Alternative E" generated the lowest average CDOD value. This alternative called for a substantial (2-fold) reduction in upstream chlorophyll concentration and the imposition of a 2 mg/L NH_4-N effluent limit on the WWTF. In contrast to "Alternative F," however, this alternative assumed low Vernalis flow and thus much lower net flows at Stockton (Table 1). Under these less-than-ideal hydraulic circumstances, CDOD nevertheless averaged about 100,000 lbs/year; a ten-fold improvement over the "No Action" condition (Figure 34). This result indicated that the DO deficit in the ship channel could be nearly eliminated using only point and non-point source control methods. But, like all the other alternatives evaluated, the "Alternative E" results also indicated that some artificial oxygenation would on average be required at some times during the year to consistently meet a 5 mg/L DO objective.

The timing of the lowest monthly DO deficit also varied among alternatives. Under the "No Action" alternative, the lowest deficit (3.5 mg/L) occurred in September. Similarly, the worst DO conditions under alternatives "C" (reduce Chl_{vern}) and "D" (boost flow) also occurred in September (Table 5). By contrast, the two alternatives requiring a 2 mg/L NH_4-N effluent limit ("B" and "E") shifted the maximum deficit to July. The "Systech Alternative" generated an intermediate response in which the worst conditions occurred in August (Figure 44).

Collectively, these results indicated that nitrification of ammonia loading from the WWTF exerted its greatest effect on DO at the beginning of fall, when NH_4-N concentration in the effluent begins to increase dramatically (Figure 11), whereas upstream algal biomass exerted its greatest effect when upstream algal production peaks in July (Figure 24).

For all the alternatives, installing the barrier at the head of Old River tended to increase DO_{min} (Figure 45). The effect of HORB on CDOD, however, differed among alternatives in part because barrier installation increases net flow in the ship channel. Thus for example, at a medium level of Chl_{ship}, HORB had essentially no effect on DO conditions under "Alternative B" (2 mg/L NH_4-N effluent limit), whereas under the "Systech Alternative" ("F"), installing the barrier reduced CDOD by 71% (Table 5). Similarly, under alternatives "D" and "E," installing the barrier improved DO conditions (reduced CDOD) by 29% and 57%, respectively. By contrast, under the "No Action" alternative and "Alternative C," the model suggested that installing the barrier could actually increase the amount of artificial oxygenation required to meet the 5 mg/L objective (Figure 46).

In contrast to the HORB effect, increasing Chl_{ship} increased DO_{min} (Figure 47) and reduced CDOD under all circumstances. Within a given alternative, the expected reduction in CDOD as Chl_{ship} increased from its monthly 10^{th} percentile value to its 90^{th} percentile value ranged on average from 69% under the "No Action" conditions to nearly 7-fold under "Alternative E" (Figure 48). The only scenario under which CDOD was zero, was the "Systech Alternative" with the HORB in place and a high level of *in situ* algal biomass (Table 5). These results indicated that *in situ* algal production on balance has tended to improve DO conditions in the ship channel.

Discussion

The statistical model generated from 19 years of compliance monitoring data (Table 4) explained a surprisingly high percentage of the variance in monthly minimum DO in the ship channel. More residual error was expected given the course (monthly) time step of the analysis and the fact that water quality conditions for many months were based on a single observation. Also, the model does not include a number of factors known to affect or suspected of affecting DO_{min} in the ship channel. Examples of factors not represented in the model include wind, which affects surface aeration, and spring-neap or other tidal flow effects. Also missing are variables representing grazing by zooplankton, clams or other herbivores. Nevertheless, the model is quite "well behaved" in its conformation with all of the assumptions regarding serial autocorrelation (Figure 33) and homogeneity of variance required for valid multiple regression analysis (Figures 34- 42). Moreover, the average error of the statistical model (14%) compares favorably with the 10% average error estimated for the Systech model (Chen and Tsai 2000). Thus, the statistical model provides a legitimate tool for improving understanding of the factors regulating DO in the ship channel and for comparing the likely efficacy of proposed management actions.

The statistical model confirmed that temperature, hydraulic conditions, ammonia loading, *in situ* algal production and upstream algal production all exert significant effects on DO conditions in the ship channel (Table 4). The predicted response of the system to a variety of hypothetical management actions (Table 5) indicated, however, that some factors may not be as effective in controlling DO in the ship channel as previously thought, whereas others may be much more important than might have been expected. These disparities have a number of implications for future modeling, monitoring or management of the system.

The negative effect of increasing water temperature on DO_{min} was not surprising. The magnitude of this effect on DO_{min} was not evaluated further in the comparative analysis of alternatives (Table 5) because there is little one can do to manage this property of the system. For comparative purposes, Temp was allowed to vary from month-to-month at its 90^{th} percentile value. Thus, like the presence of the ship channel itself, high water temperature was assumed to be just another adverse background condition for the purpose of comparing the effects of factors that can be managed.

By contrast, the less-than-stellar performance of flow enhancement as a tool for improving DO conditions in the ship channel was surprising. A greater reduction in the cumulative DO deficit (CDOD) was expected given the importance of hydraulic residence time (T_h) in regulating all the processes that consume or deliver DO in the ship channel. This result suggests that, within the range of flows considered, the beneficial effects of decreased T_h are more than offset by the increased amount of artificial oxygenation required to raise DO in the ship and by the negative effects associated with increased loading of algal biomass or other oxygen-consuming material from upstream. This finding has important management implications.

As a management action, the "boost flow" alternative ("D" in Table 5) called for maintaining Q_{vern} at its historical median level (the "2-year return flow in Jones & Stokes 2001). In a dry year (say, Q_{vern} at its 10^{th} percentile value), this management action would require the release of some 500,000 ac-ft of stored water from eastside tributaries (or the equivalent amount of auxiliary pumping via Grant Line Canal) just for the months of June through October. And yet, the average improvement in CDOD would be only 20% over the "No Action" alternative

(Table 5). Such a modest return on such a large investment would make little ecologic or economic sense and would presumably be challenged under the "waste not" doctrine of California water law. More modest levels of flow enhancement may, however, prove beneficial if combined with other management actions.

The partial coefficient associated with export pumping in the multiple regression model (Table 4) was negative, indicating that if all other factors were held constant, decreasing Q_{exp} would tend to increase DO_{min} in the ship channel. The magnitude of this partial effect was not examined further in the comparative analysis, however, because a substantial reduction in Q_{exp} was not considered a viable solution to the DO problem. If anything, Q_{exp} is likely to increase over the next 30 years given the goals outlined in the long-term water plan for the State of California (Bulletin 160). Thus, for this analysis, Q_{exp} (like temperature) was held at its 90th percentile value as just another adverse background condition for comparing management alternatives.

The beneficial effect of installing the HORB on DO_{min} in the ship channel (Figure 47) presumably stems from the fact that this action roughly doubles the flow reaching the ship channel and thus reduces T_h by about one-half. This assumption has underlain HORB operations during the fall months for decades. And yet, under the worst case alternative and several other management scenarios, installing the barrier could actually increase the amount of artificial oxygenation required to meet a 5 mg/L DO objective (Table 5). The comparative analysis of predicted CDOD values suggests that installing the barrier would be most beneficial when combined with actions that substantially reduce ammonia and upstream algal loading to the ship channel (alternatives "E" and "F" in Table 5). Given that "Alternative B" (which imposes 2 mg/L effluent limit on NH_4-N) was twice as effective as "Alternative C" (which cuts upstream algal biomass by half), the results indicate that decreasing T_h in the ship channel (by increasing Q_{vern} or installing the HORB) reduces CDOD by virtue of its effect on nitrification rather than some other process. Moreover, the ameliorative effect of reducing T_h is apparently able to overcome any negative effects associated with the resulting concomitant increase in algal biomass loading from upstream.

The predicted efficacy of imposing a 2 mg/L NH_4-N limit on the City's effluent as a means to improving DO conditions in the ship was also surprising. The Systech model had estimated that decay of algal biomass and other organic matter from upstream on average consumes some 6,900 kg of oxygen/day, whereas nitrification in the ship channel uses up only 1,600 kg/day (Chen and Tsai 2001). It would therefore have been expected that "Alternative C" (halve upstream Chl) would have reduced CDOD to a 4-fold greater extent than "Alternative B." Instead, the results indicate that limiting the concentration of NH_4-N in the City's effluent to 2 mg/L would be on average twice as effective in reducing CDOD than halving upstream algal biomass (Table 5). Both alternatives assume the same low flow conditions. Thus, these results suggest that the Systech model may be underestimating the magnitude of nitrification in the ship channel.

Nitrification is a relatively slow process conducted by very specialized forms of bacteria. Doubling times for nitrifiers are on the order of days, compared to hours for the heterotrophic bacteria that oxidize dead algae or other forms of organic matter (Chapra 1997). Consequently, the magnitude of oxygen consumption due to nitrification could be expected to be highly sensitive to T_h in the ship channel. Also, one might expect that the slow-growing nitrifiers would have evolved over time to adopt any strategies available that would reduce their loss rate from the system. Growing on the riverbed or attaching themselves to suspended particulate matter would be two strategies for reducing this loss rate.

The Systech model implicitly assumes that the nitrifiers and all the ammonia they are converting into nitrate move through the system at the same rate as the water. In other words, the Systech model assumes that the average residence time of the nitrifiers equals the average hydraulic residence time. If instead, however, the nitrifiers are assumed to be attached to suspended sediment or fine particulate organic matter, then the average residence time of the nitrifiers would be equal to the average residence time of total suspended solids (T_{tss}) in the ship channel. Litton (2002) has shown that T_{tss} in the ship channel is on average some 3-times longer than T_h. Thus, the Systech model may underestimate by 300% the amount of time available in the ship channel for nitrification to exert its negative effect on DO. This mechanism could account for the disparity between the statistical model and the Systech model results.

The consistent increase in DO_{min} and reduction in CDOD with increasing Chl_{ship} suggest that *in situ* algal production has a net beneficial effect on DO conditions in the ship channel. This result can be explained as follows. Any algal biomass produced in the ship channel itself adds a certain quantity of photosynthetically-generated oxygen to the water column. Even if all of this biomass rotted in place, the net effect on DO in the ship channel would be zero. Given that a substantial percentage of this *in situ* production probably gets washed downstream by tidal action alone, it is entirely consistent with the principle of mass balance that algal production in the ship channel should on balance reduce rather than increase the annual DO deficit. This finding too has potentially important management implications, but to understand them requires some knowledge about the ecology of the most common forms of algae inhabiting the system.

Upstream algal production is dominated by *Cyclotella*. *Cyclotella* are small (<15-microns in diameter) disk-shaped diatoms that live within a dense (compared to water) frustule that they synthesize from silica. Each one lives as a solitary, free-floating cell that depends entirely on turbulence to move vertically within the water column. When these algae are transported from the shallow, turbulent, well-lit waters of the river into the much deeper and darker water of the ship channel, they quickly settle out of the euphotic zone with little chance of return and so eventually run out of energy, die and begin to decompose.

By contrast, *Chlamydomonas* and most of the other flagellated forms that usually make up a greater percentage of total phytoplankton density in the ship channel, can actively maintain their position near the well-lit surface of the water column. This ability to move "at will" is particularly advantageous when the water column is thermally stratified, even if only slightly. *Chlamydomonas*, however, must retract their flagella before dividing asexually. Similarly, the zygotes formed by sexual reproduction usually have thick cell walls and must undergo a resting period on the river bottom before they can germinate (Smith 1933). Thus, a substantial amount of the algal biomass produced in the ship channel proper (as opposed to being imported from the river upstream) is actually being synthesized on or near the channel bed. Once cell division has been completed, however, the daughter cells either "swim" up or get swept up into the water column where they can start photosynthetically adding oxygen to the system.

All of the alternatives evaluated in this analysis required some artificial aeration to meet a 5mg/L DO objective (Table 5). The likelihood that most *in situ* photosynthesis is being performed by *Chlamydomonas* and other motile taxa may thus be an important consideration in selecting the method of artificial aeration to use. Methods that would increase circulation enough to destratify the water column could overpower the ability of the algae to swim up to or maintain their position in the illuminated near-surface water. This disruption would reduce the time algae would have to absorb light and fix carbon for subsequent use in synthesizing new biomass lower down in the water column. Thus, methods that minimize disruption of thermally stratified conditions might be preferable to those that promote circulation. Similarly, given that photosynthesis peaks in the afternoon, whereas daily minimum DO usually occurs early in the morning, artificial aeration may be most effective if applied only at night.

The negative effect of upstream algal biomass on DO_{min} was not surprising, but the limited predicted benefit associated with a 2-fold reduction in Chl_{vern} was unexpected. Although "Alternative C" was on average predicted to be about 20% more effective in reducing CDOD than the flow enhancement alternative ("D"), it did not come close to eliminating the DO deficit until it was combined with "Alternative B" (i.e., as "Alternative E"). Greater improvement was expected because the BOD loading associated with upstream algal biomass is usually an order of magnitude greater than all other sources of BOD loading to the ship channel (McCarty 1969; Schanz and Chen 1993; Jones & Stokes 1998; Lee and Jones-Lee 2000). One explanation for this finding is that a substantial amount of algal biomass is being lost between Vernalis (or Mossdale) and the ship channel, so that Chlvern overestimates upstream algal biomass entering the ship channel. Processes that could conceivably remove this much biomass include agricultural diversions (Quinn and Tulloch 2002) and grazing by zooplankton or benthic invertebrates (Alpine and Cloern 1992). Alternatively, the less-than-expected impact of reducing Chl_{vern} may indicate instead that DO dynamics in the ship channel is a "time-concentration phenomenon" rather than a strict function of BOD loading rates (Stowell 2001).

Finally, the finding that the timing of the worst DO conditions may differ among alternatives (Figure 44) is also of potential management interest. Of the six alternatives evaluated, the two requiring a 2 mg/L limit on effluent ammonia concentration shifted the worst DO conditions from the fall months (when Chinook salmon are migrating through the ship channel to spawning grounds upstream) to the summer. Thus, in addition to substantially reducing CDOD overall, control of ammonia loading to the ship channel may also do more to improve conditions for migrating fall run Chinook salmon than any of the other potential management actions.

Summary

Regression analysis of historical data compiled from IEP and other compliance monitoring activities showed that monthly minimum DO in the ship channel (DO_{min}) was largely (R^2=0.73, n=206) a function of water temperature, flow at Vernalis, barrier installation at the head of Old River, export pumping, ammonia loading from the City of Stockton's wastewater treatment facility, *in situ* algal production and upstream algal production. Temperature, export pumping, ammonia loading and upstream algal biomass exert a negative effect on DO_{min}, whereas increasing flow and *in situ* algal production tend to improve DO conditions in the ship channel. The effect of installing the barrier was mixed, but generally beneficial. Application of the model to a range of potential management scenarios indicated that: (1) increasing flow would have less of a beneficial effect on DO_{min} than expected; (2) reducing ammonia loading would have a much greater beneficial effect than expected from previous modeling results; (3) *in situ* algal production has a positive effect on DO_{min}; (4) halving the amount of upstream algal biomass would substantially improve DO conditions in the ship channel, but by much less than suggested by previous analyses; (5) the best performing alternative considered in this analysis would impose a 2 mg/L NH4-N effluent limit on the City of Stockton's wastewater treatment facility and would halve upstream chlorophyll concentration; (6) however, short of filling in the ship channel to a depth of 8 ft, no realistic combination of management alternatives is likely to guarantee year-round compliance with a 5 mg/L DO objective; (7) consequently, artificial aeration will probably be required during some months of most years; and (8) management scenarios that include reduction of ammonia loading may benefit salmon more than other management actions because reducing ammonia loading would shift the timing of maximum DO deficits from fall to summer.

Recommendations

1. The historical record of continuous monitoring data at Rough and Ready Island is remarkably good, but describes only conditions near the surface and contains many missing values. USBR and DWR should conduct a pilot study to evaluate new DO measurement technologies (e.g., optical fluorescence) that may be more reliable than the existing technology. These agencies should also pursue funds to begin monitoring near the channel bottom as well as near the surface. It will probably also become necessary to monitor at one or more locations downstream of Rough & Ready Island, especially after artificial oxygenation begins.

2. The results of this analysis seem to suggest that a substantial reduction in ammonia loading will be required to "fix" the DO problem in the ship channel. Short of spending the $40 million or so required to install nitrification facilities, the only option the City of Stockton has for accomplishing this feat is to reduce the NH_4-N concentration of water in its system of ponds. It is not clear why NH_4-N increases so dramatically in the fall (Figure 11). A preliminary analysis indicates that this increase is not simply a function of decreasing temperature or reduced light. It is recommended that the City embark on some field studies to better understand how the algal-microbial community of its pond system is processing inflowing ammonia-N, with a view toward developing some "soft-engineering" alternative to the high-cost "hard-engineering" solution that would be necessitated under a 2 mg/L effluent limit.

3. The possibility that the dynamics of nitrification in the ship is linked to the dynamics of suspended solids should be further investigated in the field and in future modeling runs.

4. Given the apparent importance of ammonia loading to DO dynamics in the ship channel, it would be worthwhile to perform a more detailed statistical analysis of this effect using daily DO, temperature, flow and ammonia loading data. This analysis may require time series (e.g., Jassby and Powell 1990), Bayesian inference (e.g., Reckhow 1990) or other more sophisticated techniques than the linear regression approached used here on the monthly-averaged data.

5. The results of this analysis suggest that artificial aeration will probably be required to ensure compliance under all circumstances and at all times of the year. Any studies designed to determine how best to accomplish this task should also consider any potential adverse effects on *in situ* algal photosynthesis.

6. Among the alternatives examined so far, the one that combines a 2 mg/L effluent limit for ammonia and a halving of upstream algal biomass seems to offer the greatest likelihood of success in eliminating DO deficits in the ship channel. Thus, in addition to evaluating how best to reduce ammonia loading, an analysis of what would be required to reduce Chl at Vernalis to half its present average value should be conducted.

7. It would be worthwhile to have someone on the TAC who is adept at building "gaming models" convert the SAS code and data sets used for this analysis into an easier-to-use spreadsheet model. Such a model could be quickly developed and made available for use by the Steering Committee in its efforts to develop a TMDL implementation plan before December 31, 2002.

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Figure 11. Box plot of summary statistics for monthly average NH_4-N loading to the ship channel from the City of Stockton wastewater treatment facility, 1983-2001.

Figure 12. Box plot of summary statistics for monthly average NH_4-N concentration in the ship channel at Buckley Cove, 1983-2001.

Figure 13. Scatter plot of monthly average NH_4-N concentration in the ship channel *vs* NH_4-N loading to the ship channel 1983-2001. Curve depicts the LOWESS trend line.

Figure 14. Scatter plots of monthly average daily minimum DO (DO_{min}) *vs* monthly average NH_4-N loading to the ship channel, 1983-2001. Curves depict the LOWESS trend lines for the full data set (empty circles, n=206) and for warm, low flow conditions only (solid squares, n=63).

Figure 15. Scatter plot of monthly average NH_4-N loading to the ship channel *vs* monthly average water temperature, 1983-2001. Curve depicts the LOWESS trend line.

Figure 16. Scatter plot of monthly average NH_4-N loading to the ship channel *vs* monthly average discharge in the San Joaquin River near Vernalis (Q_{vern}) and CVP-SWP exports, 1983-2001. Curves depict the LOWESS trend lines for Vernalis flow (empty circles) and export pumping (empty squares).

Figure 17. Box plot of summary statistics for monthly average chlorophyll concentration in the ship channel at Buckley Cove, 1983-2001.

Figure 18. Box plot of summary statistics for monthly average “health” or “age” index of suspended algal biomass in the ship channel at Buckley Cove (Light 40), 1983-2001.

Figure 19. Average monthly abundance of *Cyclotella* and *Chlamydomonas* in the ship channel at Buckley Cove (Light 40), 1983-1996.

Figure 20. Scatter plot of monthly average daily minimum DO (DO_{min}) in the ship channel *vs* monthly average chlorophyll concentration in the ship channel, 1983-2001. Curve depicts the LOWESS trend line.

Figure 21. Scatter plot of monthly average chlorophyll concentration in the ship channel *vs* monthly average water temperature in the ship channel, 1983-2001. Curve depicts the LOWESS trend line.

Figure 22. Scatter plot of monthly average chlorophyll concentration in the ship channel *vs* monthly average discharge at Vernalis or CVP-SWP exports, 1983-2001. Curve depicts the LOWESS trend line.

Figure 23. Scatter plot of monthly average chlorophyll concentration in the ship channel *vs* monthly average loading of ammonia-N from the City of Stockton's wastewater treatment ponds, 1983-2001. Curve depicts the LOWESS trend line.

Figure 24. Figure 18. Box plot of summary statistics for monthly average chlorophyll concentration in the San Joaquin River at Vernalis, 1983-2001.

Figure 25. Box plot of summary statistics for monthly average "health" or "age" index of suspended algal biomass in the San Joaquin River at Vernalis, 1983-2001.

Figure 26. Average monthly abundance of *Cyclotella* and *Chlamydomonas* in the San Joaquin River at Mossdale, 1983-1996.

Figure 27. Average monthly abundance of *Cyclotella* in the ship channel near Buckley Cove and in the San Joaquin River at Mossdale, 1983-1996.

