IMPROVING LAKE WATER QUALITY BY SOLAR POWERED CIRCULATION

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ABSTRACT

Algal blooms are prevalent during the summer months in Palmdale Lake as a result of warm stratified conditions and light availability. These blooms create unsightly lake conditions, taste and odor problems and have adverse effects on the treatment process by forcing inadequate settling, filter clogging and filter breakthrough. Also, production of toxins from cyanobacteria cannot be discounted. Traditionally, we use copper sulfate to limit the blooms. Lately, many shortcomings have been associated with the use of copper sulfate as algicide. We demonstrate in this paper that the use of a lake circulation device proved to substantially reduce algal blooms such that we almost avoided the use of copper sulfate in 2003. Seven solar powered circulation devices were strategically located on the lake for extensive coverage while avoiding re-suspension of bottom sediments. The important factors that showed the effectiveness of lake circulation are impact on lake stratification; uniformity of dissolved oxygen distribution; bio-manipulation of algal population and density; lower pH levels; increased secchi depth; lower average turbidity; and reduced concentration of chlorophyll a.

Palmdale Lake surface elevation is 2812.5ft. It has an average depth of about 17.6ft. and a maximum water depth of 25ft. The surface area is 234 acres and the capacity is 4129AF. The restriction and pattern of flow in Palmdale Lake facilitates algal blooms in the summer months when the lake surface layer is warm and light provides the energy for photosynthesis.

Nutrient supply to the lake is naturally curtailed by denitrifying bacteria (predominantly Pseudomonas aeruginosa) making phosphorus the limiting nutrient. Phosphorus loading varies widely depending on the amount of inflow from the State Water Project (SWP) and Littlerock Reservoir.

Lakes are generally classified by limnologists into one of three trophic states: oligotrophic, mesotrophic, or eutrophic. Lake Trophic State Index (TSI) developed by Carlson (1977) on the basis of Secchi disc transparency, chlorophyll a, and surface total phosphorus can be used to calculate a lake's trophic state. TSI calculated based on Secchi depth, chlorophyll-a and total phosphorus indicates that Palmdale Lake can be hypereutrophic.

$$TSI = 60 - 14.4 \ln (SD) \qquad \text{(Eqn. 1).}$$
$$TSI = 9.81 \ln (CHL) + 30.6 \qquad \text{(Eqn. 2)}$$
$$TSI = 14.42 \ln (TP) + 4.15 \qquad \text{(Eqn. 3)}$$

Where TSI = Trophic State Index
SD = Secchi Depth, meters
CHL = Chlorophyll a, μg/L
TP = Total Phosphorus, μg/L

In the summer of 2002, secchi disc transparency or Secchi depth in the lake averaged 3ft. (0.91m). Therefore based on SD, TSI = 60 – 14.4 ln(0.91) = 61

Choloropyll-a level ranged from 5.3 to 24.9µg/L with an average of 13.5µg/L. Therefore based on CHL,

TSI (minimum) = 9.81 ln(5.3) + 30.6 = 47
TSI (average) = 9.81 ln(13.5) + 30.6 = 56
TSI (maximum) = 9.81 ln(24.9) + 30.6 = 62

Phosphorus loading rate ranged from 8.75 to 400µg/L. Therefore based on TP, TSI range is,

TSI = 14.42 ln(8.75) + 4.15 = 35
TSI = 14.42 ln(400) + 4.15 = 91

From Table 1, TSI indicates that Palmdale Lake can range from being mesotrophic to hypereutrophic.

Table 1 - Quantitative Definition of Lake Trophic State

TROPHIC STATE INDEX (TSI)	TROPHIC STATE
<40	Oligotrophic
40-50	Mesotrophic
50-70	Eutrophic
>70	Hypereutrophic

Oligotrophic lakes have low nutrient levels and are usually clean and cold. Eutrophic lakes are high in nutrients and likely to be very productive in terms of weed growth and algal blooms. Mesotrophic lakes are between oligotrophic and eutrophic while a hypereutrophic lake is one that has undergone extreme eutrophication to the point of having developed undesirable aesthetic qualities (e.g. odors, algal mats, and fish kill).

