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TECHNICAL MEMORANDUM

AN ANALYSIS OF POTENTIAL MECHANISMS CONTRIBUTING TO NUISANCE ALGAL BLOOMS IN CHERRY CREEK RESERVOIR

Background

Long-term limnological monitoring at Cherry Creek (1987-2003) has documented a slight increase in algal biomass (measured as chlorophyll *a*) and physiologically important nutrient concentrations (nitrogen and phosphorus) during the growing season (July – September). In 2000, the CWQCC set seasonal mean chlorophyll *a* standards of 15 µg/L with the intention that this limit would be met nine out of ten growing seasons, and total phosphorus (TP) guidelines of 40 µg/L. The phased net annual allowable total phosphorus load (TMAL) was set at 14,270 lbs.

Since 1992, the chlorophyll *a* standard has only been met during the 1993 (14.8 µg/L), 1994 (6.2 µg/L), and 1995 (9.0 µg/L) growing seasons with the long-term seasonal average being 21.9 µg/L (Fig. 1). Given the recreational importance of Cherry Creek, great efforts have been taken to minimize phosphorus loading into Cherry Creek Reservoir. Wetlands constructed by the Cherry Creek Basin Water Quality Authority (Authority) on the Cottonwood Creek and Shop Creek, tributaries upstream of Cherry Creek Reservoir, have significantly reduced annual total phosphorus loads in those tributaries by 39% and 54%, respectively. Phosphorus loads have steadily decreased (51%) from the peak season of 1999. During 1999, average seasonal chlorophyll-*a* concentrations were 30.9 µg/L, and TP load was 20,209 lbs, the only year in which the TMAL has been exceeded.

Although the Authority’s efforts have significantly reduced the amount of phosphorus loading, nuisance algal blooms still occur during the growing season and detract from the overall aesthetics of the reservoir. Presented herein, is an evaluation of the potential mechanisms contributing to the sporadic nuisance algal blooms, which could possibly provide a technical basis for future discussions of remedial solutions.

Statement of the Problem

There are a number of environmental conditions that may act independently or synergistically to affect algal production. The most common aquatic ecological condition is excessive nutrient loading, primarily phosphorus, which often accelerates algal production. For balanced algal growth, aquatic ecosystems generally must possess carbon, nitrogen and phosphorus in the following relationship, 106:16:1 (molar ratio), and is referred to as the Redfield Ratio (Redfield, 1958). Because nitrogen and phosphorus are commonly the most limiting nutrients in aquatic systems, the total nitrogen to total phosphorus ratio (TN:TP, 16:1) is often used as an indicator of ecosystem health.

Historically, Cherry Creek Reservoir has been considered a phosphorus limited system (DRCOG, 1985), although recent bioassay studies have shown that algal production can be nitrogen limited during the growing season (Lewis et al., 2004). Long-term nutrient monitoring has further supported the nitrogen limitation concept by documenting phosphorus loads from tributary streams. Subsequent steps have been taken to reduce external loading (i.e., constructed wetlands and bank stabilization). These projects have significantly reduced the amount of external phosphorus loading, but it is unclear what affect they have had on N:P ratios of influent or receiving waters in the reservoir. In addition, since 2000, the Front Range of Colorado has been experiencing severe drought conditions, significantly reducing the amount of precipitation, and hence, runoff entering the reservoir. Observed decreases in external phosphorus loads may ultimately be a combination of the effectiveness of the PRFs as well as very low stream flow during drought conditions, lending more support to the potential for the importance of “internally driven” algal blooms. Because nutrient loading has primarily been examined from an “external” standpoint, the “internal” sources have not been well quantified.

Benthic sediments primarily act as a sink for “bound” nutrients, accumulating phosphorus during favorable aerobic conditions (oxidizing environment). Phosphate readily binds with iron (Fe), manganese (Mn), aluminum (Al, clays) and calcium (Ca^{2+}) forming more complex oxides and precipitates. During anaerobic conditions (reducing environment) this process is reversed, thereby, releasing phosphorus (and other ions) into the water column.