Figure 28. Average monthly abundance of *Chlamydomonas* in the ship channel near Buckley Cove and in the San Joaquin River at Mossdale, 1983-1996.

Figure 29. Scatter plot of monthly average daily minimum DO (DO_{min}) in the ship channel *vs* monthly average chlorophyll concentration in the San Joaquin River at Vernalis, 1983-2001. Curve depicts the LOWESS trend line.

Figure 30. Scatter plot of monthly average chlorophyll concentration in the San Joaquin River at Vernalis *vs* monthly average water temperature in the ship channel, 1983-2001. Curve depicts the LOWESS trend line.

Figure 31. Scatter plot of monthly average chlorophyll concentration in the San Joaquin River at Vernalis *vs* monthly average discharge at Vernalis or CVP-SWP exports, 1983-2001. Curve depicts the LOWESS trend line.

Figure 32. Scatter plot of monthly average chlorophyll concentration in the San Joaquin River at Vernalis *vs* monthly average loading of ammonia-N from the City of Stockton's wastewater treatment ponds, 1983-2001. Curve depicts the LOWESS trend line.

Figure 33. Residual error of the multiple regression model plotted against observation number sorted to form a continuous monthly time series, May 1983-December 2001.

Figure 34. Plot of residual error *vs* monthly average daily minimum DO (DO_{min}) in the ship channel predicted from the multiple regression model.

Figure 35. Plot of residual error *vs* monthly average water temperature in the ship channel.

Figure 36. Plot of residual error *vs* monthly average flow at Vernalis.

Figure 37. Plot of residual error *vs* monthly average CVP-SWP exports.

Figure 38. Plot of residual error *vs* monthly average ammonia-N loading from the City of Stockton's wastewater treatment ponds.

Figure 39. Plot of residual error *vs* monthly average chlorophyll concentration in the ship channel.

Figure 40. Plot of residual error *vs* monthly average chlorophyll concentration in the San Joaquin River at Vernalis.

Figure 41. Plot of residual error *vs* monthly values of the ammonia loading-Vernalis flow interaction term used in the multiple regression model.

Figure 42. Plot of residual error vs monthly values of the Vernalis chlorophyll-Vernalis flow interaction term used in the multiple regression model.

Figure 43. Comparison of the average cumulative dissolved oxygen deficit (lbs/year) predicted by the statistical model for the six management alternatives summarized in Table 1 (see Table 5).

Figure 44. Comparison of the predicted monthly average dissolved oxygen deficit in the ship channel under six management alternatives with HORB closed and low *in situ* chlorophyll concentration. Note the shift in the annual maximum deficit from September to July for alternatives involving reduction in ammonia loading rate (see Table 5).

Figure 45. Effect of installing the head of Old River barrier (HORB) on the dissolved oxygen deficit in the ship channel under six management alternatives (see Table 5).

Figure 46. Effect of installing the head of Old River barrier (HORB) on the cumulative dissolved oxygen deficit assuming median *in situ* chlorophyll concentration (see Table 5).

Figure 47. Effect of *in situ* chlorophyll concentration on the dissolved oxygen deficit in the ship channel under six management alternatives (see Table 5).

Figure 48. Effect of *in situ* chlorophyll concentration on the cumulative dissolved oxygen deficit in the ship channel under six management alternatives (see Table 5).

Table 1. Matrix of alternatives compared using the statistical model.

Alternative	Conditions		Scenario	HORB	Chl_{ship}
No Action	Low Q_{vern}	10th percentile	A1	Out	Low
	High AmmLd	90th percentile	A2	In	"
	High Chl_{vern}	90th percentile	A3	Out	High
			A4	In	"
			A5	Out	Med
			A6	In	"
Reduce Ammnonia in Effluent	Low Q_{vern}	10th percentile	B1	Out	Low
	Low AmmLd	486 lbs/day	B2	In	"
	High Chl_{vern}	90th percentile	B3	Out	High
			B4	In	"
			B5	Out	Med
			B6	In	"
Reduce Upstream Chlorophyll	Low Q_{vern}	10th percentile	C1	Out	Low
	High AmmLd	90th percentile	C2	In	"
	Low Chl_{vern}	Half of mean	C3	Out	High
			C4	In	"
			C5	Out	Med
			C6	In	"
Boost Flow	Med Q_{vern}	50th percentile	D1	Out	Low
	High AmmLd	90th percentile	D2	In	"
	High Chl_{vern}	90th percentile	D3	Out	High
			D4	In	"
			D5	Out	Med
			D6	In	"
Reduce Ammonia and Upstream Chl	Low Q_{vern}	10th percentile	E1	Out	Low
	Low AmmLd	486 lbs/day	E2	In	"
	Low Chl_{vern}	Half of mean	E3	Out	High
			E4	In	"
			E5	Out	Med
			E6	In	"
Systech Alternative	Med Q_{vern}	2,200 or 1,200 cfs	F1	Out	Low
	Med AmmLd	25% cut in median	F2	In	"
	Med Chl_{vern}	25% cut in mean	F3	Out	High
			F4	In	"
			F5	Out	Med
			F6	In	"

Table 2. Summary statistics for variables used in this analysis. n=206, except for NH_4-N (n=195) and Total Kjeld-N (n=203)

Variable	Units	Mean	CV(%)	Min	Percentile 10th	Percentile 50th	Percentile 90th	Max
DO_{min}	mg/L	6.2	27	1.5	4.0	6.0	8.6	10.3
Saturation	%	63	23	17	45	62	82	94
Temperature	C	18.0	32	7.2	9.8	18.5	25.2	27.1
Q_{vern}	cfs	4,416	132	447	993	2,161	11,696	35,057
Q_{exp}	cfs	6,685	42	1,316	2,905	6,847	10,363	11,648
AmmLd	lbs/day	1,971	91	0	46	1,486	4,481	7,593
NH_4-N_{ship}	mg/L	0.36	120	0.02	0.04	0.19	0.87	2.4
Total Kjeld-N_{ship}	mg/L	1.1	59	0.2	0.5	0.9	1.9	3.7
Chl_{ship}	ug/L	10.5	76	1.4	4.5	8.5	18.0	58.4
Health $Index_{ship}$	---	0.54	27	0.1	0.34	0.56	0.73	1
Chl_{vern}	ug/L	32	136	1.6	6.9	18	63	389
Health $Index_{vern}$	---	0.63	21	0.18	0.46	0.64	0.79	0.91

Table 3. Spearman's rank-order correlation coefficients for variables used in the analysis.
(Bold signifies $p<0.05$; p-values in italics, n=206, except for NH_4-N_{ship} which has n=195)

	DO_{min}	%Saturation	Temp	Q_{vern}	Q_{exp}	AmmLd	NH_4-N_{ship}	Chl_{vern}	Chl_{ship}
DO_{min}	**1**	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*0.77*	*0.47*	*<0.0001*	*0.09*
%Saturation	**0.90**	**1**	*0.001*	*<0.0001*	*<0.0001*	*<0.0001*	*0.001*	*<0.0001*	*0.001*
Temp	**-0.61**	**-0.23**	**1**	*0.004*	*0.56*	*<0.0001*	*<0.0001*	*<0.0001*	*0.004*
Q_{vern}	**0.57**	**0.59**	**-0.20**	**1**	*0.68*	*0.03*	*0.31*	*<0.0001*	*0.003*
Q_{exp}	**-0.30**	**-0.35**	0.04	-0.03	**1**	*0.01*	*0.01*	*0.27*	*0.15*
AmmLd	-0.02	**-0.28**	**-0.44**	**-0.16**	**0.17**	**1**	*<0.0001*	*0.001*	*0.44*
NH_4-N_{ship}	0.05	**-0.25**	**-0.60**	-0.07	**0.18**	**0.57**	**1**	*<0.0001*	*0.31*
Chl_{vern}	**-0.67**	**-0.46**	**0.69**	**-0.49**	0.08	**-0.23**	**-0.29**	**1**	*0.06*
Chl_{ship}	0.12	**0.24**	**0.20**	**0.21**	-0.10	-0.05	-0.07	0.13	**1**

Table 4. Partial regression coefficients and associated error estimates for multiple regression model. ($n=206$, $F=68.3$, $p<0.0001$, $s=0.88$ mg/L, CV=14%, $R^2=0.74$)

Variable	Parameter estimate	Standard error	t value	p
Intercept	14.533	1.144	12.71	<0.0001
Temp	-0.156	0.017	-9.33	<0.0001
AmmLd	-0.00216	0.00038	-5.72	<0.0001
AmmLd*$LogQ_{vern}$	0.00057	0.00011	5.13	<0.0001
$LogChl_{vern}$	-2.547	0.66	-3.86	0.0002
$LogChl_{vern}$*$LogQ_{vern}$	0.527	0.233	2.27	0.02
HORB	0.713	0.208	3.43	0.0007
$LogQ_{exp}$	-1.36	0.293	-4.64	<0.0001
$LogChl_{ship}$	1.017	0.299	3.4	0.0008

Table 5. Calculated DO deficit (relative to 5 mg/L objective) for each month under 36 alternative-scenario combinations (see Table 1).

Alternative	Scenario	HORB	Chl_{ship}	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Cumulative Deficit (lbs DO/year)	Mean
No Action	A1	Out	Low	-1.2	-0.2	-0.7	-0.7	-0.7	-1.9	-2.2	-3.3	-3.5	-2.4	-1.7	-0.5	1,215,016	
	A2	In	"	-0.5	0.6	0	0	0	-1.2	-1.5	-2.6	-2.8	-1.7	-1	0.2	1,256,083	
	A3	Out	High	-0.7	0.3	-0.2	-0.1	0.1	-1.4	-1.6	-2.5	-2.9	-1.9	-1	0.1	711,253	
	A4	In	"	0	1	0.6	0.6	0.8	-0.7	-0.9	-1.8	-2.2	-1.2	-0.3	0.9	751,648	
	A5	Out	Med	-1	0.2	-0.4	-0.4	-0.3	-1.7	-1.9	-3.1	-3.2	-2.2	-1.4	-0.2	960,757	
	A6	In	"	-0.3	0.9	0.3	0.3	0.4	-1	-1.2	-2.4	-2.5	-1.5	-0.7	0.5	1,049,290	990,675
Reduce Ammnonia in Effluent	B1	Out	Low	1.4	1.3	0.8	0.1	-0.2	-1.6	-2	-1.8	-1.4	-0.4	0.8	1.4	364,646	
	B2	In	"	2.1	2	1.5	0.8	0.5	-0.9	-1.3	-1.1	-0.7	0.3	1.5	2.1	375,613	
	B3	Out	High	1.9	1.8	1.3	0.7	0.6	-1.1	-1.5	-1	-0.8	0.1	1.5	2	207,425	
	B4	In	"	2.6	2.5	2.1	1.4	1.3	-0.4	-0.8	-0.3	-0.1	0.8	2.2	2.7	150,174	
	B5	Out	Med	1.6	1.7	1.1	0.4	0.2	-1.4	-1.7	-1.6	-1.1	-0.2	1.1	1.7	286,133	
	B6	In	"	2.3	2.4	1.8	1.1	0.9	-0.7	-1	-0.9	-0.4	0.5	1.8	2.4	280,082	277,345
Reduce Upstream Chlorophyll	C1	Out	Low	-0.6	0.3	-0.2	-0.3	-0.1	-1.2	-1.6	-2.7	-2.8	-2	-1.3	0.1	760,760	
	C2	In	"	0.1	1	0.5	0.4	0.6	-0.5	-0.8	-2	-2.1	-1.3	-0.5	0.8	779,609	
	C3	Out	High	-0.1	0.8	0.4	0.4	0.7	-0.7	-1	-1.9	-2.2	-1.5	-0.6	0.7	439,725	
	C4	In	"	0.6	1.5	1.1	1.1	1.4	0	-0.3	-1.2	-1.5	-0.8	0.1	1.4	380,036	
	C5	Out	Med	-0.5	0.6	0.1	0.1	0.3	-1	-1.2	-2.5	-2.5	-1.7	-1	0.4	584,626	
	C6	In	"	0.3	1.3	0.8	0.8	1	-0.3	-0.5	-1.8	-1.8	-1	-0.3	1.1	607,694	592,075
Boost Flow	D1	Out	Low	1	1.1	0.4	0.2	0.2	-0.8	-1.5	-1.8	-1.8	-0.7	-0.6	0.7	1,192,604	
	D2	In	"	1.8	1.9	1.1	1	0.9	-0.1	-0.8	-1	-1.1	0	0.1	1.4	946,760	
	D3	Out	High	1.5	1.6	1	0.9	1	-0.4	-0.9	-1	-1.2	-0.2	0	1.3	603,515	
	D4	In	"	2.2	2.3	1.7	1.6	1.7	0.3	-0.2	-0.2	-0.4	0.5	0.8	2	252,688	
	D5	Out	Med	1.2	1.5	0.7	0.6	0.5	-0.7	-1.2	-1.6	-1.5	-0.4	-0.3	1	937,664	
	D6	In	"	1.9	2.2	1.4	1.3	1.3	0.1	-0.4	-0.9	-0.8	0.3	0.4	1.7	664,864	766,349
Reduce Ammonia and Upstream Chl	E1	Out	Low	2	1.8	1.3	0.5	0.4	-0.9	-1.4	-1.2	-0.7	0	1.3	2	196,968	
	E2	In	"	2.7	2.5	2	1.3	1.1	-0.2	-0.7	-0.5	0	0.7	2	2.7	129,260	
	E3	Out	High	2.5	2.2	1.9	1.2	1.2	-0.4	-0.8	-0.4	-0.1	0.5	1.9	2.6	79,437	
	E4	In	"	3.2	2.9	2.6	1.9	1.9	0.3	-0.1	0.3	0.6	1.2	2.6	3.3	9,623	
	E5	Out	Med	2.1	2.1	1.6	0.9	0.8	-0.7	-1.1	-1	-0.4	0.3	1.5	2.3	149,202	
	E6	In	"	2.8	2.8	2.3	1.6	1.5	0	-0.4	-0.3	0.3	1	2.3	3	64,589	104,846
Systech Alternative	F1	Out	Low	1.6	1.4	1	0.5	0.6	-0.3	-0.8	-0.8	-0.7	-0.2	0.6	1.7	453,600	
	F2	In	"	1.8	1.6	1.3	1	1.1	0.1	-0.4	-0.4	-0.5	-0.1	0.6	2.1	226,800	
	F3	Out	High	2.1	1.8	1.5	1.2	1.4	0.1	-0.3	0	-0.1	0.3	1.2	2.4	64,800	
	F4	In	"	2.3	2.1	1.8	1.6	1.9	0.5	0.2	0.4	0.1	0.4	1.3	2.7	0	
	F5	Out	Med	1.7	1.7	1.3	0.9	0.9	-0.2	-0.5	-0.6	-0.4	0	0.9	2	275,400	
	F6	In	"	2	2	1.6	1.3	1.4	0.3	-0.1	-0.2	-0.2	0.2	0.9	2.4	81,000	183,600

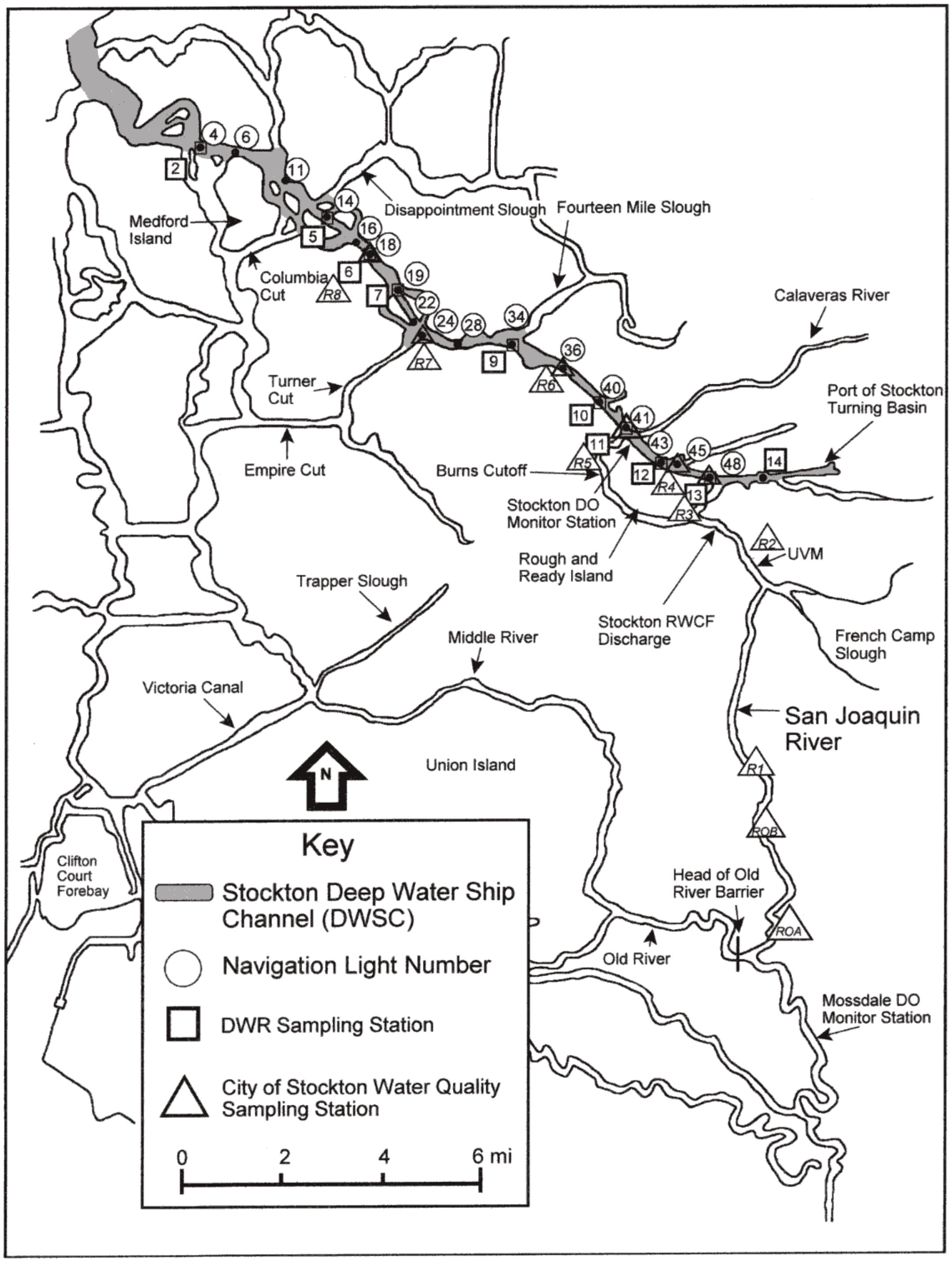

Figure 1. Map of Stockton deepwater ship channel (shaded) and vicinity. The Vernalis flow gage and water quality sampling station is located 2.6 miles downstream from the confluence with the Stanislaus River.

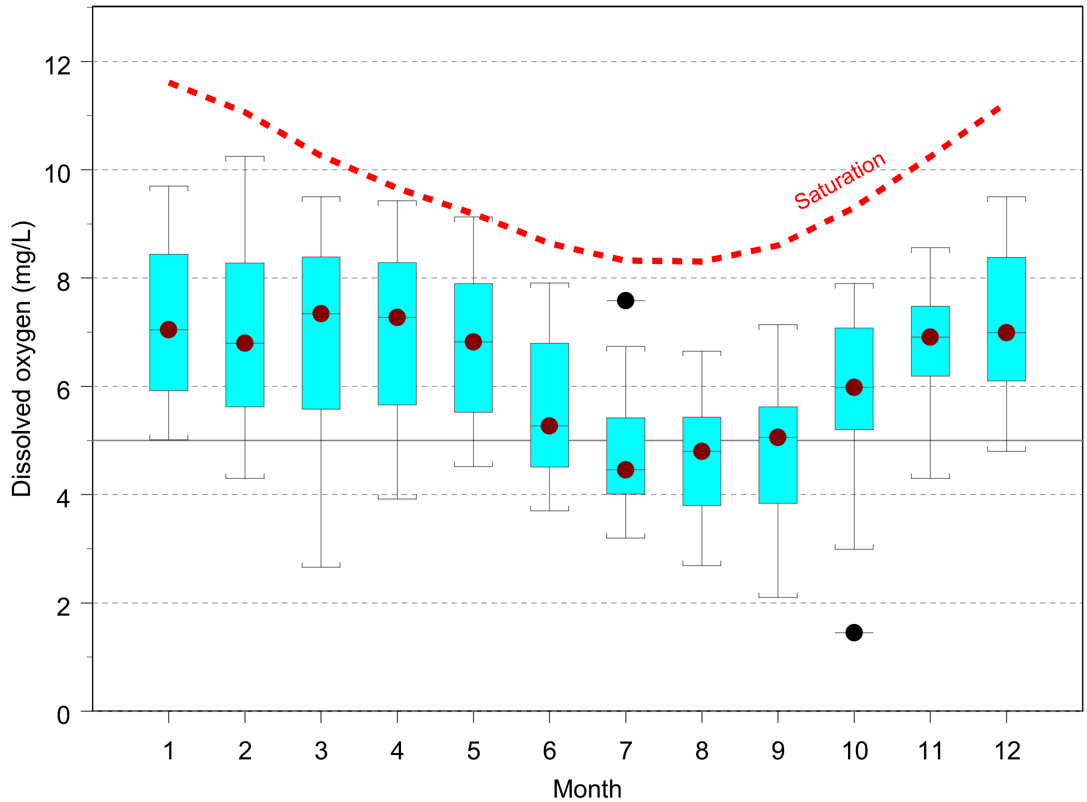

Figure 2. Box plot of summary statistics for monthly average values of daily minimum DO in the ship channel at the Rough and Ready Island continuous monitoring station (DO_{min}), 1983-2001 (n=19/month).