This paper examines the influence of stratification, dissolved oxygen dynamics, temperature, pH, nutrient loading and chlorophyll a level on incidence of spring/summer algal blooms in the lake's natural state between March and October 2002 and after a forced circulation device was installed in November 2002. The constant water movement induced by circulation substantially reduced the occurrences of algal blooms thereby resulting in savings due to minimal chemical treatment of the lake.

Study Sites and Methods

Lake Monitoring Sites

Five locations on the lake were selected to monitor pH, temperature, turbidity, dissolved oxygen, conductivity and chlorophyll a at different water columns. Composite samples from these sites were also analyzed for zooplankton and algae identification and enumeration.

1. **Boat Ramp.**

   Located in the southwest corner, about ten feet (10ft.) east of the boat dock, this site represents stagnant sections of the lake. Algae and zooplankton activities are prevalent making this site a good sampling location for identification of algae and plankton that thrive in the lake. Water quality in this part can be used to predict the quality under low flow or no flow lake situations. Average water depth is 8ft.

2. **Aqueduct Inlet.**
This location is situated about three hundred feet (300ft.) from the shoreline at the aqueduct inlet. Samples from this location will be representative of the immediate changes in quality of the lake water compared to aqueduct sample collected at the hydroelectric facility. Average water depth is 15ft.

3. **Palmdale Ditch Inlet.**
This location is situated in the center of the Littlerock ditch inlet channel. The water conveyed through the ditch from Littlerock Reservoir travels up to 9 miles and has high TOC and turbidity. Due to occurrence of algae bloom at Littlerock reservoir, the water may carry high algae population. The distinct influence of the water quality from the ditch on the lake will be determined from samples collected at this location. Average water depth is 7ft.

4. **Center of the Lake.**
This represents the deepest part of the lake. Samples pulled at different depths of this location will determine the necessity to draw water at selected depth due to variations in quality. Average water depth is 22ft.

5. **Lake Outlet Structure.**
This location is about sixty feet (60ft) due south of the outlet structure in the center of the channel. Water samples at different depths of this location will shed a light on the quality profile at the last point of the lake before water is pulled into the treatment plant. Average water depth is 22ft.

Details of Monitoring

The five selected locations on the lake are identified with anchored buoys to ensure sample point consistency throughout the study period. The following parameters are measured at least twice a month between March and September and once a month between October and February using a six probe sonde and a hand held data-logger*: pH, temperature, turbidity, DO, conductivity, and chlorophyll a.

Measurements are recorded at the one foot (surface), four feet, ten feet, fifteen feet and twenty two feet depending on the average depth at the sample location. Data were collected down to four feet at locations 1 and 3, fifteen feet at location 2, and twenty two feet at locations 4 and 5. The sonde was calibrated with treated water before each sampling event. The treated water was tested for all parameters using calibrated bench-top instruments. Chlorophyll-a was assumed to be less than 0.1μg/L in the treated water. Numbers from the bench-top instruments are used for one point calibration of the sonde.

Total phosphorus (TP) loading rate from lake entry point, site 2, and composite TP from the other locations were measured fifteen times during the study using an Ion Chromatograph*.

Composite sample for crustacean zooplankton and algal enumeration and identification from all lake sources were also collected twice a month from March to September and once a month from October to February. Algal analysis was performed by settling the whole water samples in sedimentation chambers. Settled samples were then analyzed to determine total algal composition and abundance at the genus level. Algal counts calculated in cells/ml are presented as taste and odor algae, filter clogging algae, toxin producing algae, polluting algae, and total algae. Algae sample was collected from each location at about 3feet (the usual Secchi depth) using a Van Dorn sampler. 200ml from each location is mixed for a composite sample volume of 1000ml. 125ml of this well mixed composite sample is preserved with 25 drops of Lugol's iodine solution and sent to the laboratory for analysis*.

Preserved zooplankton samples were quantitatively sub-sampled using a wide-bore (Hensen-Stempel) pipet, dispensed in counting chamber, identified at 10-40x magnification using a stereozoom dissecting microscope, and enumerated using a tally pad. Sufficient sub-sample volume was used to assure either 200 individuals or 10% of the total sample is quantified*. Results provided estimates of the density (#/L) of each genus. Composite zooplankton sample was collected by towing a 153µm simple conical tow net submerged horizontally just below the water surface from 100yards away from each sampling location buoy to concentrate the sample. 200ml from each location is then mixed for a composite volume of 1000ml sample which is further concentrated by filtering through the net to 250ml final volume and preserved with 4% sugar buffered formaldehyde.