These types of internal inputs may greatly affect algal production in the surface waters. Long-term temperature and dissolved oxygen profiles show that the reservoir periodically stratifies during the growing season, creating favorable conditions for oxygen depletion. At depths greater than 4m, oxygen concentrations are often below the Colorado standard of 5 mg/L for warm-water aquatic life, and in the deep waters (<6m) typically reach levels <1 mg/L.

Past modeling efforts estimated net internal phosphorus loadings within Cherry Creek Reservoir to be approximately 4,000 lbs annually (Nürnberg and LaZerte, 2000). This value nearly equals Cherry Creek’s external load of 4,637 lbs to the reservoir in 2003 (CEC, 2004), potentially accounting for roughly 50% of total loads to the reservoir that year. Similarly, internal phosphorus loading accounted for 68% of the total summer load in 14 of 17 Western Washington lakes (Welch and Jacoby, 2001). Obviously, internal loadings may play a significant role in short-term nuisance algal blooms.

Environmental conditions that affect the duration of stratification, and potentially the release of sediment “bound” phosphorus include external forces such as wind speed and direction, and the turbulent agitation due to recreational boating activities. Given the shallow nature of the reservoir, density gradients created by thermal stratification may not be strong enough to maintain long periods of stratification (as evidenced in the monitoring record). Thus, during the growing season there may be the potential for multiple short-term phosphorus release events by the sediments.

Research Objectives

CEC proposed to further examine the nutrient-chlorophyll relationships of Cherry Creek Reservoir and to potentially identify mechanisms that affect short-term “nuisance” algal production. In this case, “nuisance” algal blooms are defined as chlorophyll-*a* concentrations >35 µg/L in the surface (top 3 m) waters of the reservoir. For the purpose of this study, we chose to primarily focus our efforts on one season (1999) that consistently exhibited high chlorophyll-*a* concentrations and to explore mechanisms that possibly lead to the nuisance algal blooms. Secondarily, we examined specific dates from other years that exhibited high chlorophyll-*a* concentrations to examine whether there were correlations to results obtained for the 1999 season.

Parameters Investigated

N:P Ratios: Long-term monitoring has created a database that is well suited for the calculation of N:P ratios and the development of seasonal nutrient mass balance models for the reservoir. If internal phosphorus loading is an important part of summer algal blooms, the analysis of long-term N:P ratios for the reservoir may lend support to an underlying mechanism.

Meteorology: We examined relationships between chlorophyll-*a* and meteorological data (wind velocity, air temperature, and precipitation), from the National Weather Station at Centennial Airport and Cherry Creek Dam weather station. Because CCR is a discontinuous, polymictic shallow reservoir, favorable weather conditions must persist for a short period of time before thermal stratification can occur. Once a density gradient is sufficient to minimize internal mixing, oxygen depletion will occur in the deep layers. Stratification and anoxia will persist until cooler waters or wind driven mixing destroys the density gradient. Given favorable anoxic conditions above the sediment layer in CCR (<1 mg O_2/L), phosphorus will disassociate from its oxidized form and be transported back into the water column via turbulent flows (Selig et al. 2002).

In-Lake Conditions: Lastly, we examined in-lake temperature and dissolved oxygen profiles to determine the strength of the relationship between intermittent stratification and nuisance algal blooms. During nuisance algal bloom events, and selected sampling dates prior to the an event, *in situ* reservoir conditions were categorized based on thermal stratification and whether anoxic conditions persisted at the sediment layer. These data along with precipitation data were also used in multiple regression analysis to determine the strength of the relationship with nuisance algal biomass.

Results and Discussion

Nutrients and chlorophyll relationships

Long-term seasonal chlorophyll-*a* concentrations have consistently been above the seasonal goal of 15 µg/L, sporadically rising above the "nuisance level" of 35 µg/L. During the 1999 season, chlorophyll-*a* concentrations were either at or above the nuisance level on 10 of the 13 weekly sampling dates.