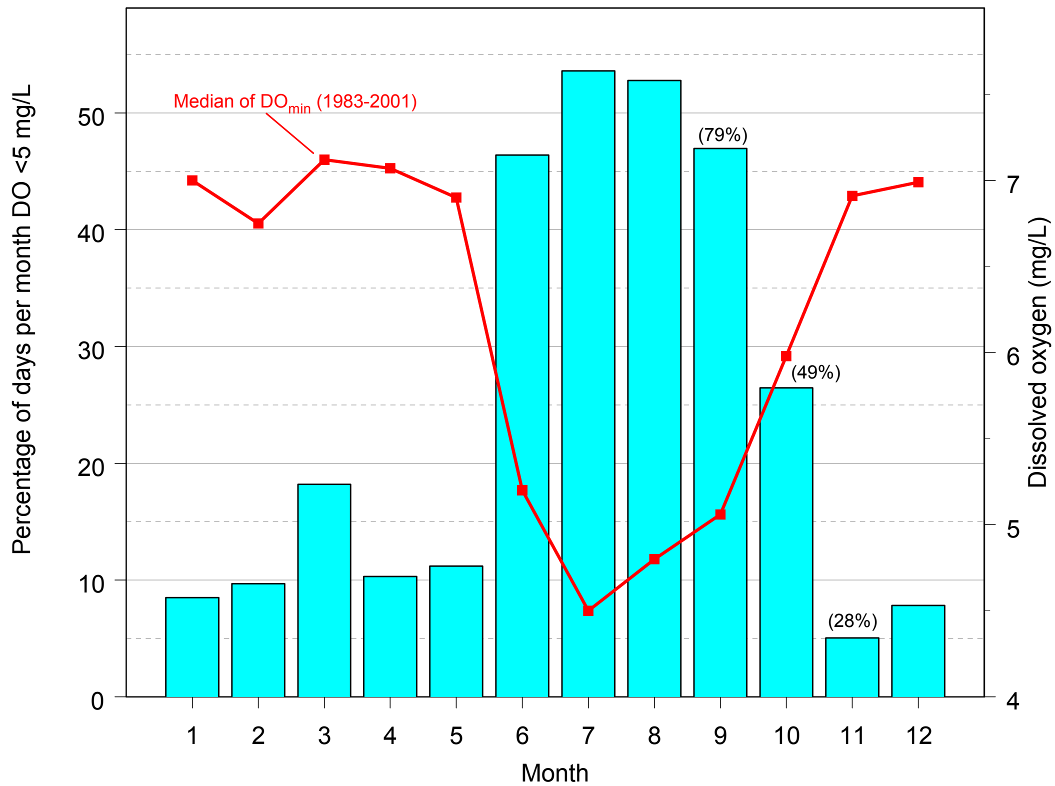

Figure 3. Frequency of daily minimum DO <5 mg/L in the ship channel at the Rough and Ready Island continuous monitoring station, 1983-2001 (n=377 to 543/month). Percentages in parentheses indicate the frequency of DO <6 mg/L during September-October.

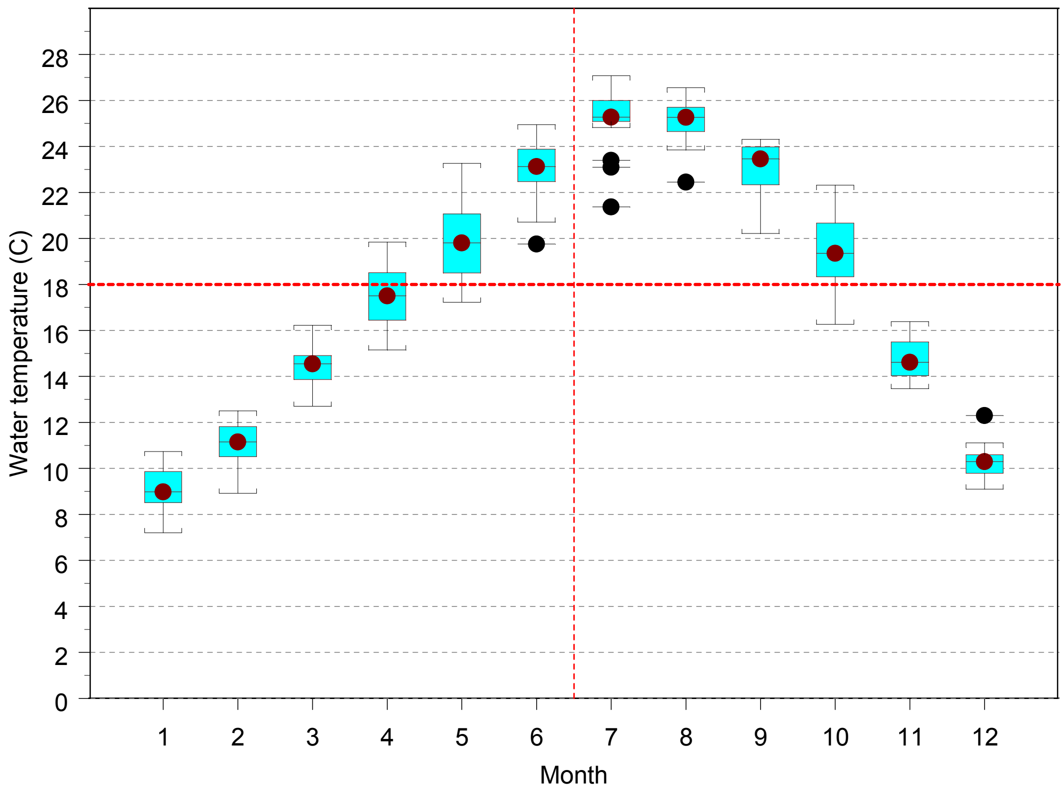

Figure 4. Box plot of summary statistics for monthly average values of daily mean water temperature in the ship channel at the Rough and Ready Island continuous monitoring station, 1983-2001 (n=19/month). Horizontal reference line is the overall mean value (Table 2).

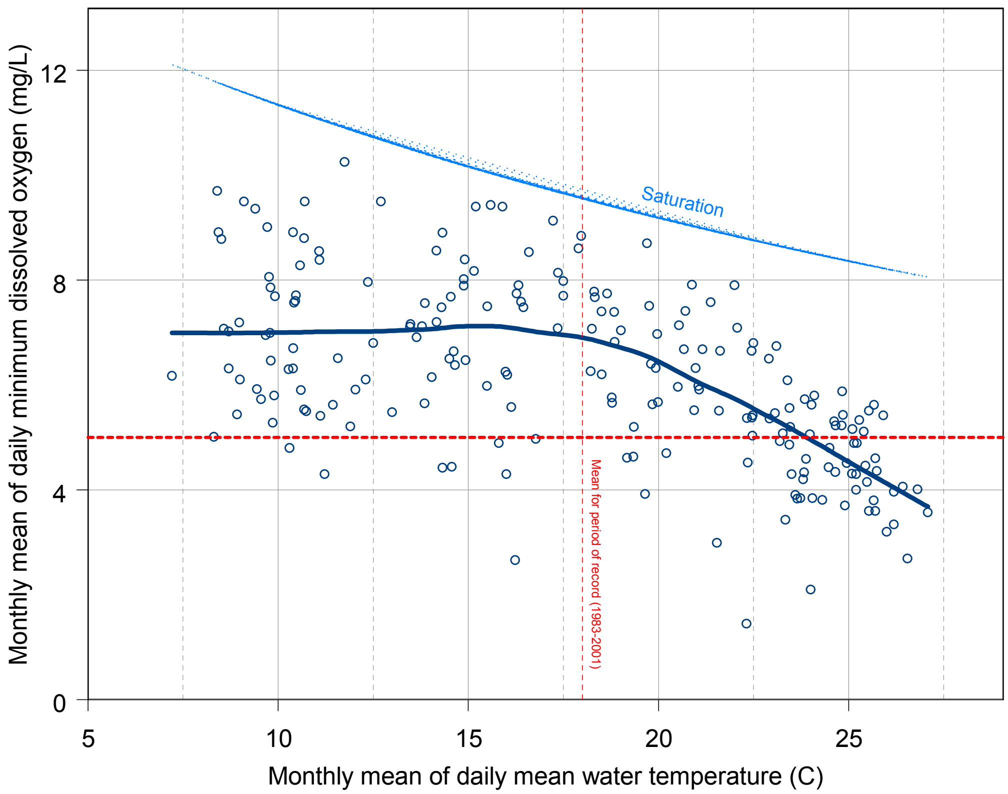

Figure 5. Scatter plot of monthly average daily minimum DO (DO_{min}) *vs* monthly average water temperature in the ship channel at Rough and Ready Island, 1983-2001. Curve depicts the LOWESS trend line.

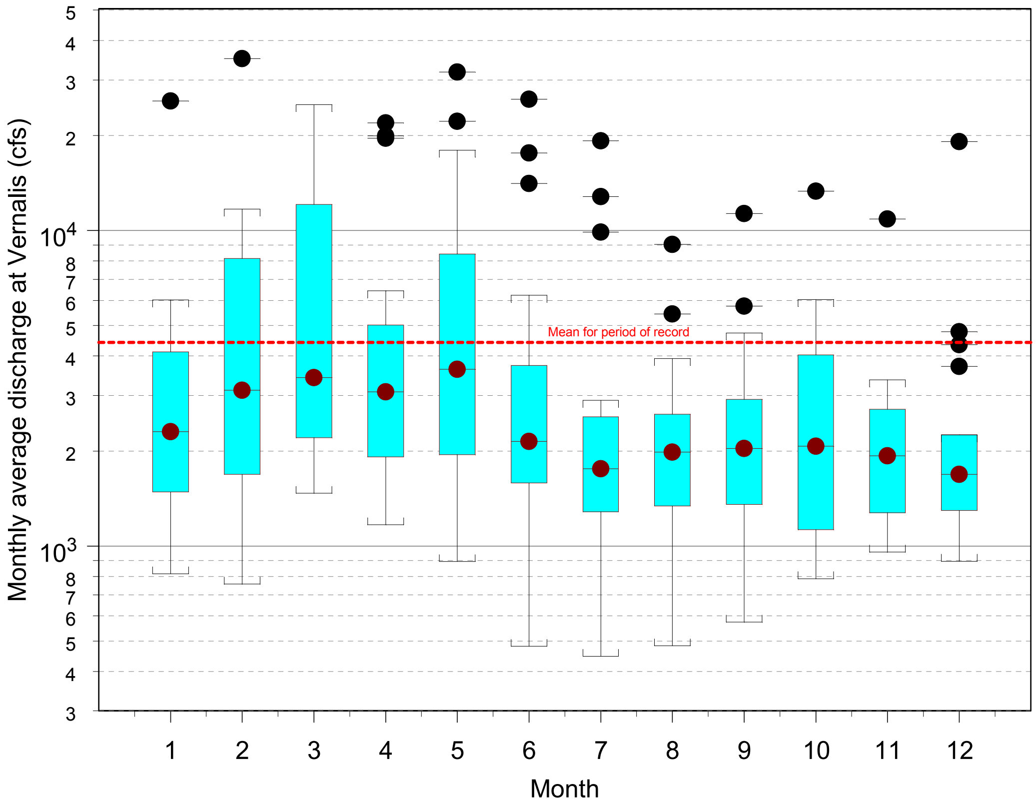

Figure 6. Box plot of summary statistics for monthly average discharge in the San Joaquin River near Vernalis (Q_{vern}), 1983-2001.

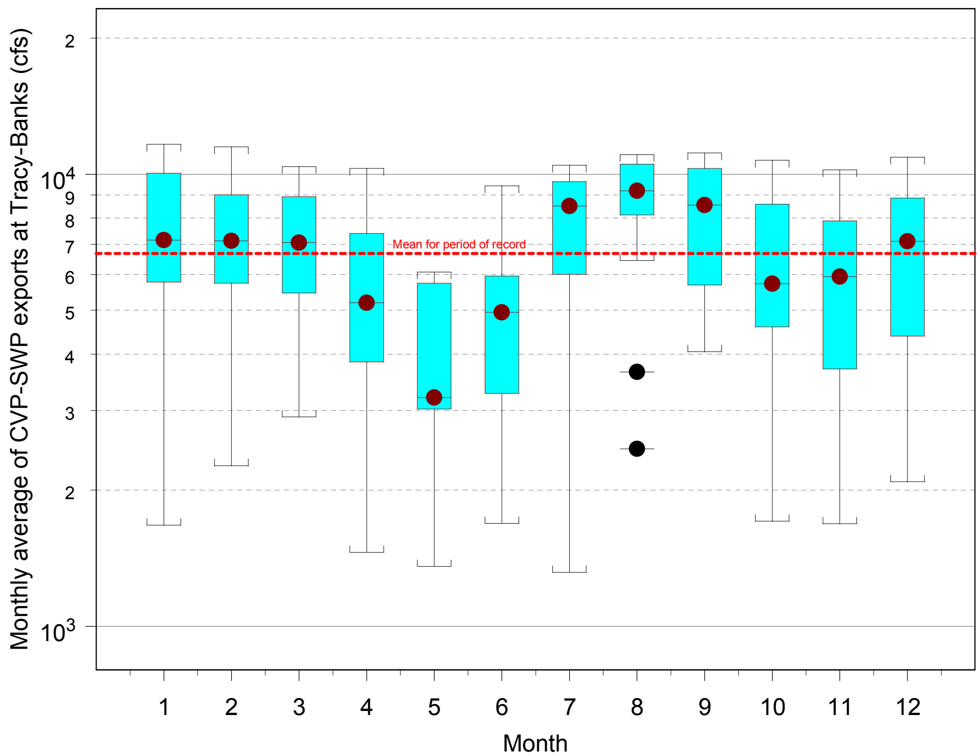

Figure 7. Box plot of summary statistics for monthly average of combined CVP and SWP exports at Tracy and Banks pumping plants (Q_{exp}), 1983-2001.

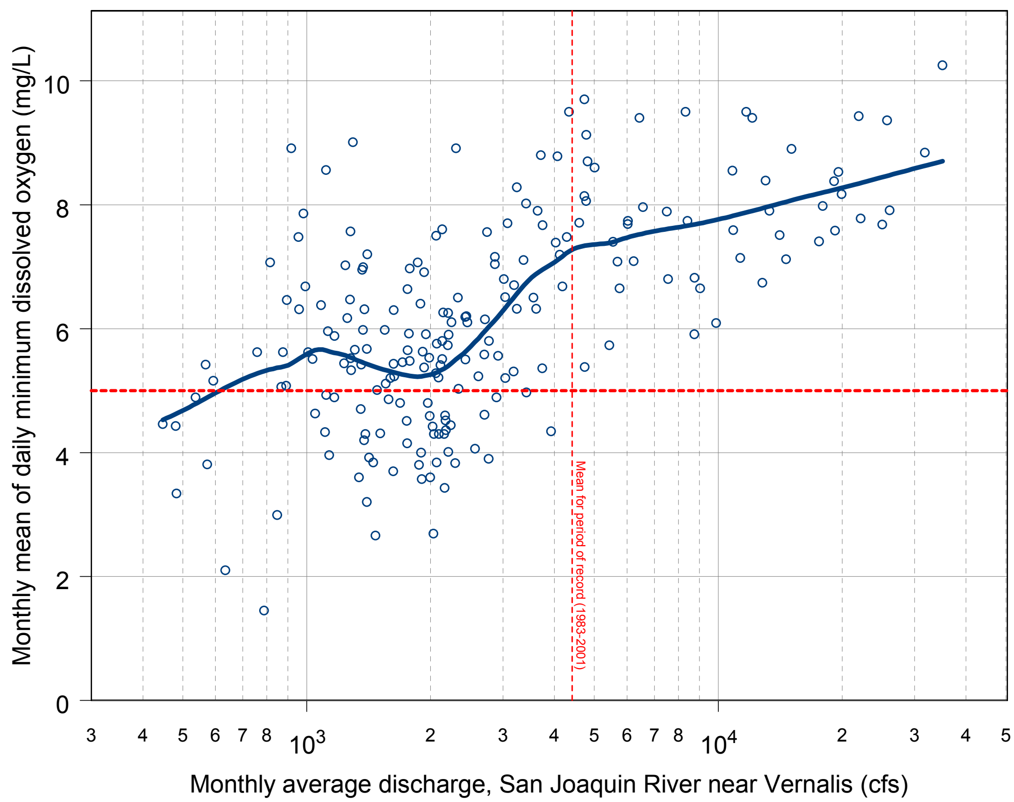

Figure 8. Scatter plot of monthly average daily minimum DO (DO_{min}) in the ship channel *vs* monthly average discharge in the San Joaquin River near Vernalis (Q_{vern}), 1983-2001. Curve depicts the LOWESS trend line.

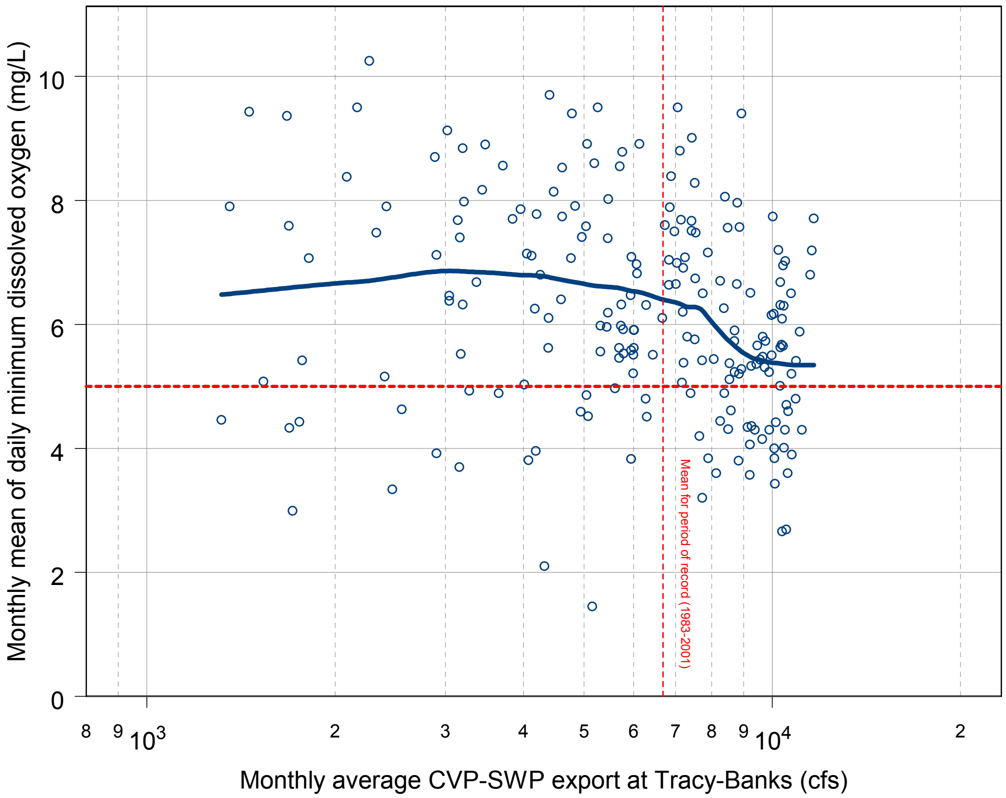

Figure 9. Scatter plot of monthly average daily minimum DO (DO_{min}) in the ship channel *vs* monthly average of combined CVP and SWP exports at Tracy and Banks pumping plants (Q_{exp}), 1983-2001. Curve depicts the LOWESS trend line.