*YSI 6600 Multi-parameter Water Quality Monitor, YSI 650 MDS data-logger; algae analysis performed at Northern Kentucky University; zooplankton analysis performed at Lake Superior State University.

Results and Discussion

Algae, Nutrient Supply and Crustacean Zooplankton

Average monthly algae population - classified as taste & odor, toxin producers, filter cloggers excluding diatoms, and pollution indicators - from the sole source of supply (SWP) to the lake between March and August of 2002 averaged 59units/ml. For the same period in 2003, SWP supplied 80% of the inflow while Littlerock flow contributed 20%. Average algae population from SWP was 69units/ml. Littlerock supplied the lake mainly in June and contributed 5,031units/ml for the duration of the flow. The corresponding total algae population in the lake surface layer for the same period in 2002 was 1,323units/ml and 2,120units/ml in 2003. The lake was treated almost once a week with copper sulfate powder and liquid between March and September in 2002 culminating to a total of 27,250Ibs of copper sulfate powder and 258 gallons of liquid. The lake was treated three times in 2003 with 7,000Ibs of copper sulfate powder and 60gallons of liquid. Chlorophyll a level (Fig 1) was consistently above the threshold of 15µg/L in the summer of 2002 despite weekly treatment. The threshold number coincides with observed poor lake aesthetic conditions and increased pH levels (>8.9) that compromise the ability of aluminum sulfate to perform as the primary coagulant in the treatment plant. At the threshold concentration of 15µg/L the lake is eutrophic.

Chlorophyll a level remained consistently below the threshold throughout the summer of 2003 and the downward trend of the pH is more pronounced (Fig 2). Chlorophyll a exceeded the threshold in March 2003 at 20.1µg/L marking the period of spring turnover. Algal analysis during this incident revealed the predominance of diatoms in the algae population (Figs 3, 4, & 5). Diatoms are not blue-green algae but could lead to filter clogging if allowed to proliferate. Algae proliferation during the 2003 spring turnover was short-lived. This is believed to occur because circulation promotes rapid reproduction of diatoms by maintaining them in suspension throughout the lake area thereby exposing them to nutrients. This enables diatoms to out-compete other kinds of algae for food and eventually die off as phosphorus becomes limited. Chlorophyll a level dropped significantly from 20.1µg/L in March 27, 2003 to 3µg/L in April 4, 2003 without any lake treatment.

Nutrient supply to the lake is naturally curtailed by denitrifying bacteria predominantly Pseudomonas aeruginosa making phosphorus the limiting nutrient. Phosphorus loading (Fig 6) varies widely depending on the amount of inflow from the State Water Project (SWP) and Littlerock Reservoir. A mathematical model (Equation 4) was developed to predict phosphorus loading or chlorophyll a level in the lake. The accuracy for chlorophyll a prediction is within ±10% and phosphorus is predicted within a range of 0 - 2.5µg/L and 0 - 50µg/L depending on the total phosphorus index (TPI) (Table 2) for phosphorus concentration between 2µg/L and 400µg/L.

$$C = 10^{(\exp(pH+0.05))(1.6806 \times 10^{-4})} + \prod^{1/T} + \ln(TPI) \qquad \text{(Eqn. 4)}$$

where:
C = Chlorophyll a, µg/L
pH = pH of lake water, units
T = Temperature of lake water, ^{o}C
TPI = Total Phosphorus Index

Table 2: Total Phosphorus Index (TPI)

TP	TPI
≥400	10000.00
350-400	1000.00
300-350	500.00
250-300	100.00
200-250	50.00
150-200	25.00
100-150	10.00
75-100	3.00
65-75	1.00
55-65	0.50
50-55	0.25
45-50	0.10
20-45	0.05
15-20	0.015
10-15	0.010
7.5-10	0.001
5-7.5	0.0005
2-5	0.0002
<2	0.00002

For example:

Phosphate loading to the lake is 98µg/L. Lake temperature is 21.68^{o}C and the pH is 8.32. What is chlorophyll a concentration in µg/L?

$$C = 10^{(\exp(pH+0.05))(1.6806 \times 10^{-4})} + \prod^{1/T} + \ln(TPI)$$

exp(pH+0.05) = 4315.6
$10^{(\exp(pH+0.05))(1.6806 \times 10^{-4})} = 5.31$
$\prod^{1/21.68} = 3.142^{1/21.68} = 1.054$

ln (TPI) = ln 3 = 1.0986
Predicted chlorophyll a, C = 5.31 + 1.054 + 1.0986 = 7.5µg/L
Actual chlorophyll a = 7.1µg/L
Difference = 5.6%

The amount of phosphorus in the lake at any time, vary from below detection limit of 10µg/L to as much as 100 % of the input concentration before lake circulation. With lake circulation in place, phosphorus level ranged from below detection limit to 50% of the input irrespective of input concentration.

Correlation between chlorophyll-a and algae population could not be established because algae enumeration was performed on composite sample from all five locations whereas chlorophyll a measurements were performed in-situ at each site.

Zooplankton population also mimics algae proliferation. Abundant quantities of Cladocera and Copepoda during peak algal activities indicate availability of food supply for zooplankton reproduction because lake circulation distributes limited nutrients evenly among the planktons. As nutrient becomes limited for algae survival resulting in algal mortality, zooplankton food source dwindles and their population also decreases since zooplanktons feed on algae. This phenomenon is elucidated in Fig 7 with two peaks for zooplankton population in 2003.