Visually, long-term total phosphorus concentrations have slightly increased since 1992 (Fig. 2). Since 1997, TP has remained relatively unchanged and generally above the 60 µg/L level that should theoretically limit chlorophyll-*a* to 15 µg/L (Nürnberg and LaZerte 2000). The long-term record for total nitrogen (TN) is even more problematic. Between 1994 and 1998, TN was not analyzed and attempts to sum Kjeldahl nitrogen and nitrite-nitrate concentrations produced results that were not comparable to long-term TN results. Therefore, TN:TP ratios could not be calculated for this time period.

Interpretation of the TN:TP mass ratios (Fig. 3) suggest that CCR algal communities are periodically nitrogen limited (TN:TP < 10), but most often experience simultaneous nitrogen and phosphorus limitation (10< TN:TP <17), according to Smith (1982). Algal bioassay experiments performed by Lewis et al. (2003) showed that CCR was primarily nitrogen limited during the 2003 summer season, with one occurrence of simultaneous nitrogen - phosphorus limitation in mid July 2003. TN:TP ratios during the 2003 summer season basically indicate simultaneous nitrogen - phosphorus limitation, weakly supporting the bioassay results of Lewis et al.

Given the results of this analysis, it appears TN:TP ratios may be of limited use in determining causes for nuisance algal blooms in CCR. In fact, TN:TP ratios were not significantly correlated to either nuisance chlorophyll-*a* concentrations or lake-wide chlorophyll-*a* concentrations in general.

Weather Conditions and Chlorophyll

Meteorological data was acquired from the National Weather Service Station located at Centennial Airport (http://www.met.utah.edu/cgi-bin/droman/meso_base.cgi?stn=apa). These data were used to evaluate the relationships between climatological parameters (air temperature, wind velocity, and precipitation) and chlorophyll-*a* concentrations during the summer of 1999 (July to September). Mean daily values were computed from raw 10-minute data for air temperature and wind velocity, while daily totals were computed for precipitation (Figs. 4 & 5). Because algal communities exhibit a lag-time response to changes in their environment (Dodds, 2002), we computed 3-day and 5-day averages prior to sampling events for air temperature and wind velocity, and 3-day and 5-day totals for precipitation. Presumably, three and five day averages would also correlate to the periodic thermal stratification and anoxia. Longer time periods were not necessary because sampling schedules in 1999 were on a 7-day cycle. The nuisance algal events occurring in 1999 were used in regression analyses to evaluate relationships with climatic parameters. Results from 3-day regression analyses were very similar to the 5-day analyses so they have not been presented.

Nuisance chlorophyll-*a* concentrations during the 1999 season exhibited a weak positive relationship (Fig. 6) to 5-day average temperature ($R^2 = 0.32$, $p > 0.09$) and slight negative relationship to 5-day total precipitation ($R^2 = 0.36$, $p > 0.06$). There was no significant relationship to wind speed prior to sampling (Fig. 6). This suggests that algal production may have responded positively to the warmer (Fig. 4) and drier (Fig. 5) periods during that summer period, periods when conditions would potentially be more favorable for thermal stratification.

However, this pattern is not as evident when specific nuisance sample dates are examined. On 20 July 1999, CCR experienced a large precipitation event (30 mm), which obviously affected algal growth during the following week - chlorophyll-*a* concentrations increased from 7.2 µg/L on 20 July to 40.5 µg/L on 27 July (Fig. 5). Yet, other precipitation events during the 1999 season did not appear to have an obvious affect on algal biomass.

Stratification, Anoxia and Chlorophyll

Temperature and dissolved oxygen profiles for each sampling trident of CCR were examined for the summer 1999 season, along with other nuisance algal events occurring in 1998, 2000, 2001, and 2003 (Table 1). Each site was considered to be thermally stratified if there was a >1 °C temperature change below four meters from the surface waters. If there was <1°C change from the surface waters to the bottom depth sampled then the site was considered isothermal. If neither criteria was met, then the site was considered not thermally stratified. The bottom waters, near the sediment surface, were considered anoxic if dissolved oxygen concentrations were <1 mg/L. This corresponds to the redox potential required for remobilization of phosphorus from the sediments (Selig et al. 2002).