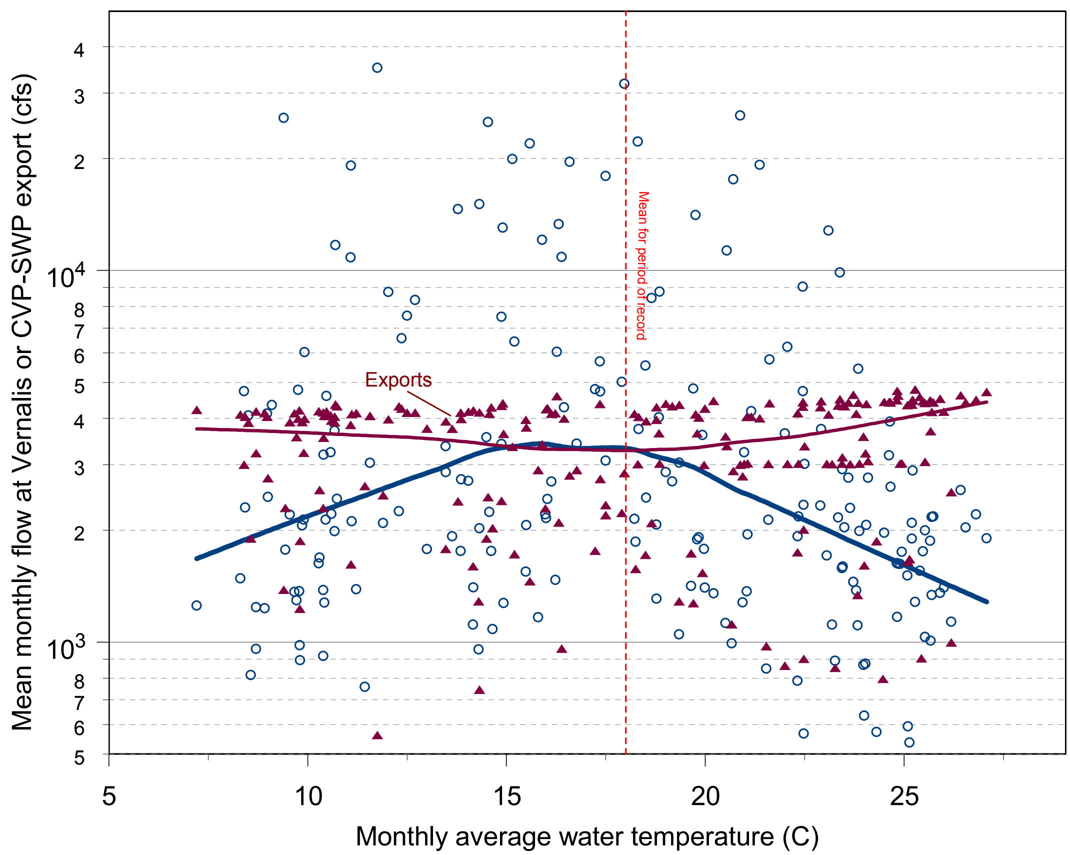

Figure 10. Scatter plots of monthly average flow at Vernalis and CVP-SWP exports *vs* monthly average water temperature in the ship channel, 1983-2001. Curves depict the LOWESS trend lines.

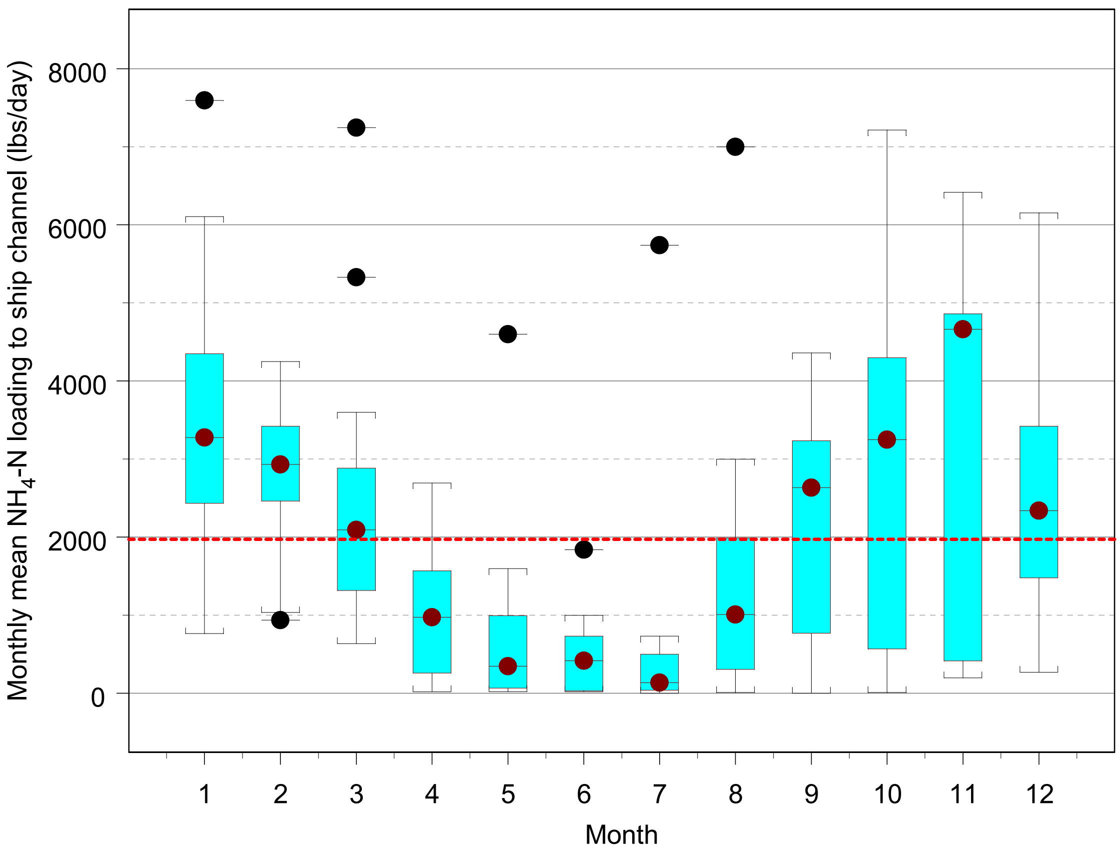

Figure 11. Box plot of summary statistics for monthly average NH_4-N loading to the ship channel from the City of Stockton wastewater treatment facility, 1983-2001.

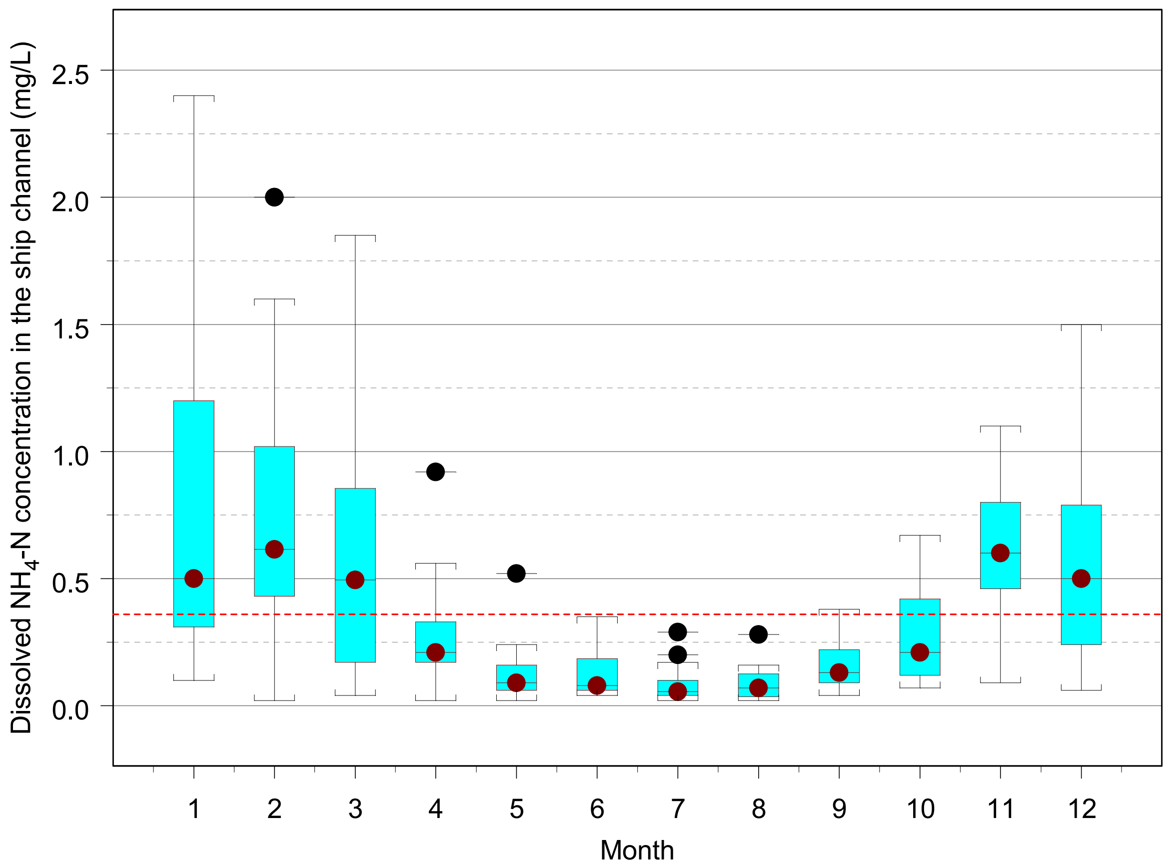

Figure 12. Box plot of summary statistics for monthly average NH_4-N concentration in the ship channel at Buckley Cove, 1983-2001.

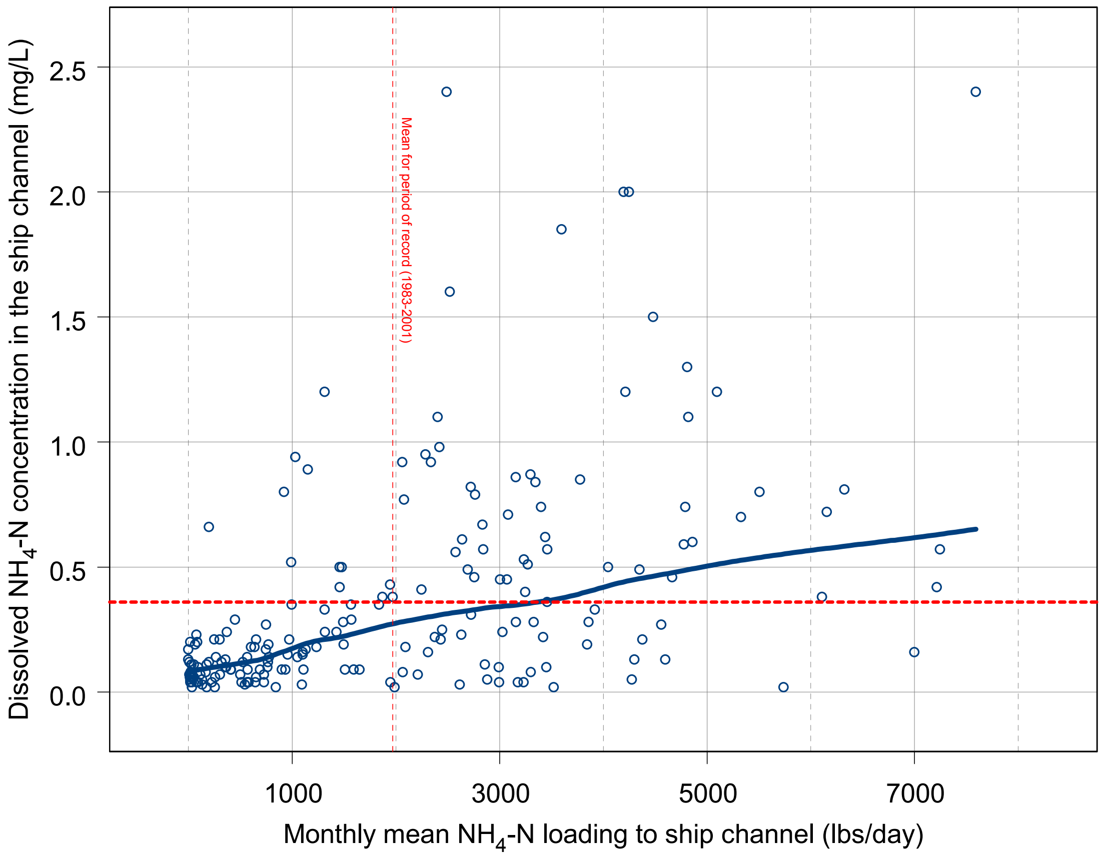

Figure 13. Scatter plot of monthly average NH_4-N concentration in the ship channel *vs* NH_4-N loading to the ship channel 1983-2001. Curve depicts the LOWESS trend line.

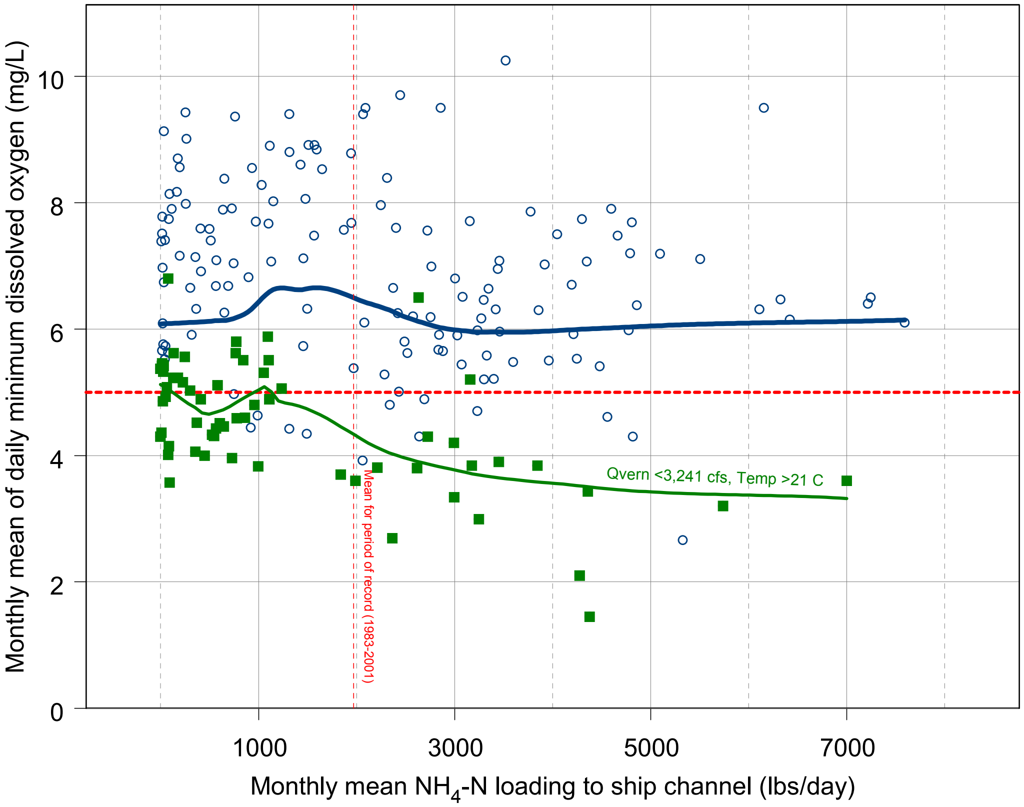

Figure 14. Scatter plots of monthly average daily minimum DO (DO_{min}) *vs* monthly average NH_4-N loading to the ship channel, 1983-2001. Curves depict the LOWESS trend lines for the full data set (empty circles, n=206) and for warm, low flow conditions only (solid squares, n=63).

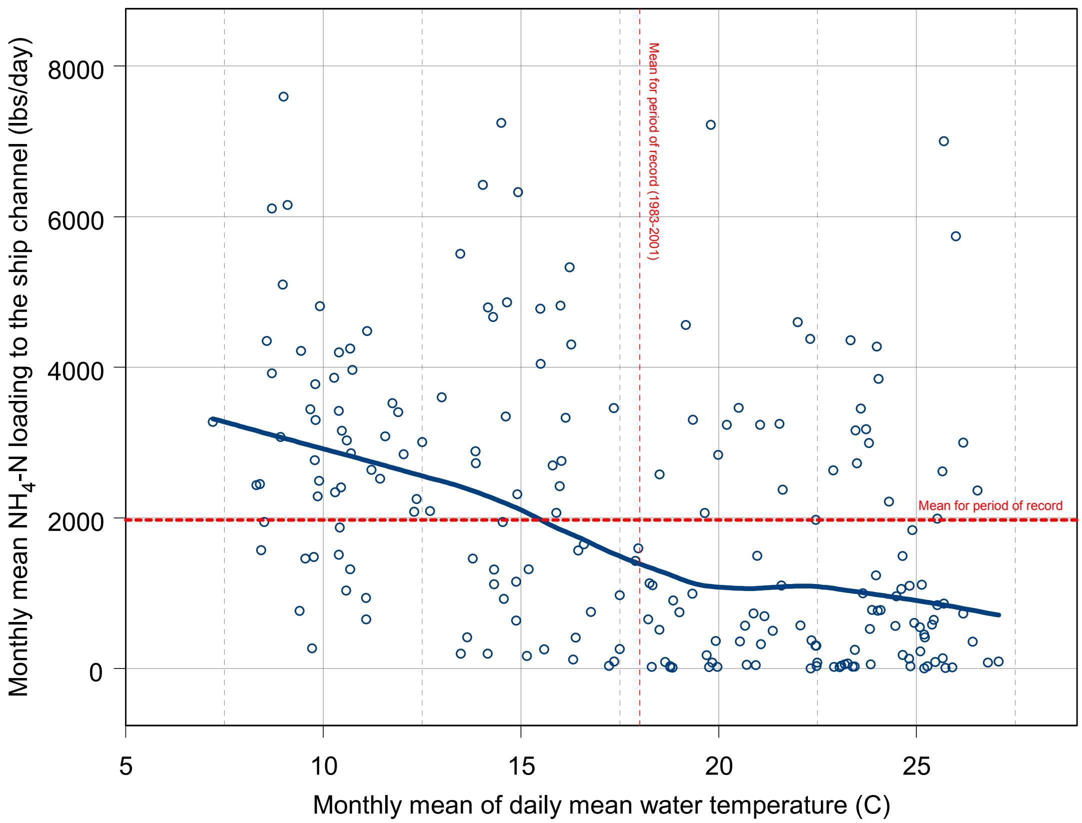

Figure 15. Scatter plot of monthly average NH_4-N loading to the ship channel *vs* monthly average water temperature, 1983-2001. Curve depicts the LOWESS trend line.

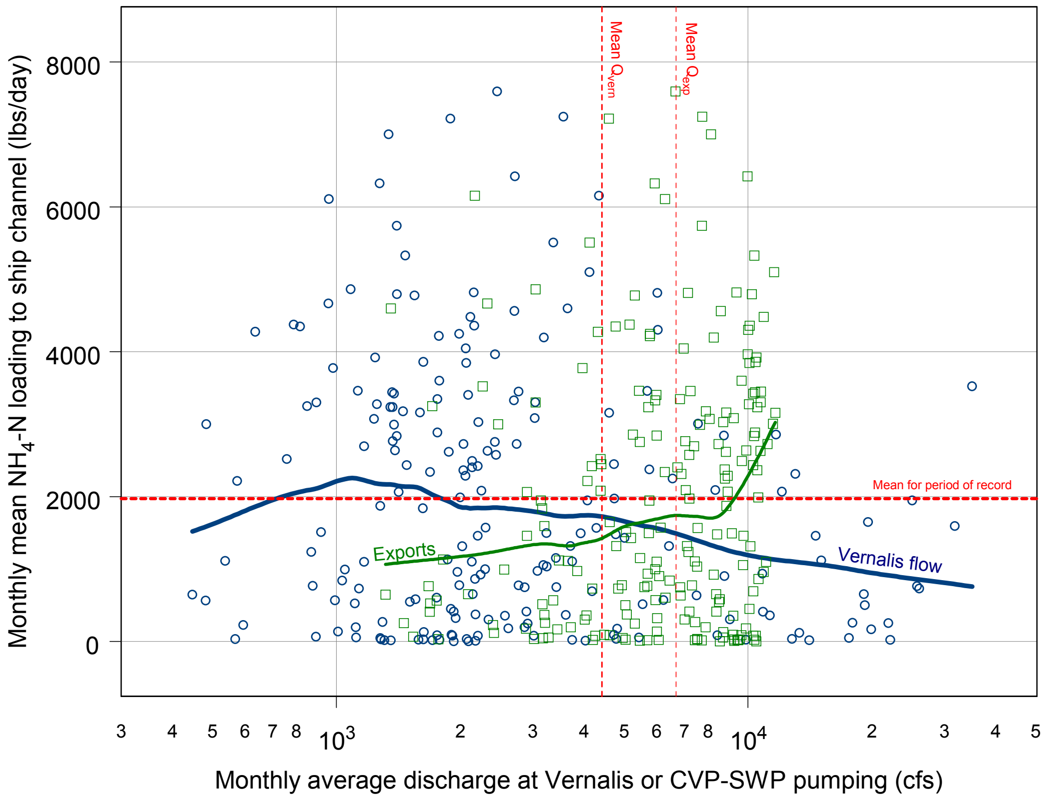

Figure 16. Scatter plot of monthly average NH_4-N loading to the ship channel *vs* monthly average discharge in the San Joaquin River near Vernalis (Q_{vern}) and CVP-SWP exports, 1983-2001. Curves depict the LOWESS trend lines for Vernalis flow (empty circles) and export pumping (empty squares).