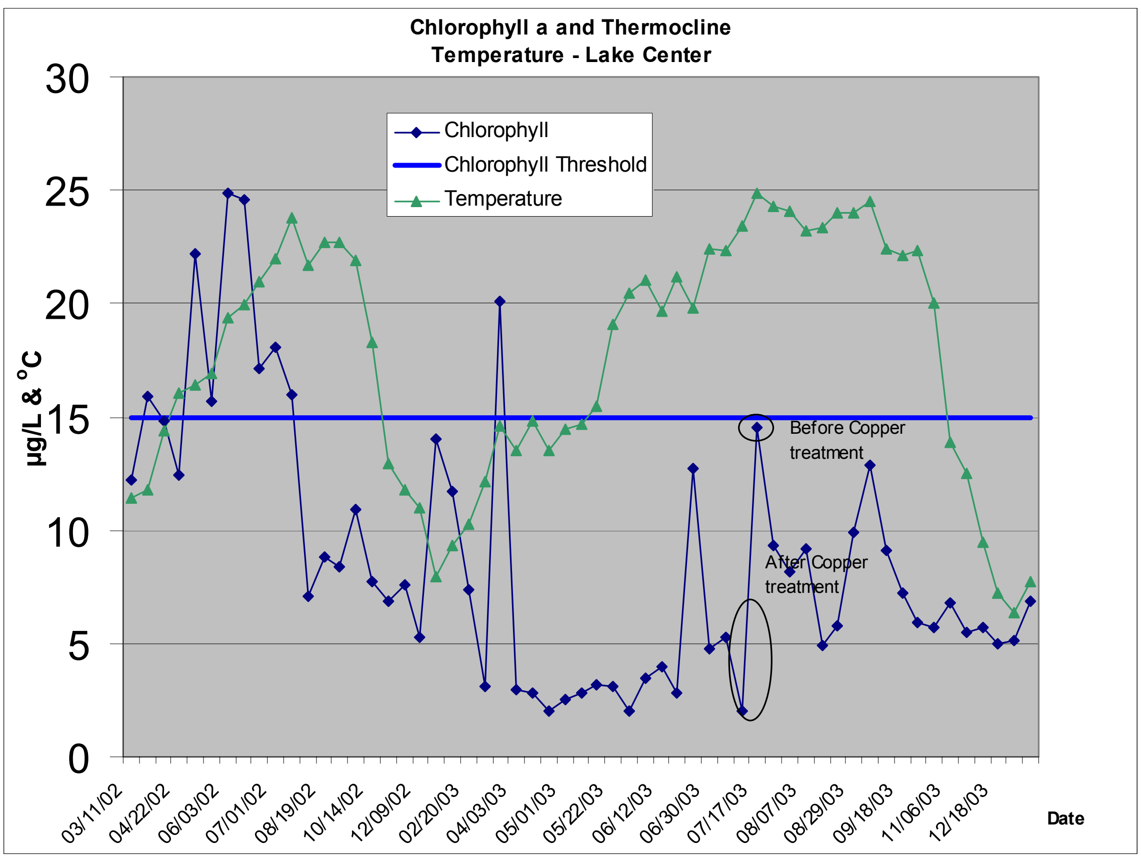

Figure 1: Chlorophyll a and Thermocline Temperature – Lake Center

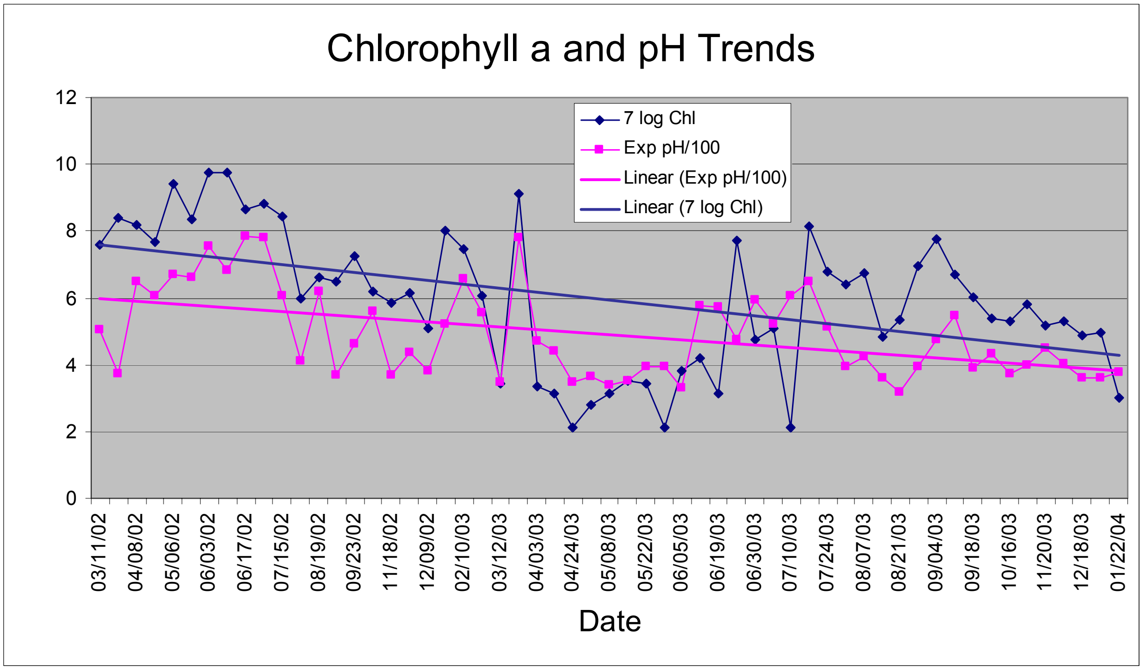