During the 1999 season and for other sample dates, it is apparent that thermal stratification was not a prerequisite for anoxic bottom conditions. At the CCR-2 sampling location (located at the deepest portion of the reservoir), 7 of the 13 sampling events indicated that the water column was not stratified, but anoxic conditions persisted above the sediment layer (Table 1). This condition infers the potential for microbially mediated anoxia in the bottom waters (Dodds, 2002). In 1999, the CCR-2 sampling location exhibited anoxic conditions throughout most of the summer period when nuisance algal blooms were present. This trend was evident during the 1998 season, as well, when chlorophyll-*a* levels were near the nuisance algal level. Other nuisance algal blooms occurring in 2000 appeared to show more of a “lag-response” to stratification and anoxia conditions present prior to the sampling date. In late August 2000, the bottom waters at the CCR-2 location became anoxic for a short period of time, apparently allowing for an internal pulse of phosphorus to occur. During the subsequent sampling routines at CCR-2, the bottom waters had re-oxygenated, while algal biomass remained at nuisance levels.

A multiple regression analysis was performed using chlorophyll concentrations, as the response variable, compared to 5-day precipitation totals as a numeric predictor variable and recoded stratification and anoxic data as categorical predictor variables. These three-predictor variables showed a significant relationship to nuisance chlorophyll-*a* concentrations and all three were included in the final model ($R^2 = 0.65$, $p < 0.001$). Even though the model has limited predictor capabilities given the use of categorical variables and nuisance algal biomass data, it appears to show there is a significant correlation between thermal stratification, bottom water anoxia and elevated chlorophyll-*a* concentrations.

Preliminary Conclusions

These findings are certainly preliminary and additional analysis could be conducted. But, there appears to be enough information to suggest that the periodic stratification (and subsequent anoxic conditions in the bottom waters) observed in the lake may be strongly related to nuisance algal blooms in Cherry Creek Reservoir. Such findings would tend to support the potential use of destratification (e.g., coarse-bubble aeration) as an in-lake management option.

References

Dodds, W.K. 2002. Freshwater Ecology: Concepts and Environmental Applications. Academic Press, San Diego, CA.

Lewis, et al. 2003.

Nürnberg, G. and B. LaZerte. 2000. Modeling future scenarios for Cherry Creek Reservoir. Prepared for The Cherry Creek Basin Water Quality Authority.

Redfield, A.C., 1958. The biological control of chemical factors in the environment. Am. Sci. 46, 205-221.

Selig, U.; T. Hubener; and M. Michalik. 2002. Dissolved and particulate phosphorus forms in a eutrophic shallow lake. Aquat. Sci. 64:97-105.

Smith, V.H. 1982. The nitrogen and phosphorus dependence of algal biomass in lakes: An empirical and theoretical analysis. Limnol. Oceanogr. 27:101-112

Table 1. Thermal stratification and anoxic conditions, at the three sampling locations, for nuisance algal blooms and selected sampling dates prior to nuisance algal blooms.