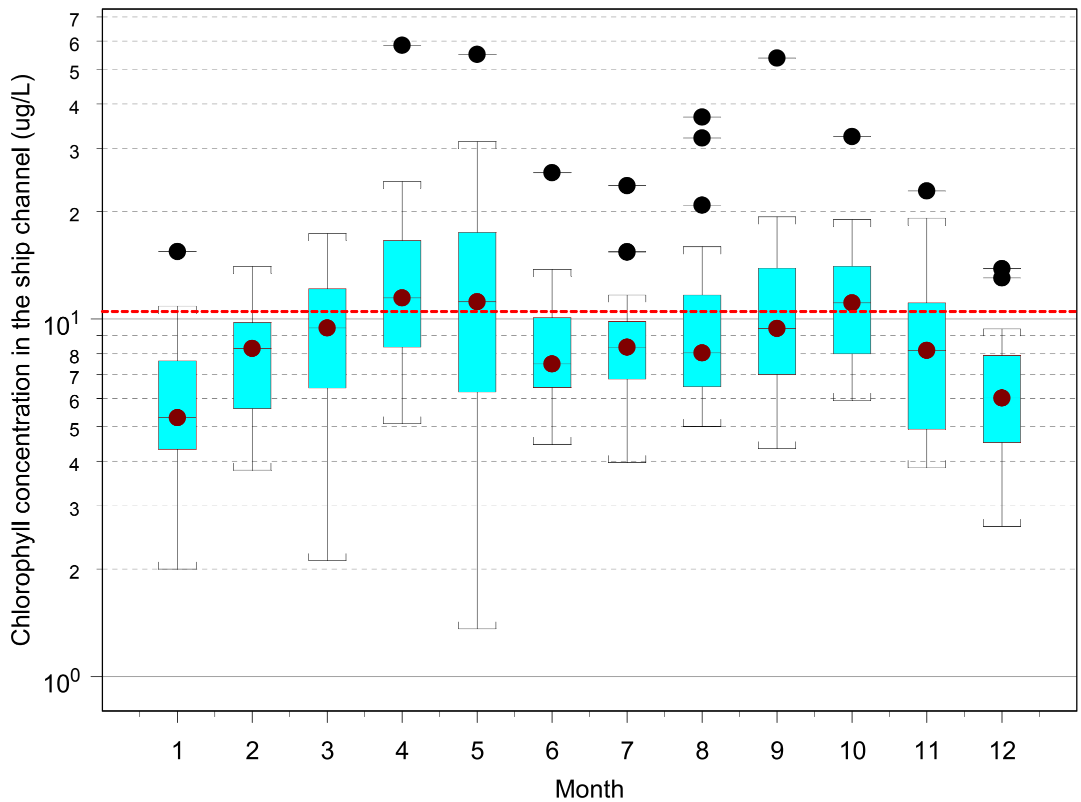

Figure 17. Box plot of summary statistics for monthly average chlorophyll concentration in the ship channel at Buckley Cove, 1983-2001.

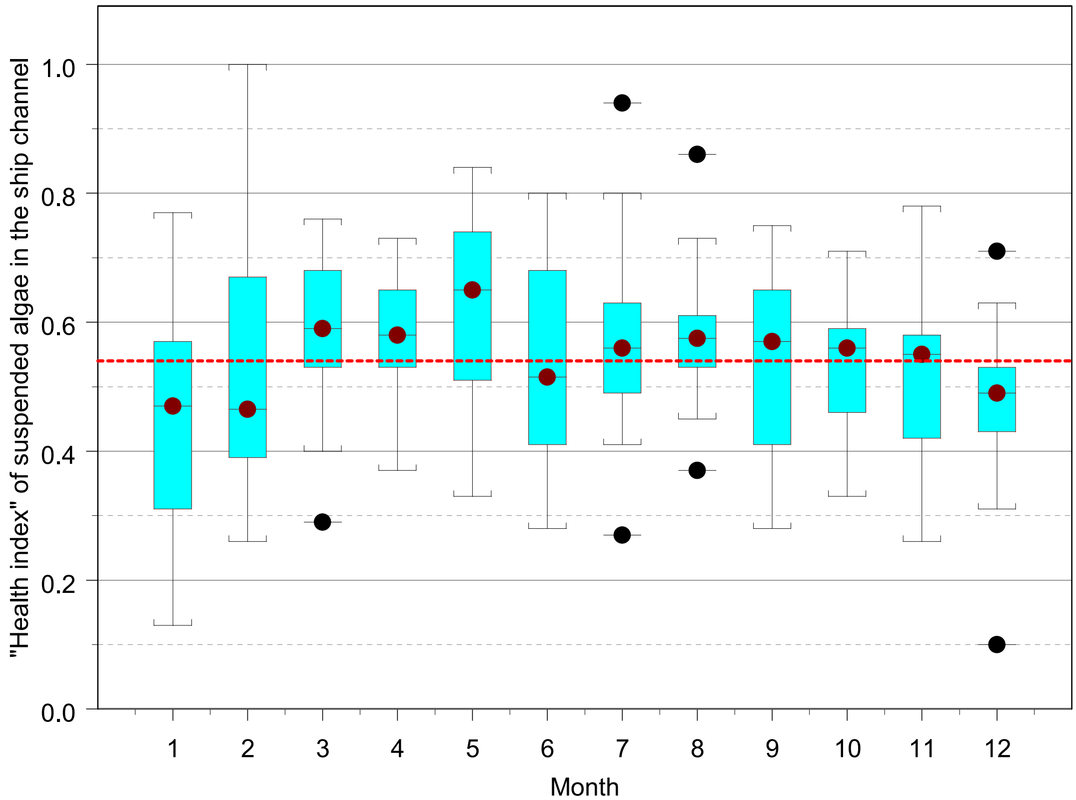

Figure 18. Box plot of summary statistics for monthly average "health" or "age" index of suspended algal biomass in the ship channel at Buckley Cove (Light 40), 1983-2001.

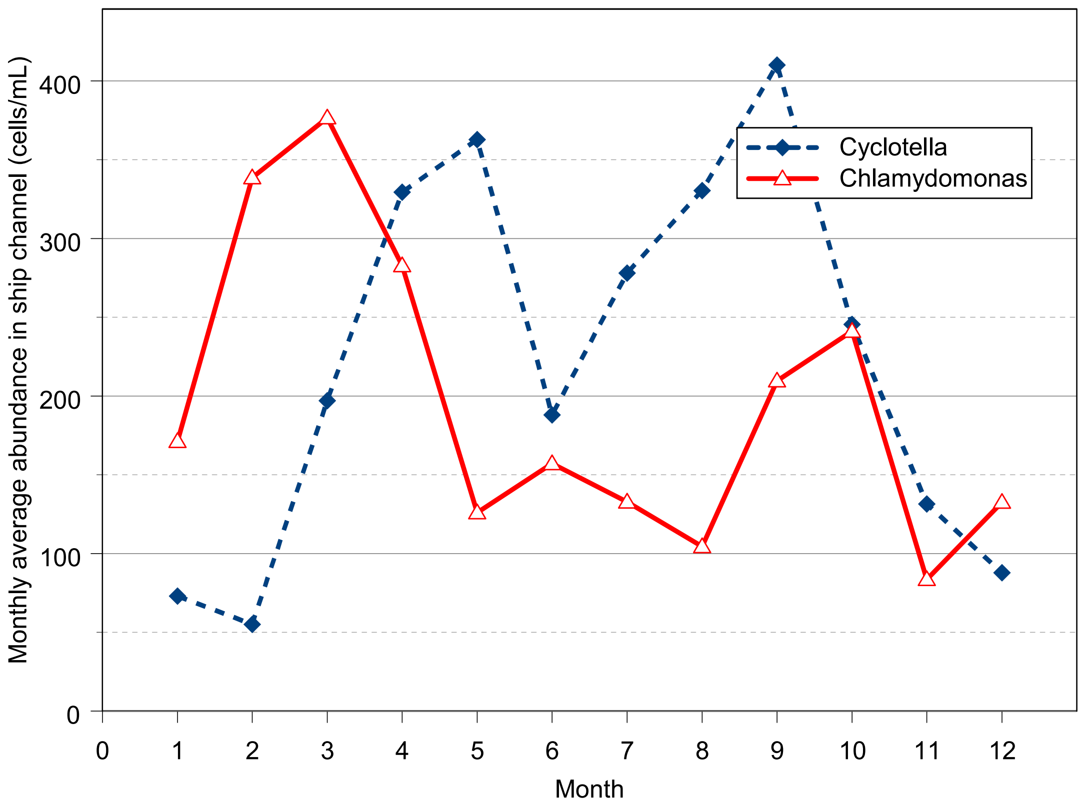

Figure 19. Average monthly abundance of *Cyclotella* and *Chlamydomonas* in the ship channel at Buckley Cove (Light 40), 1983-1996.

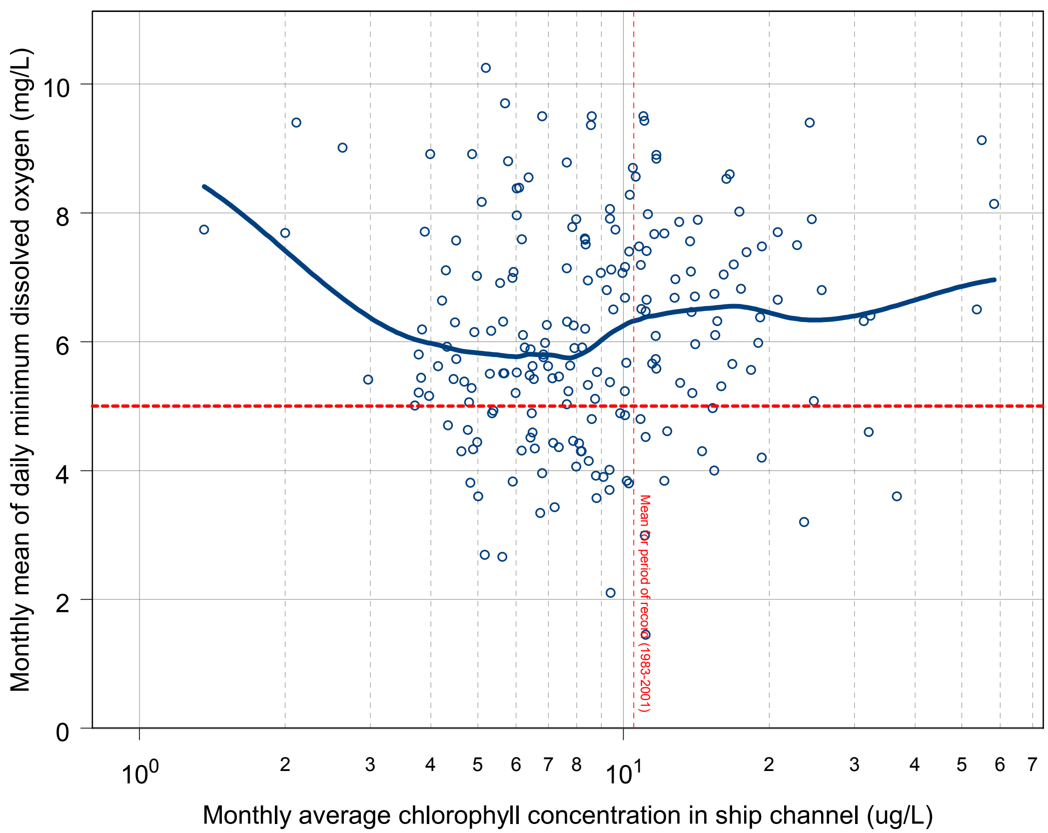

Figure 20. Scatter plot of monthly average daily minimum DO (DO_{min}) in the ship channel *vs* monthly average chlorophyll concentration in the ship channel, 1983-2001. Curve depicts the LOWESS trend line.

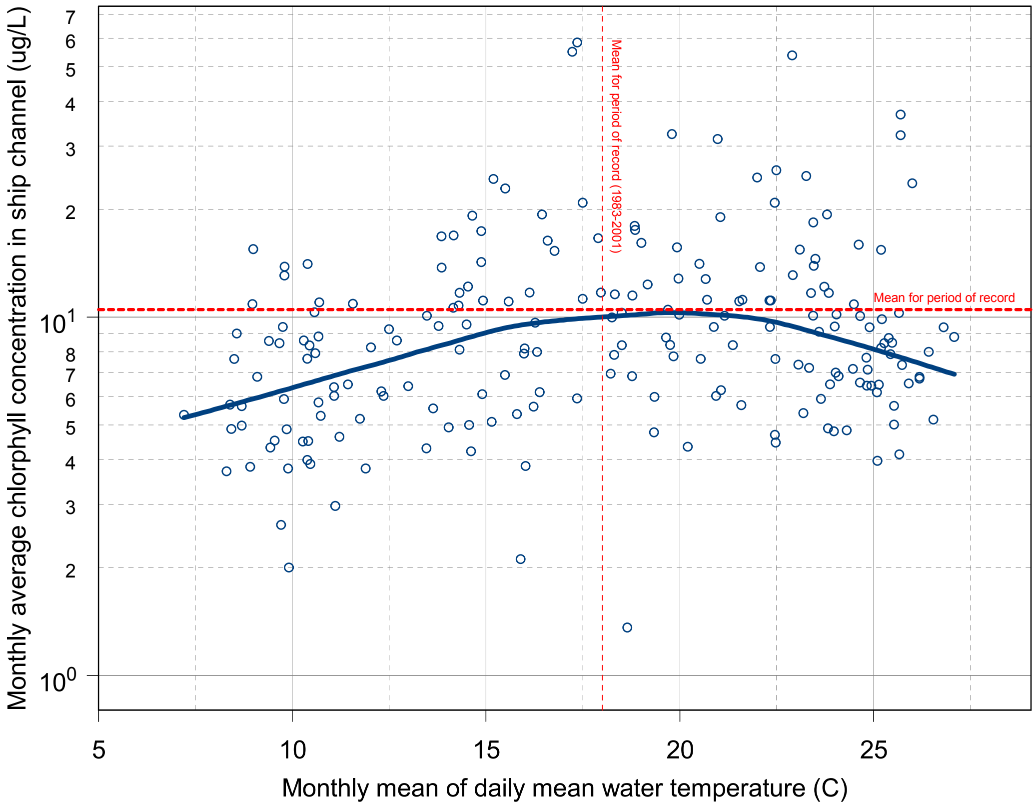

Figure 21. Scatter plot of monthly average chlorophyll concentration in the ship channel *vs* monthly average water temperature in the ship channel, 1983-2001. Curve depicts the LOWESS trend line.

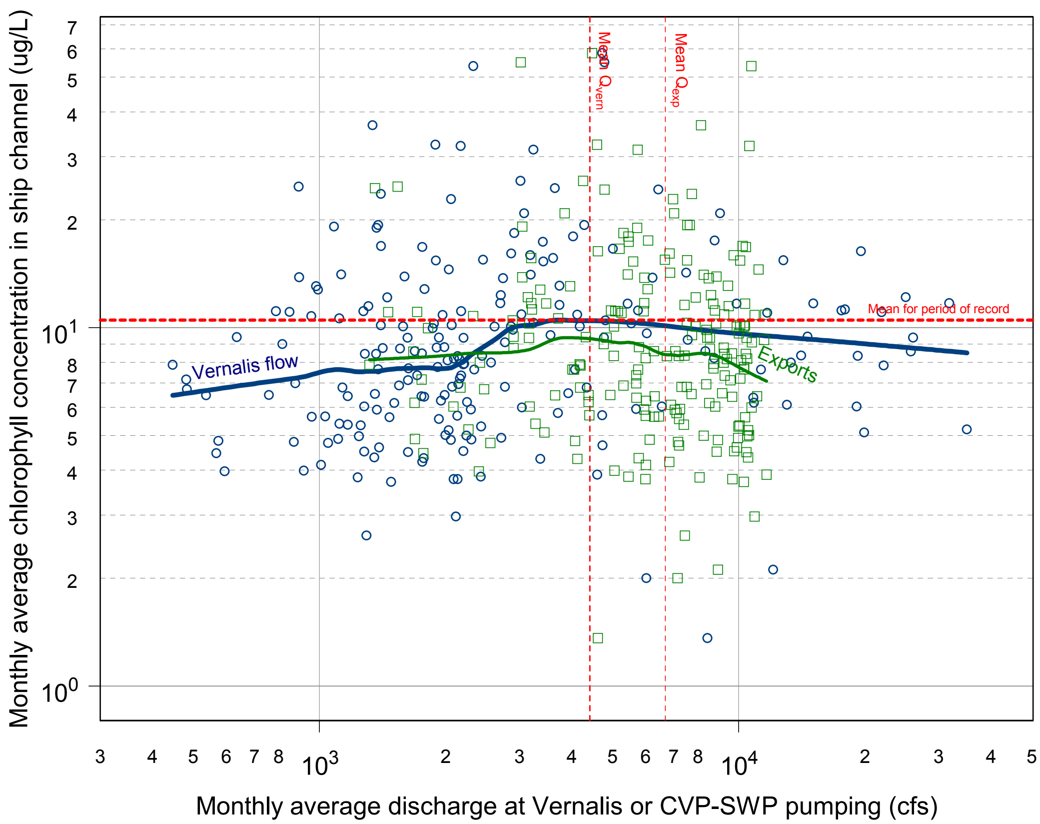

Figure 22. Scatter plot of monthly average chlorophyll concentration in the ship channel *vs* monthly average discharge at Vernalis or CVP-SWP exports, 1983-2001. Curve depicts the LOWESS trend line.

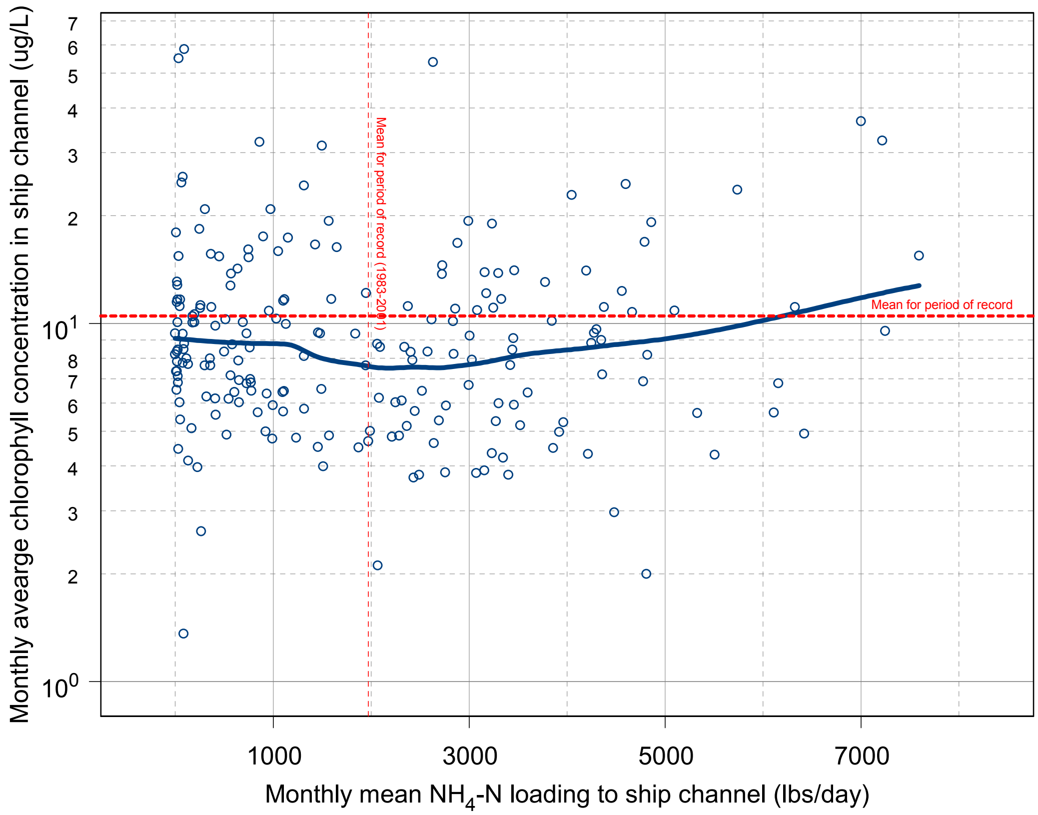

Figure 23. Scatter plot of monthly average chlorophyll concentration in the ship channel *vs* monthly average loading of ammonia-N from the City of Stockton's wastewater treatment ponds, 1983-2001. Curve depicts the LOWESS trend line.