Figure 2: Chlorophyll a and pH Trends

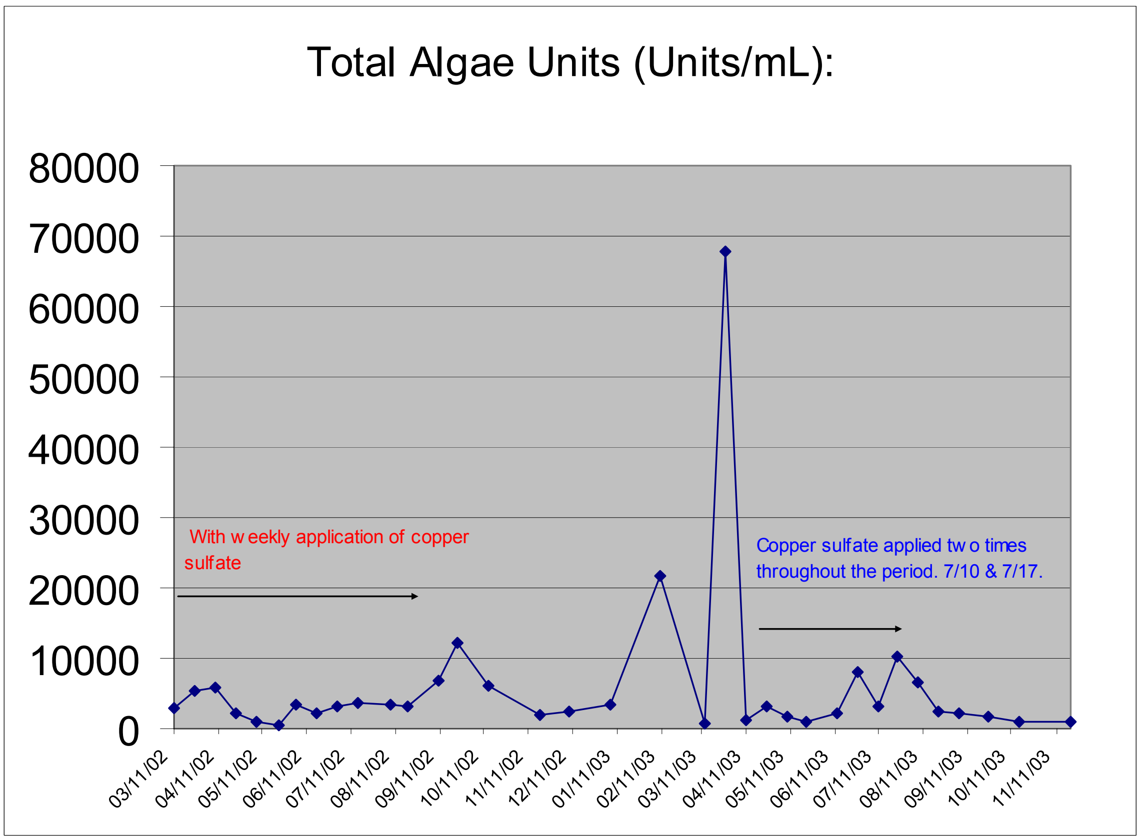

Figure 3: Total Algae – Lake Surface (units/mL)