	CCR-1		CCR-2		CCR-3		Chlorophyll-*a*
Collection date	Stratified	Anoxic	Stratified	Anoxic	Stratified	Anoxic	Lake-wide Average (µg/L)
4-Aug-98	isothermal	Yes	isothermal	Yes	NA	NA	32.0
1-Sep-98	No	Yes	No	Yes	NA	NA	24.3
8-Sep-98	No	Yes	No	Yes	NA	NA	19.8
15-Sep-98	No	No	No	No	NA	NA	32.6
22-Sep-98	isothermal	No	No	No	NA	NA	32.8
6-Jul-99	Yes	No	Yes	Yes	isothermal	No	4.6
13-Jul-99	Yes	No	Yes	Yes	No	No	15.7
20-Jul-99	No	No	No	Yes	No	No	7.2
27-Jul-99	No	Yes	No	Yes	No	No	40.5
3-Aug-99	No	No	No	Yes	isothermal	No	30.4
10-Aug-99	isothermal	No	No	Yes	No	No	34.2
17-Aug-99	isothermal	No	No	Yes	No	No	50.8
24-Aug-99	isothermal	No	No	Yes	No	No	45.6
31-Aug-99	isothermal	No	No	Yes	No	No	33.3
7-Sep-99	isothermal	No	No	Yes	No	No	40.0
14-Sep-99	isothermal	No	isothermal	No	No	No	34.5
21-Sep-99	isothermal	No	isothermal	No	No	No	33.8
28-Sep-99	isothermal	No	isothermal	No	isothermal	No	31.3
22-Aug-00	isothermal	No	No	Yes	No	No	39.6
5-Sep-00	isothermal	No	isothermal	No	isothermal	No	33.8
12-Sep-00	isothermal	No	No	No	No	No	39.4
26-Sep-00	isothermal	No	No	No	isothermal	No	28.3
24-Jul-01	isothermal	NA	No	NA	No	NA	79.8
15-Jul-03	No	Yes	Yes	Yes	No	Yes	38.6

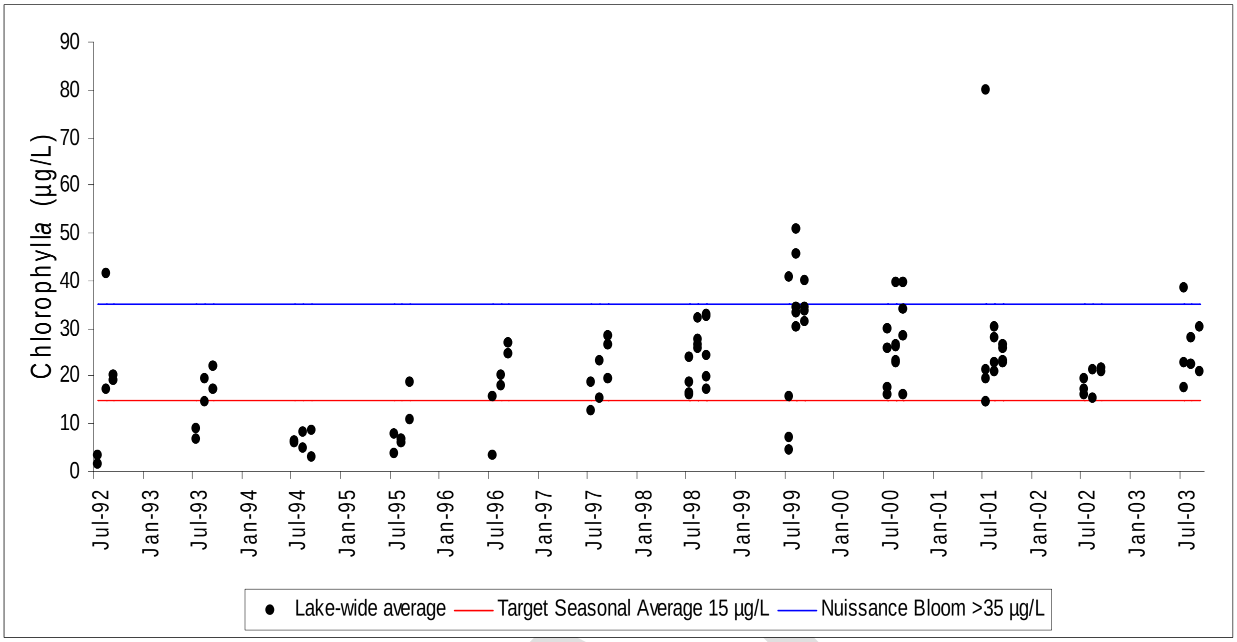

Figure 1. Lake-wide chlorophyll-*a* averages between July and September from 1992 to 2003. Red line represents target seasonal standard of 15 µg/L, and the blue line represents the lower level of the nuisance algal bloom (35 µg/L).