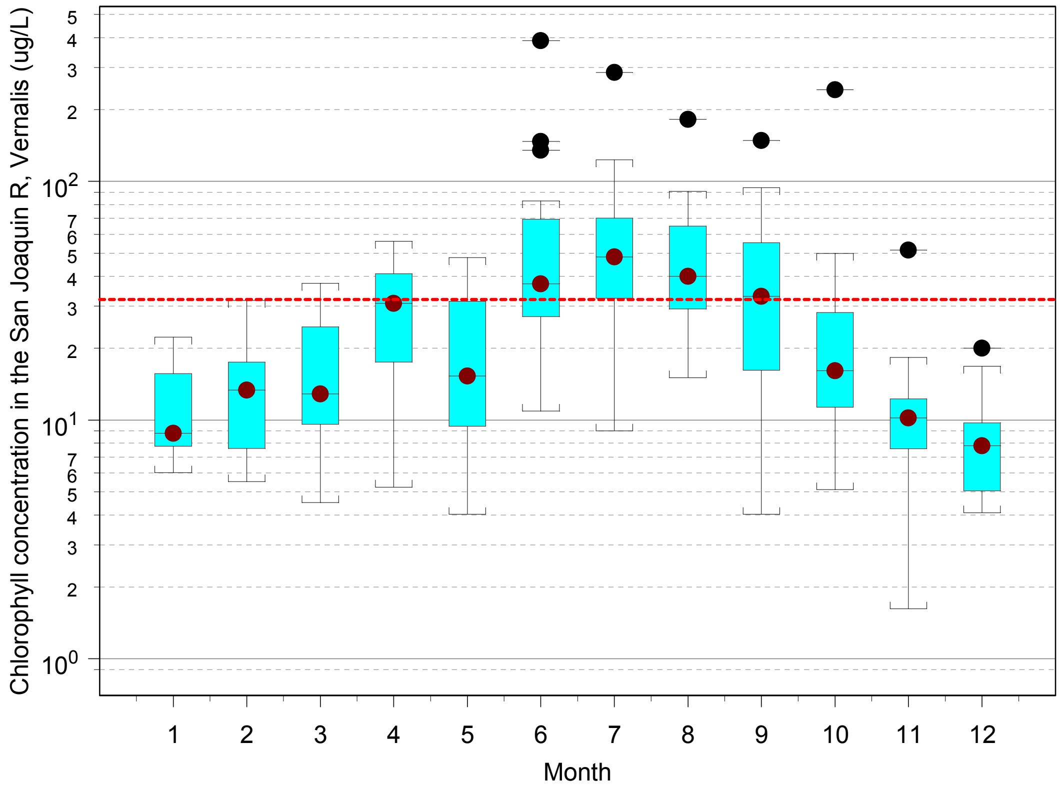

Figure 24. Box plot of summary statistics for monthly average chlorophyll concentration in the San Joaquin River at Vernalis, 1983-2001.

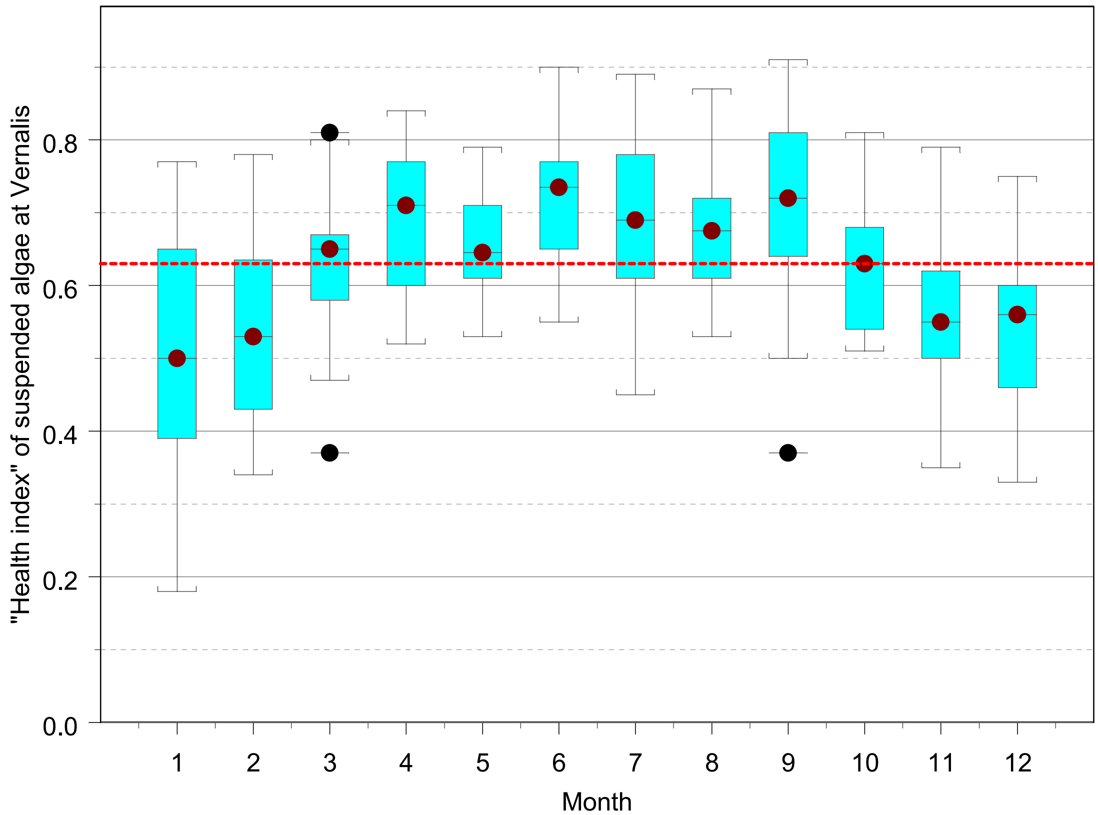

Figure 25. Box plot of summary statistics for monthly average "health" or "age" index of suspended algal biomass in the San Joaquin River at Vernalis, 1983-2001.

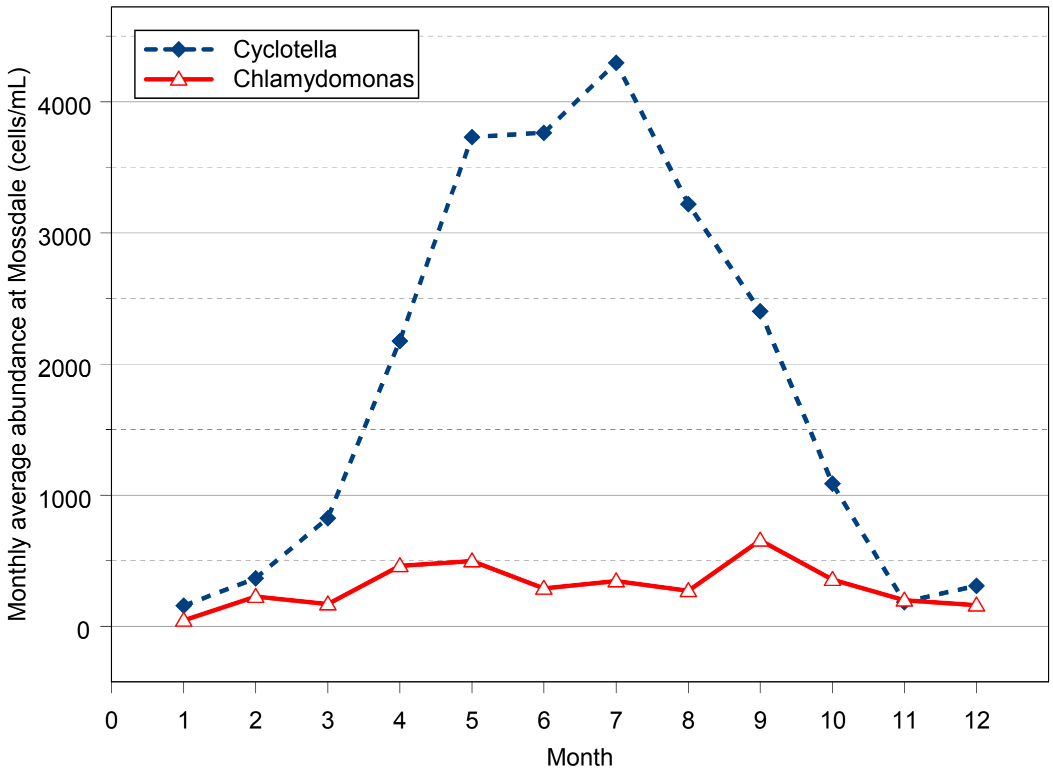

Figure 26. Average monthly abundance of *Cyclotella* and *Chlamydomonas* in the San Joaquin River at Mossdale, 1983-1996.

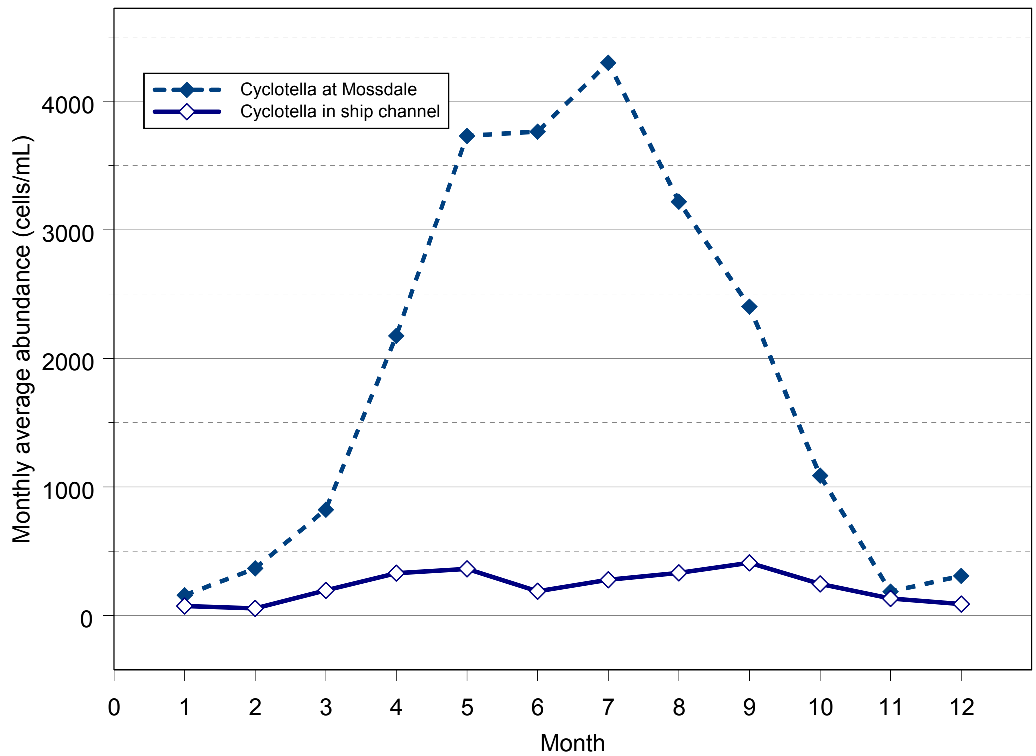

Figure 27. Average monthly abundance of *Cyclotella* in the ship channel near Buckley Cove and in the San Joaquin River at Mossdale, 1983-1996.

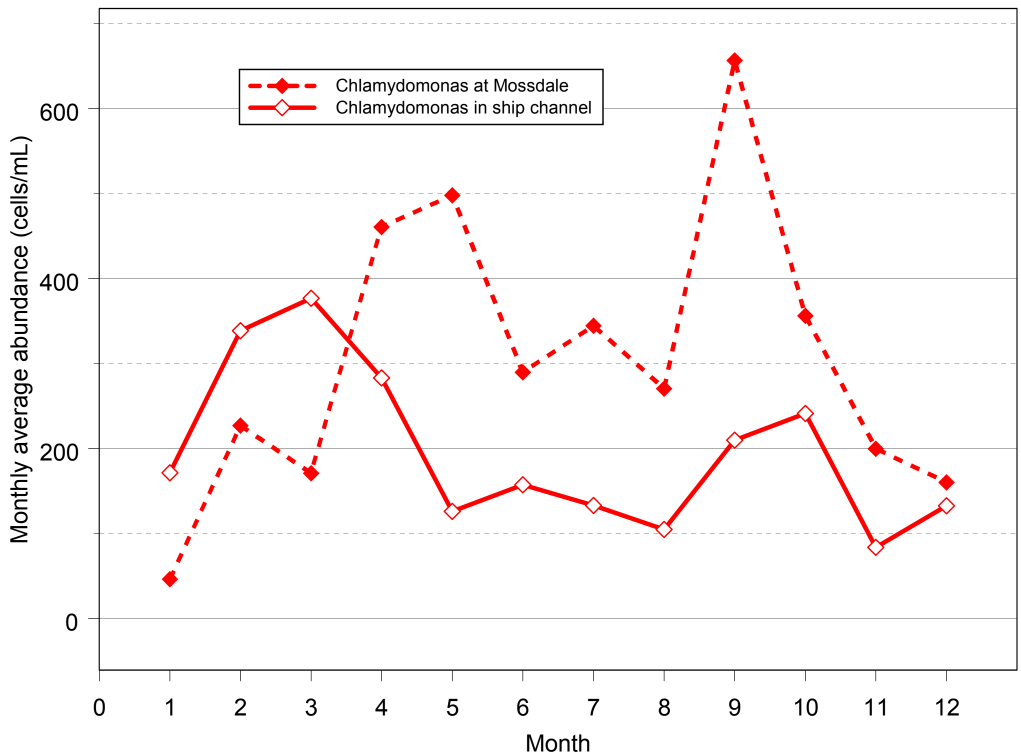

Figure 28. Average monthly abundance of *Chlamydomonas* in the ship channel near Buckley Cove and in the San Joaquin River at Mossdale, 1983-1996.

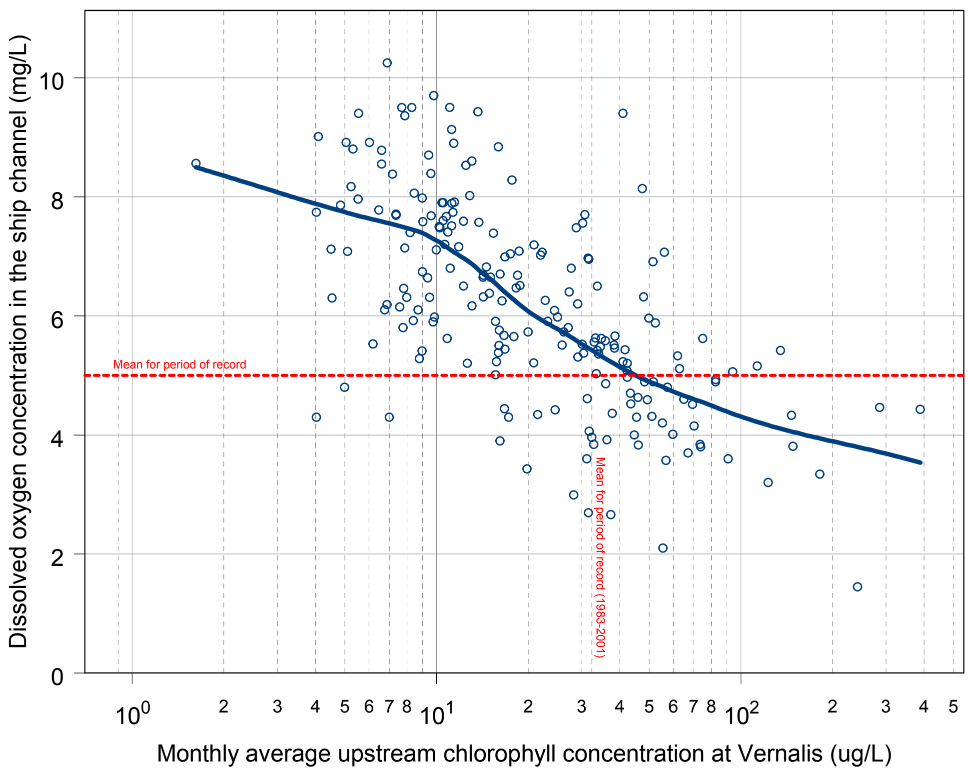

Figure 29. Scatter plot of monthly average daily minimum DO (DO_{min}) in the ship channel *vs* monthly average chlorophyll concentration in the San Joaquin River at Vernalis, 1983-2001. Curve depicts the LOWESS trend line.

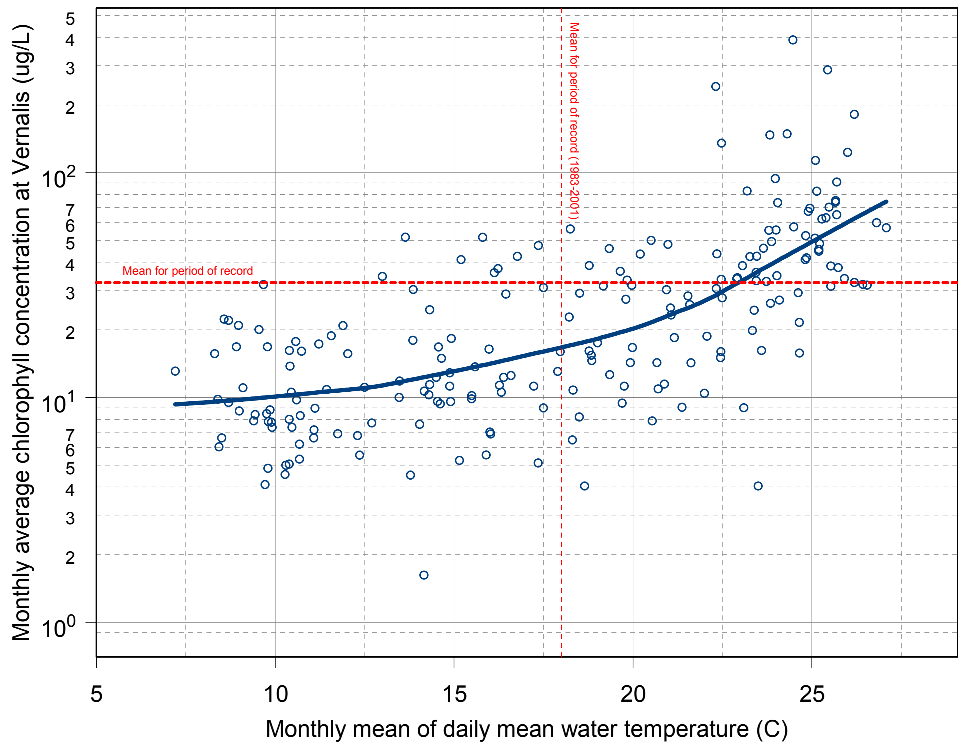

Figure 30. Scatter plot of monthly average chlorophyll concentration in the San Joaquin River at Vernalis *vs* monthly average water temperature in the ship channel, 1983-2001. Curve depicts the LOWESS trend line.

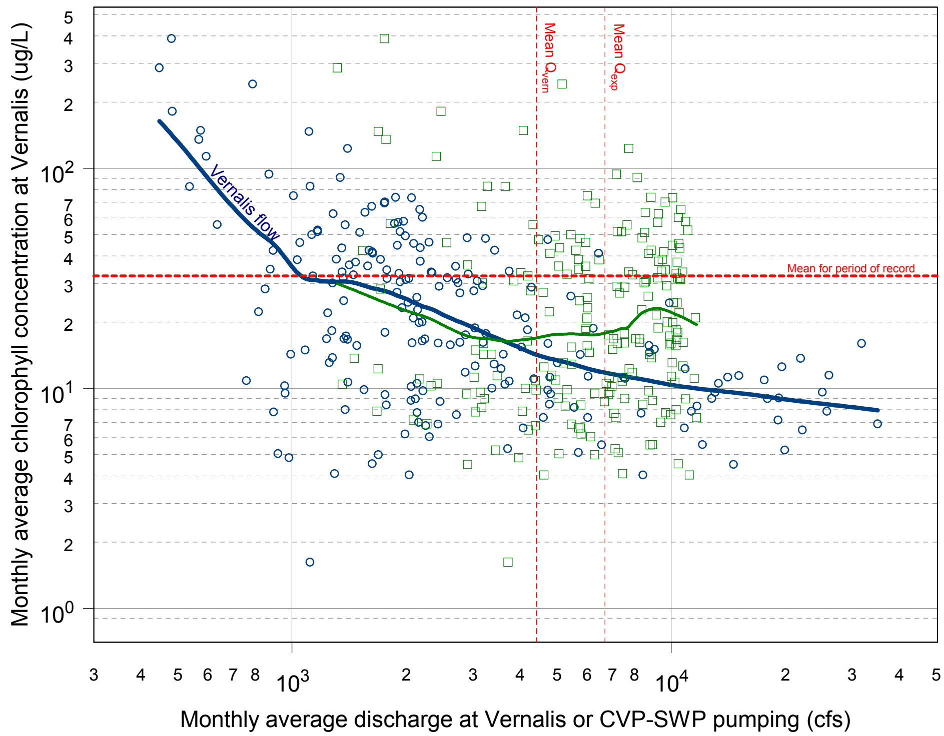

Figure 31. Scatter plot of monthly average chlorophyll concentration in the San Joaquin River at Vernalis *vs* monthly average discharge at Vernalis or CVP-SWP exports, 1983-2001. Curve depicts the LOWESS trend line.