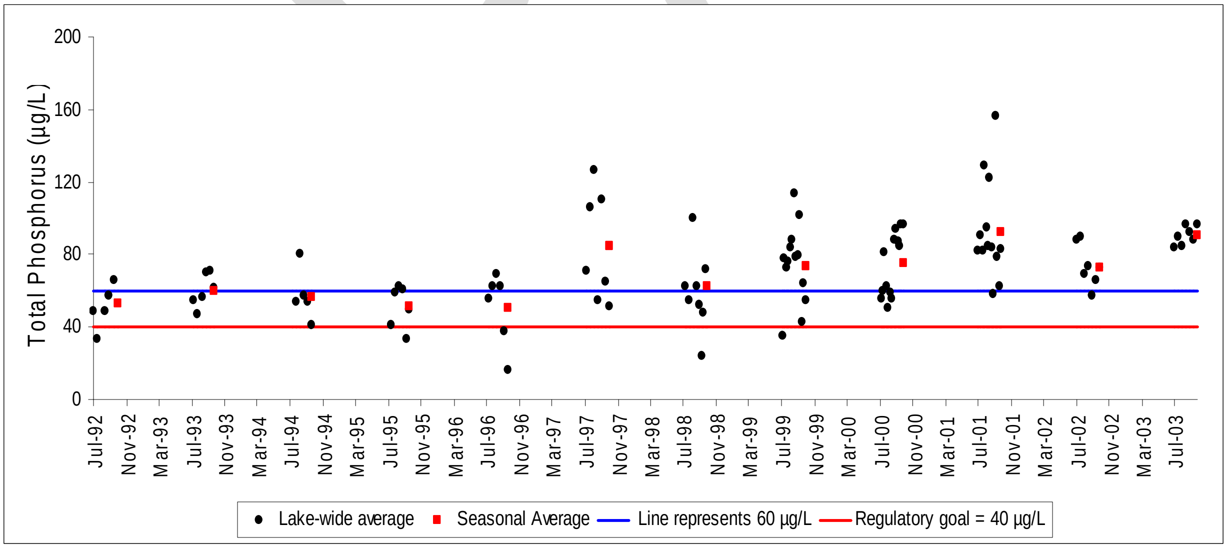

Figure 2. Lake-wide total phosphorus averages between July and September from 1992 to 2003. Blue line represents the value of 60 µg/L that theoretically limits chlorophyll-*a* production to 15 µg/L. Red line represents the regulatory goal of 40 µg/L.