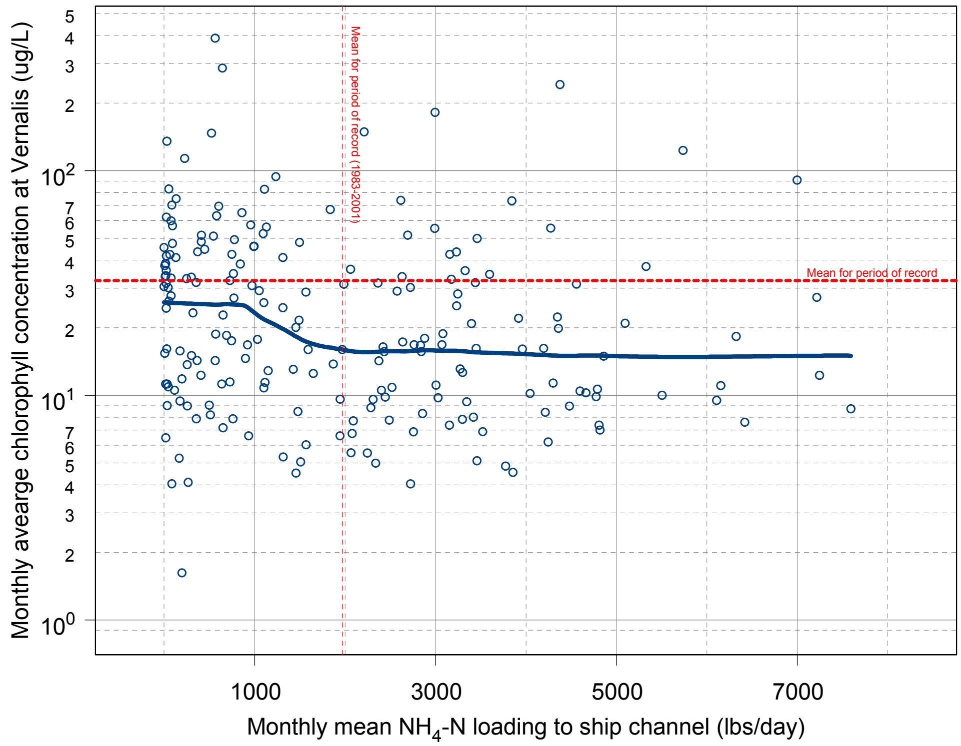

Figure 32. Scatter plot of monthly average chlorophyll concentration in the San Joaquin River at Vernalis *vs* monthly average loading of ammonia-N from the City of Stockton's wastewater treatment ponds, 1983-2001. Curve depicts the LOWESS trend line.

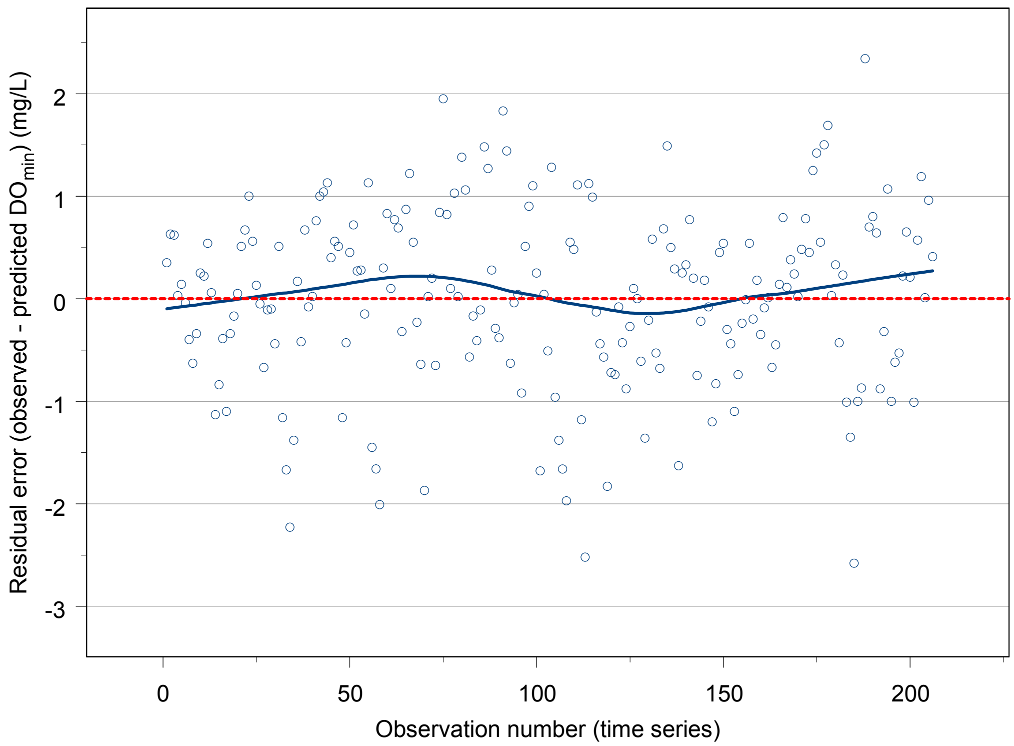

Figure 33. Residual error of the multiple regression model plotted against observation number sorted to form a continuous monthly time series, May 1983-December 2001.

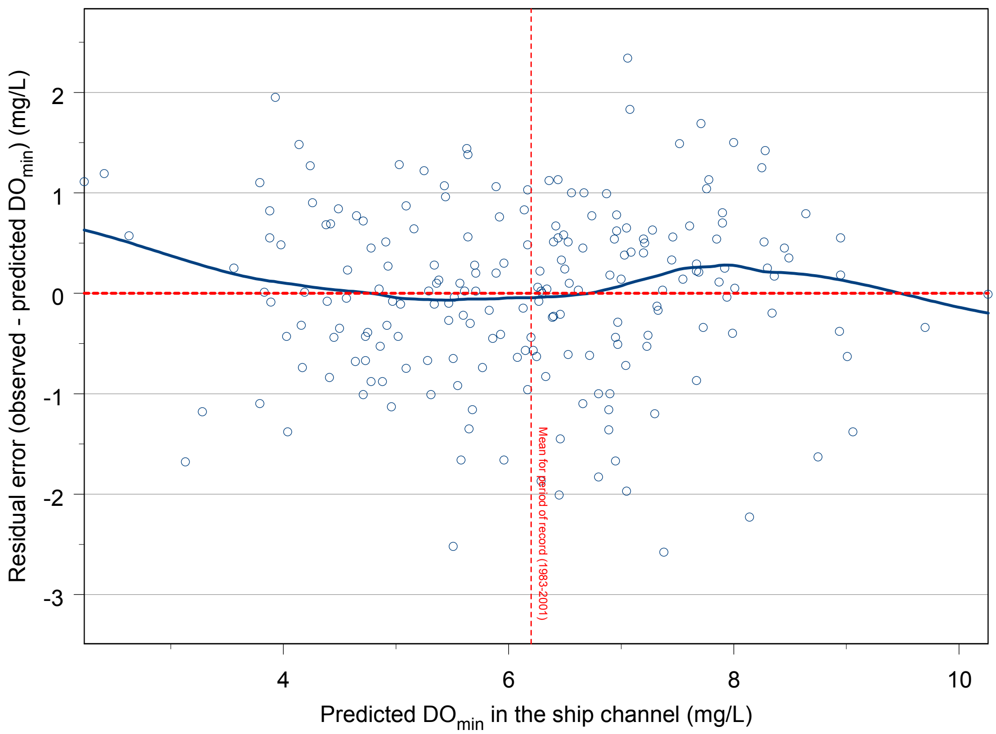

Figure 34. Plot of residual error *vs* monthly average daily minimum DO (DO_{min}) in the ship channel predicted from the multiple regression model.

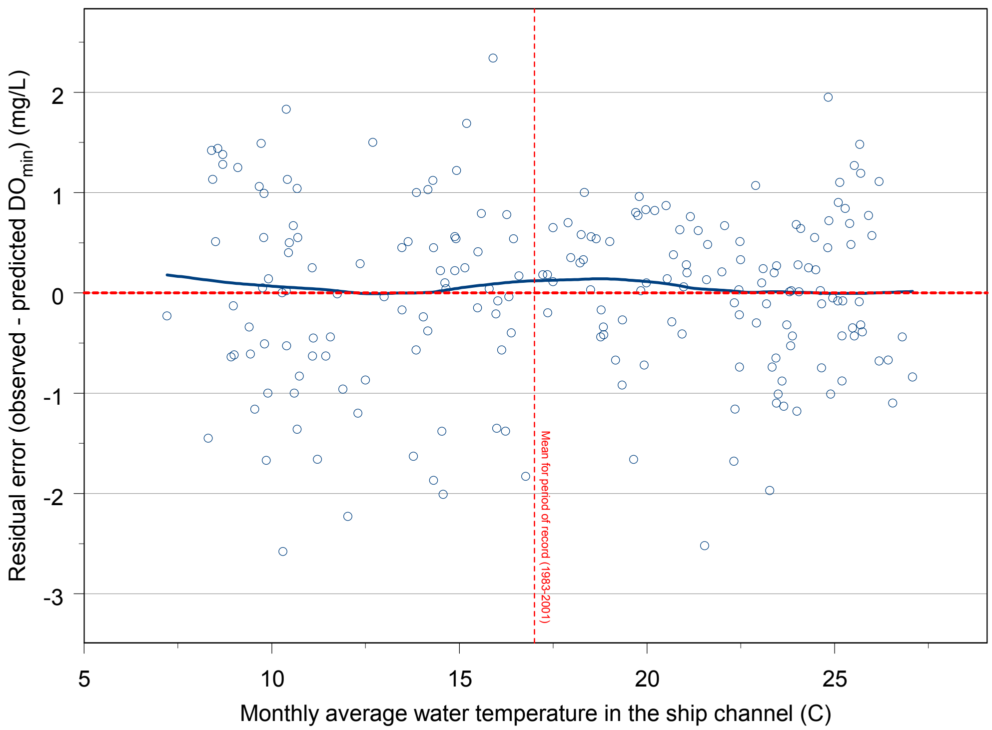

Figure 35. Plot of residual error *vs* monthly average water temperature in the ship channel.

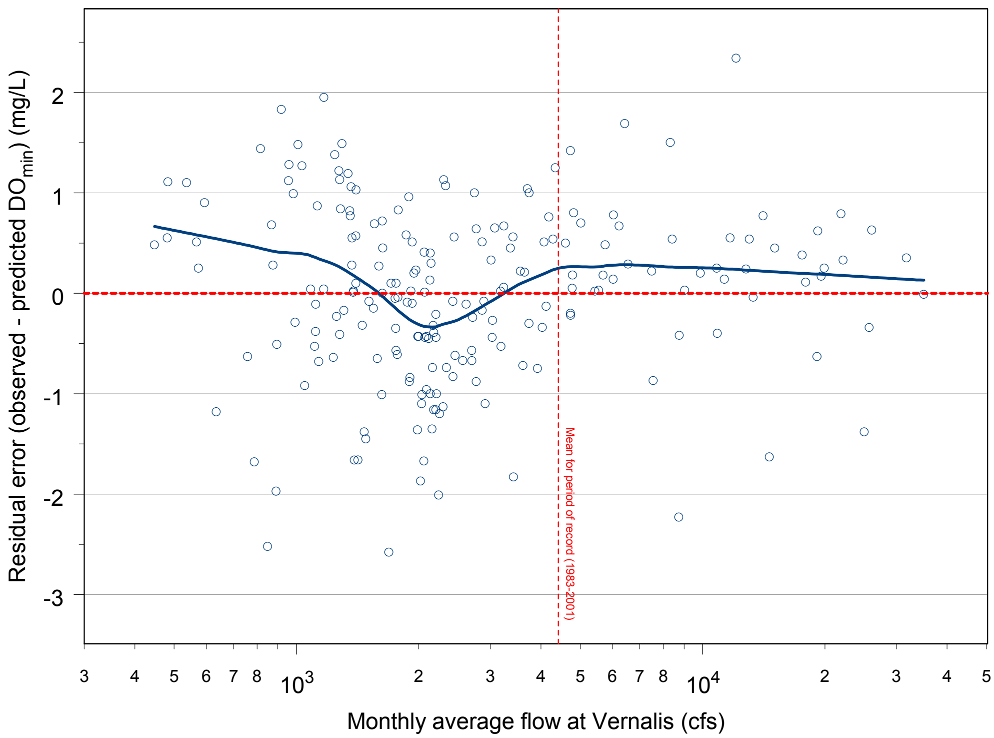

Figure 36. Plot of residual error *vs* monthly average flow at Vernalis.

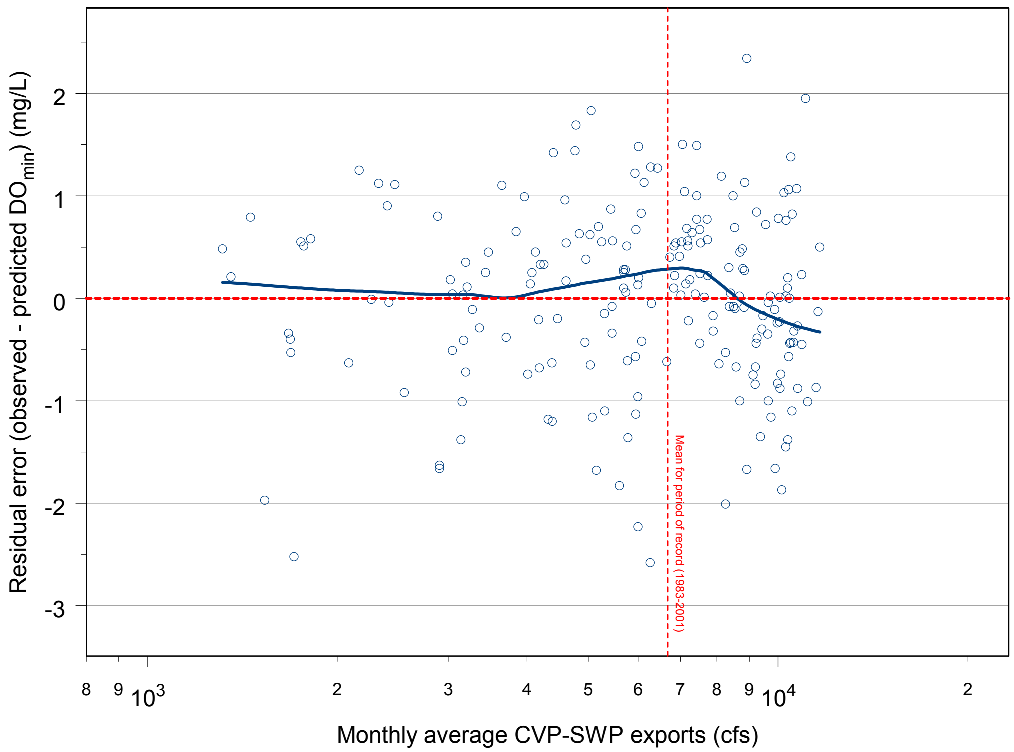

Figure 37. Plot of residual error *vs* monthly average CVP-SWP exports.

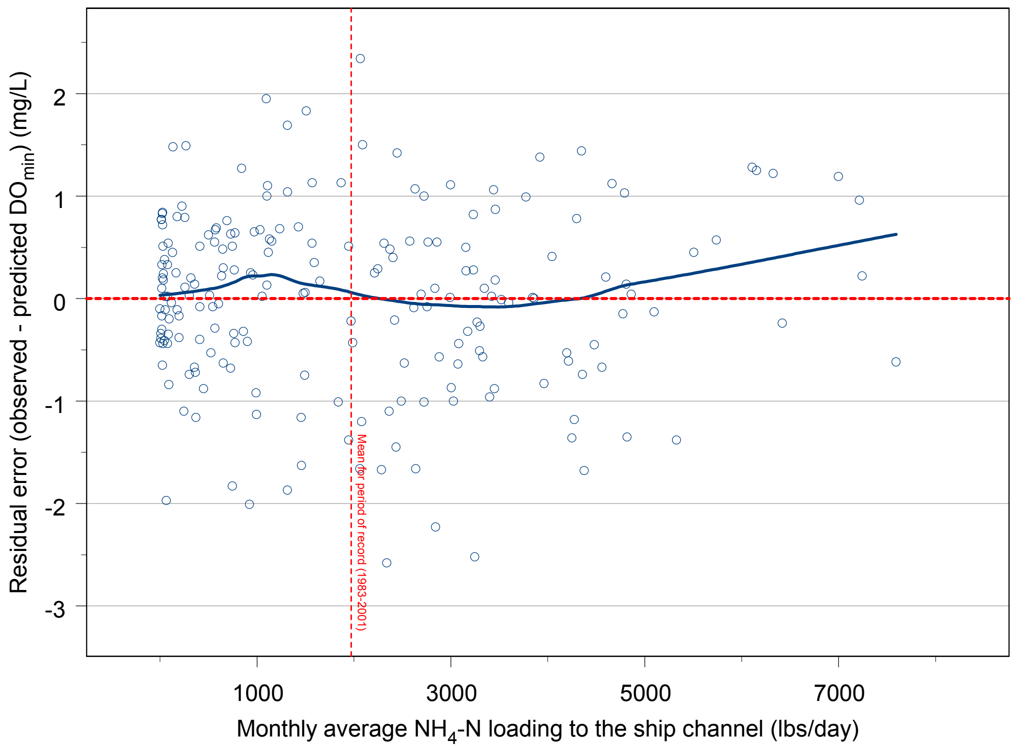

Figure 38. Plot of residual error *vs* monthly average ammonia-N loading from the City of Stockton's wastewater treatment ponds.

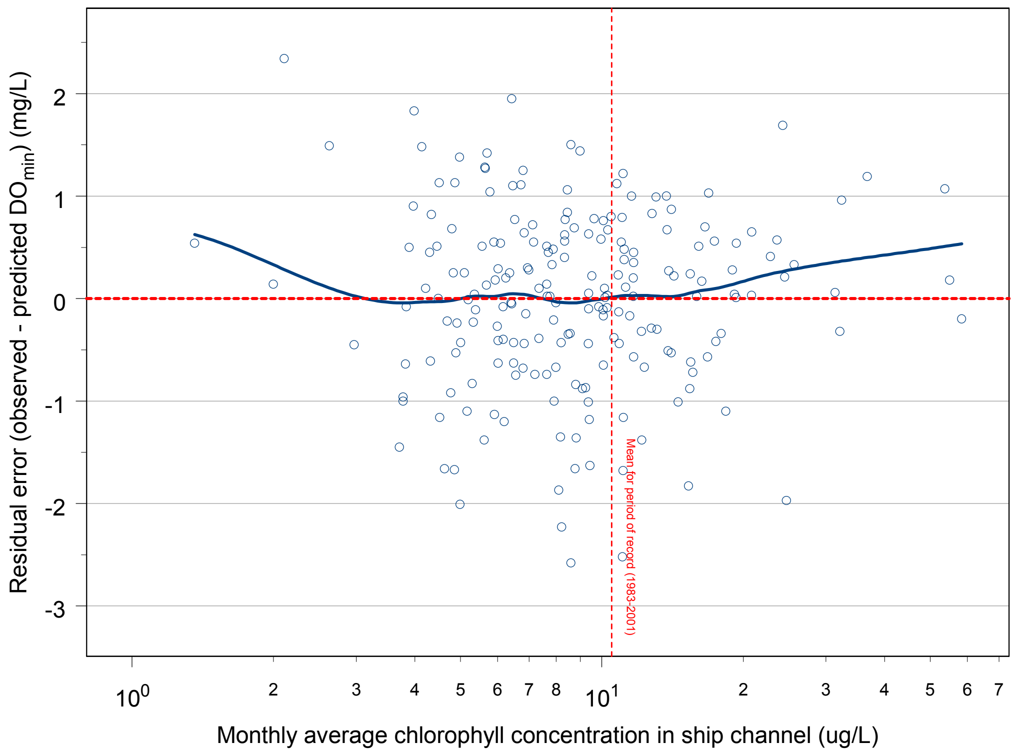

Figure 39. Plot of residual error *vs* monthly average chlorophyll concentration in the ship channel.

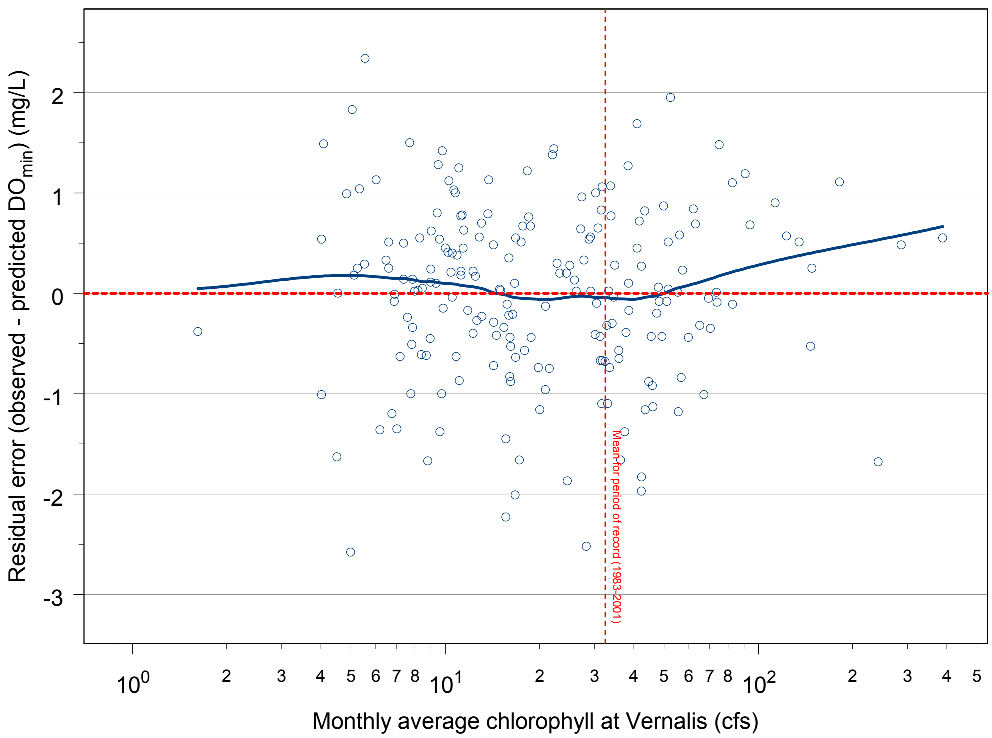

Figure 40. Plot of residual error *vs* monthly average chlorophyll concentration in the San Joaquin River at Vernalis.

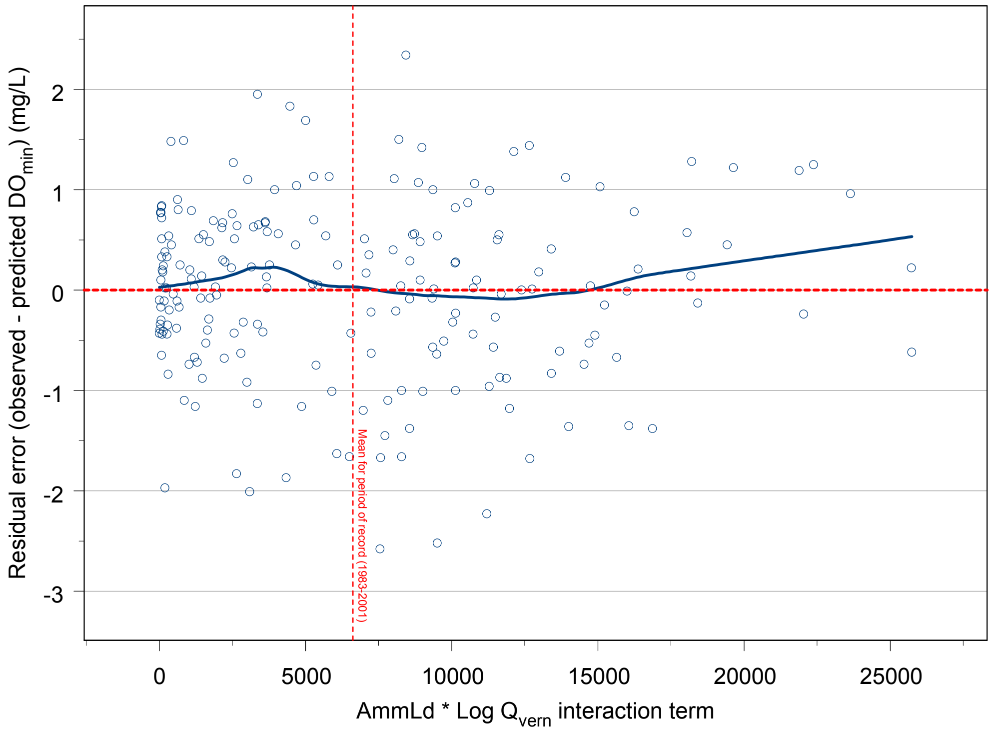

Figure 41. Plot of residual error *vs* monthly values of the ammonia loading-Vernalis flow interaction term used in the multiple regression model.

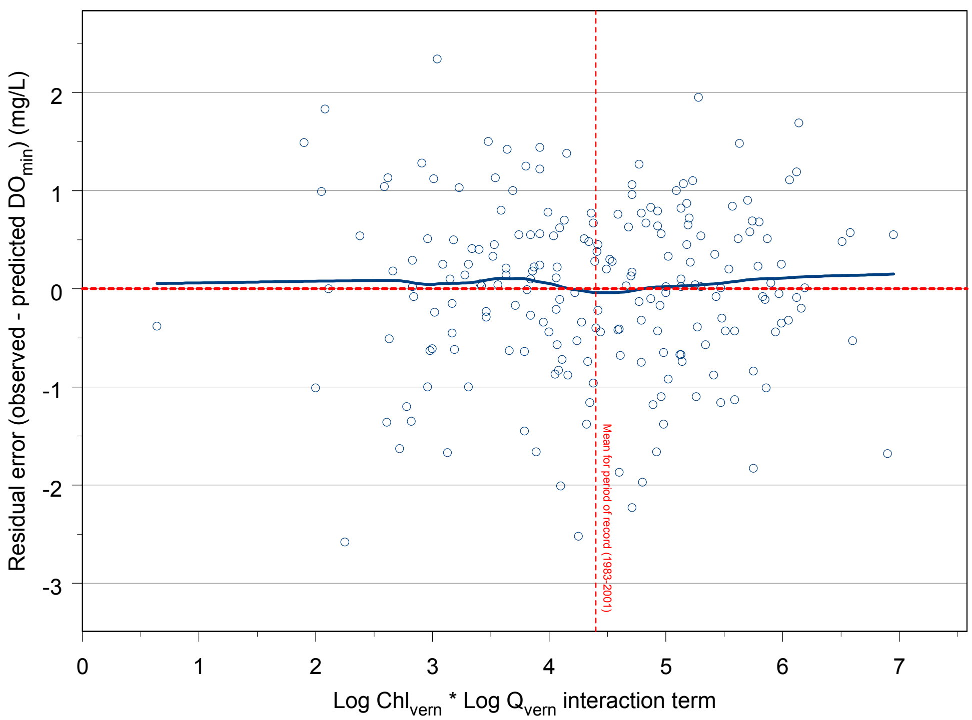

Figure 42. Plot of residual error vs monthly values of the Vernalis chlorophyll-Vernalis flow interaction term used in the multiple regression model.

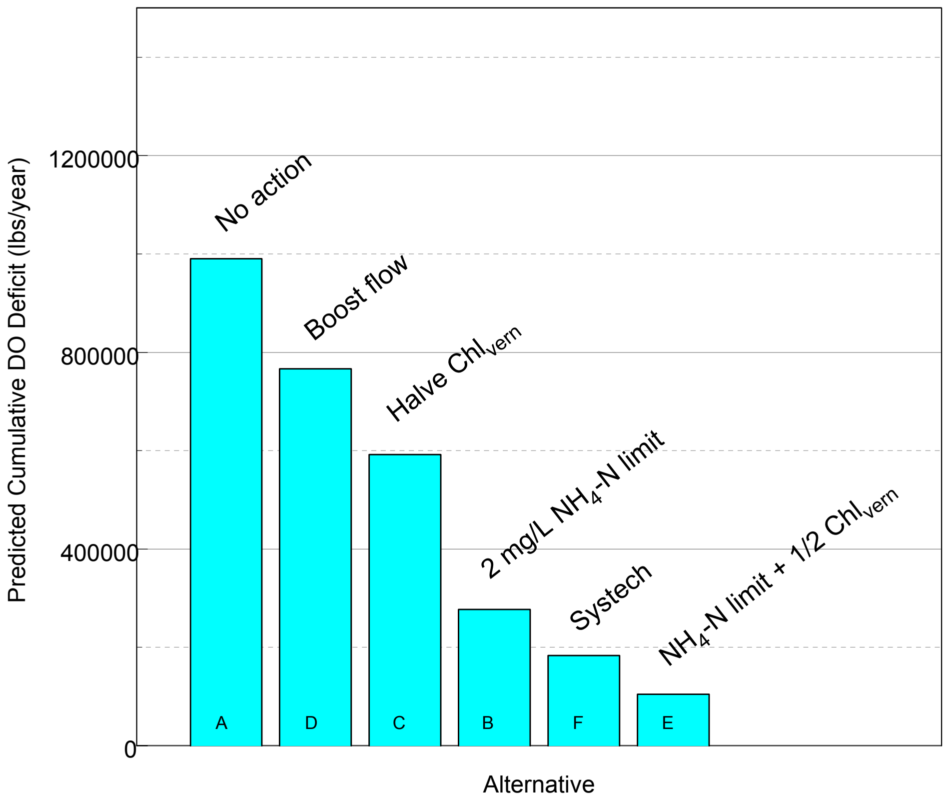

Figure 43. Comparison of the average cumulative dissolved oxygen deficit (lbs/year) predicted by the statistical model for the six management alternatives summarized in Table 1 (see Table 5).

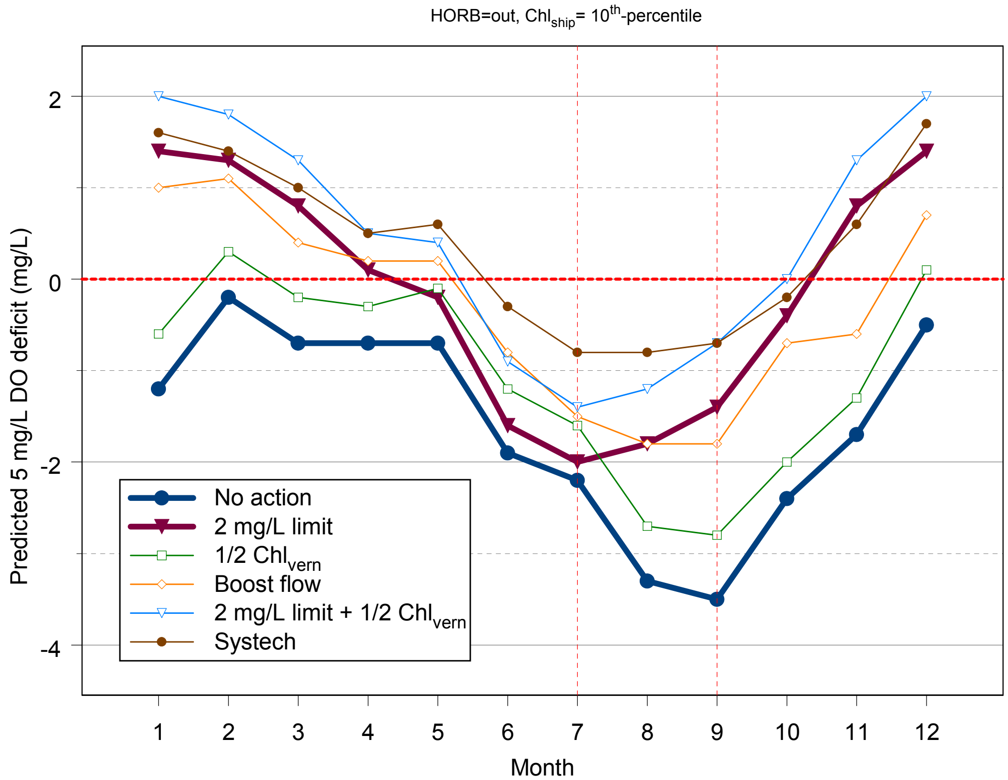

Figure 44. Comparison of the predicted monthly average dissolved oxygen deficit in the ship channel under six management alternatives with HORB closed and low *in situ* chlorophyll concentration. Note the shift in the annual maximum deficit from September to July for alternatives involving reduction in ammonia loading rate (see Table 5).

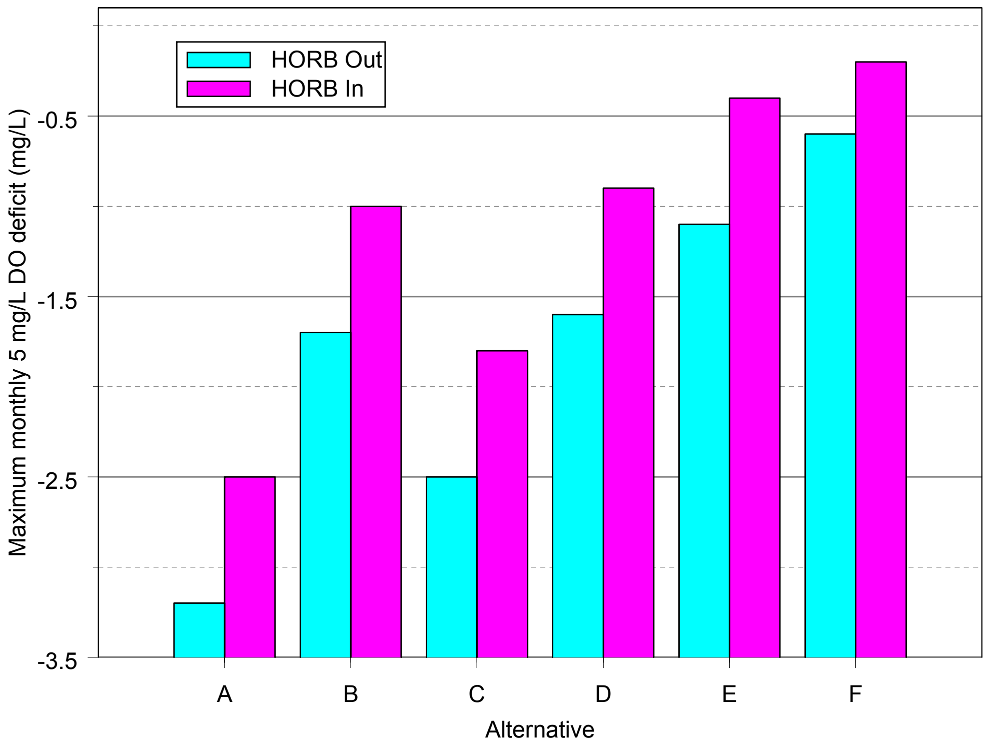

Figure 45. Effect of installing the head of Old River barrier (HORB) on the dissolved oxygen deficit in the ship channel under six management alternatives (see Table 5).

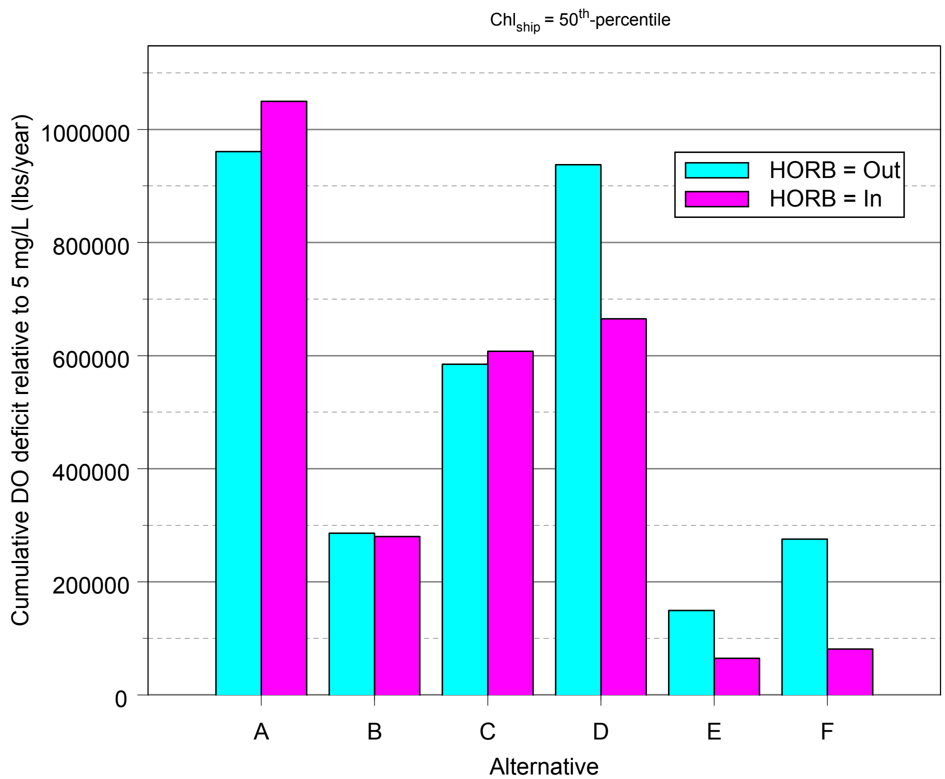

Figure 46. Effect of installing the head of Old River barrier (HORB) on the cumulative dissolved oxygen deficit assuming median *in situ* chlorophyll concentration (see Table 5).

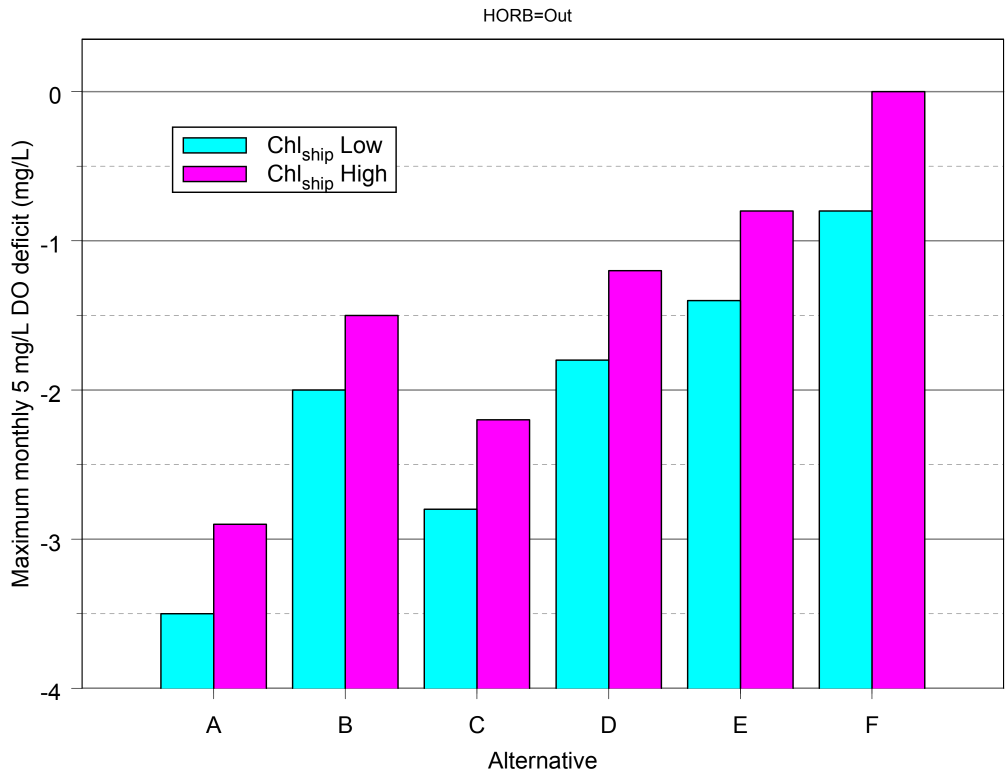

Figure 47. Effect of *in situ* chlorophyll concentration on the dissolved oxygen deficit in the ship channel under six management alternatives (see Table 5).

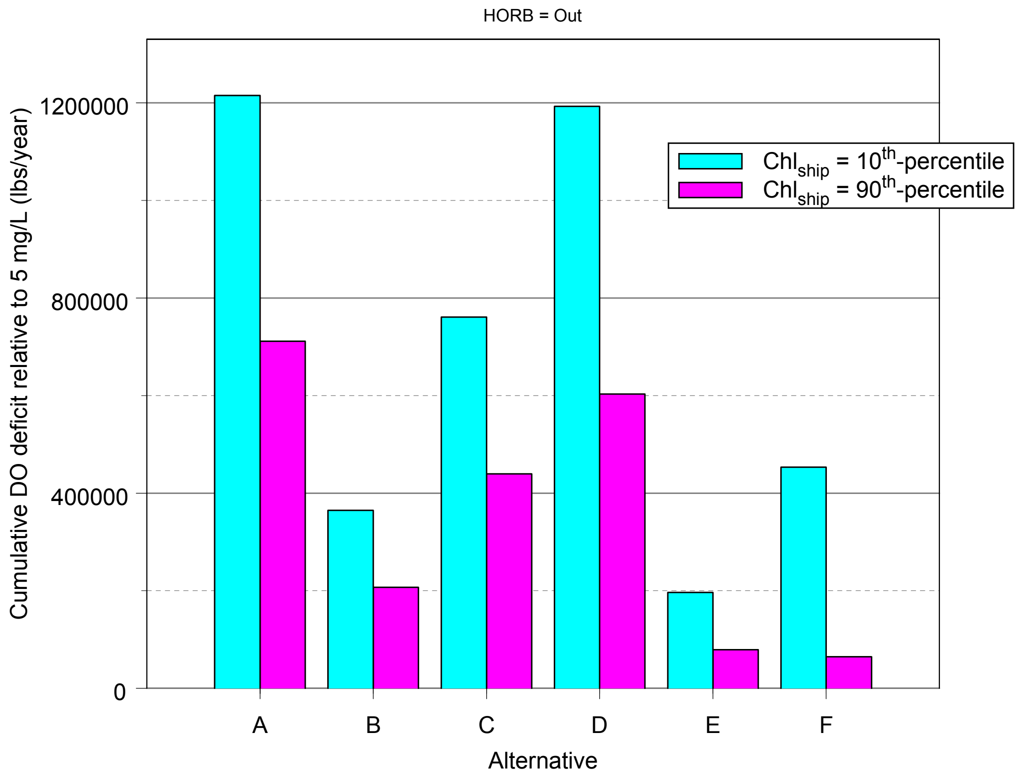

Figure 48. Effect of *in situ* chlorophyll concentration on the cumulative dissolved oxygen deficit in the ship channel under six management alternatives (see Table 5).