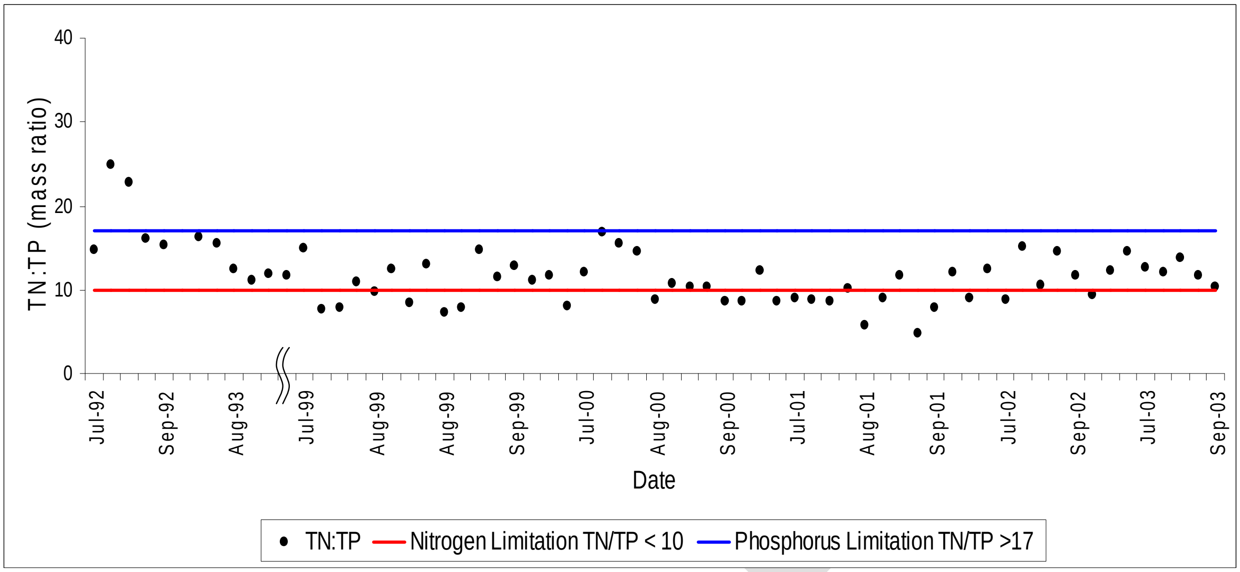

Figure 3. Lake-wide TN:TP ratios between July and September from 1992-1993 and 1999 to 2003.

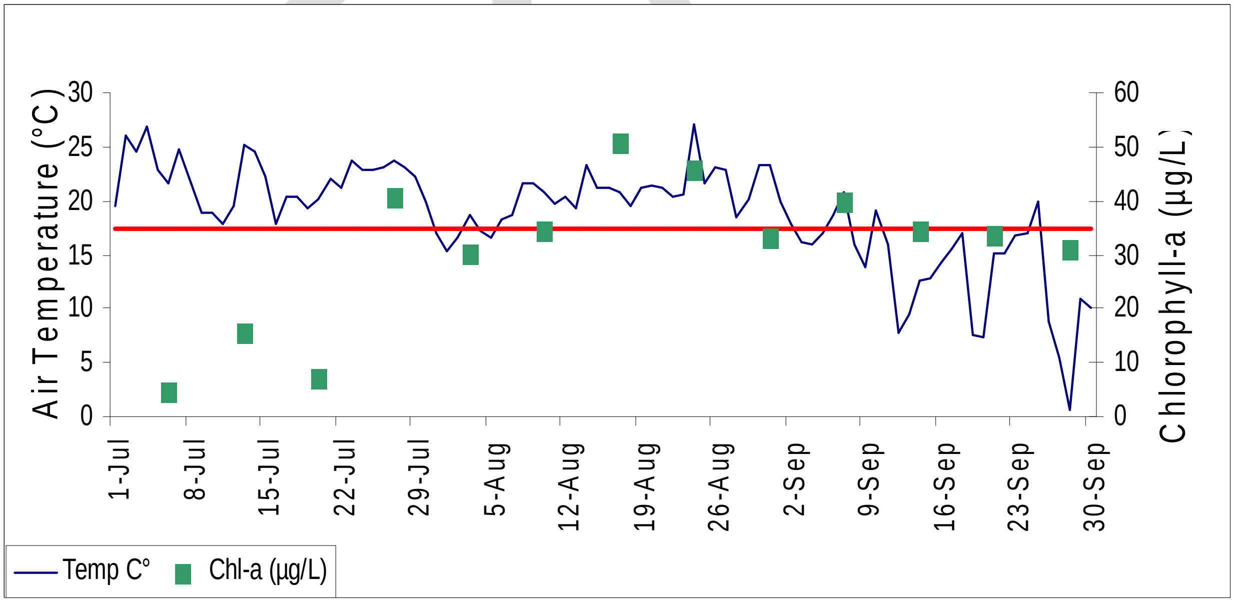

Figure 4. Mean daily air temperature and chlorophyll-*a* concentrations during the 1999summer season. Red line indicates the lower limit for nuisance algal blooms.

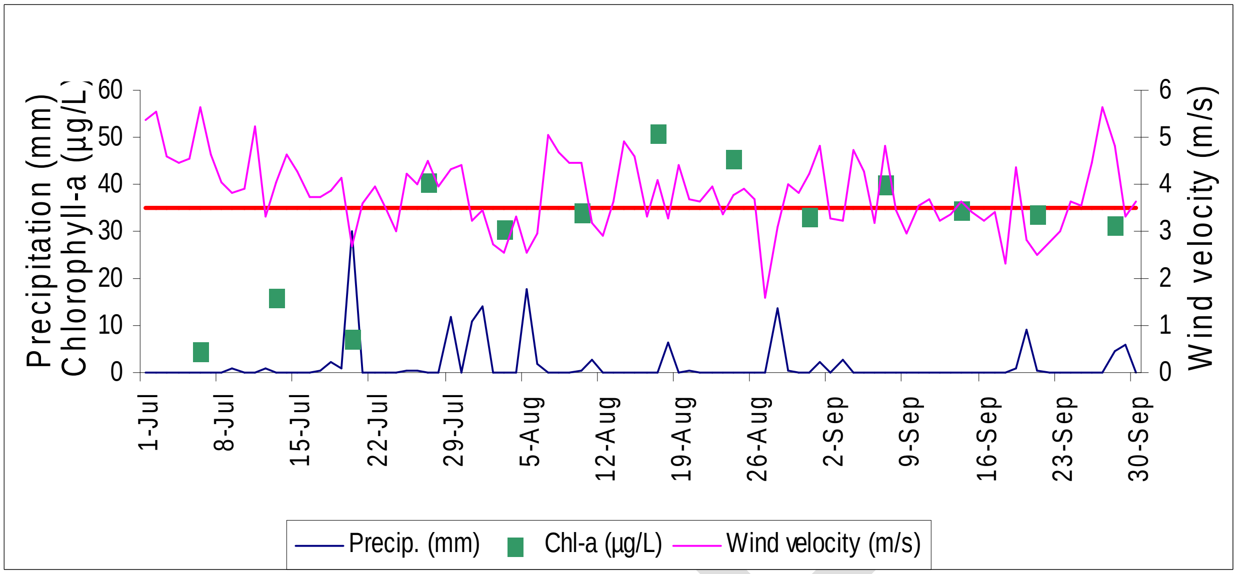

Figure 5. Total precipitation, chlorophyll-*a* concentrations, and mean daily wind velocity during the 1999summer season. Red line indicates the lower limit for nuisance algal blooms.

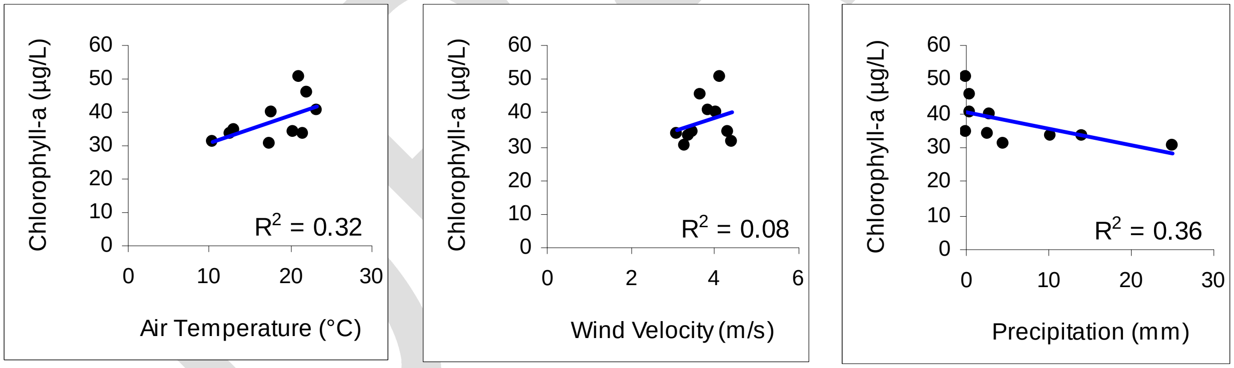

Figure 6. Nuisance chlorophyll-*a* relationships to the preceding 5-day averages for air temperature and wind velocity and 5-day total precipitation during the 1999 season.