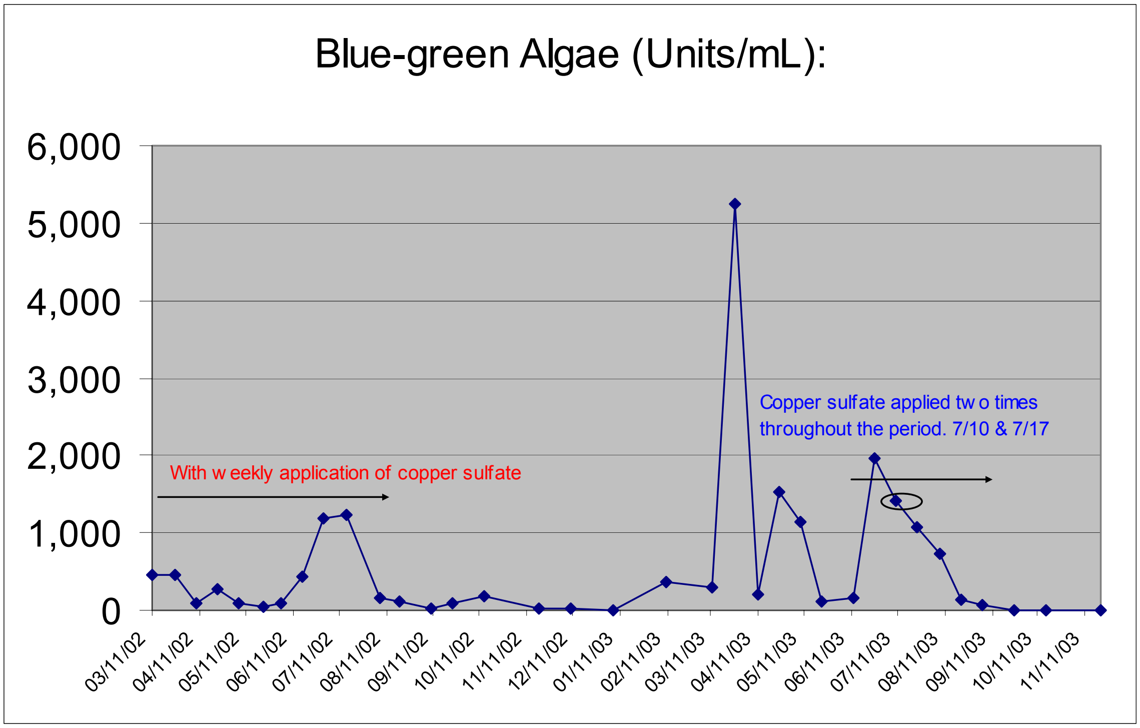

Figure 4: Blue-Green Algae – Lake Surface (units/mL)

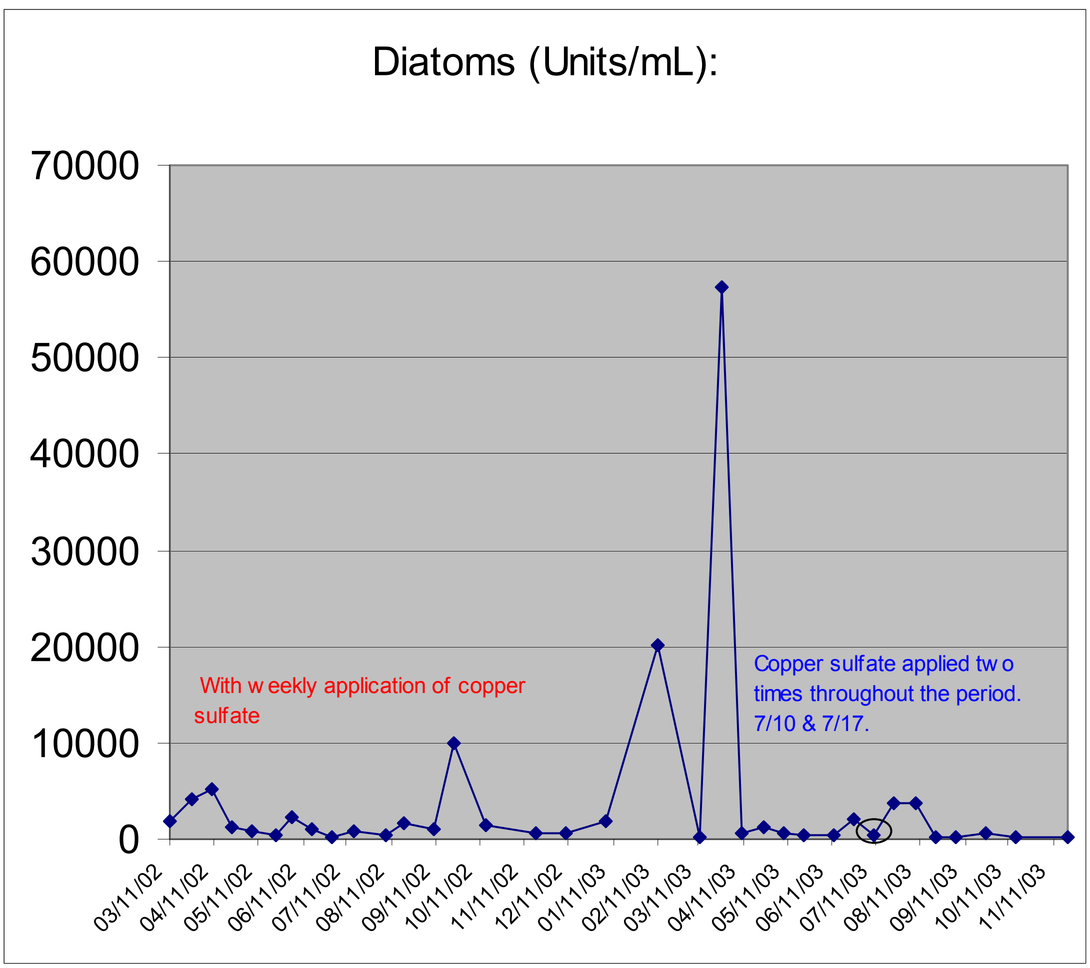

Figure 5: Diatoms – Lake Surface (units/mL)

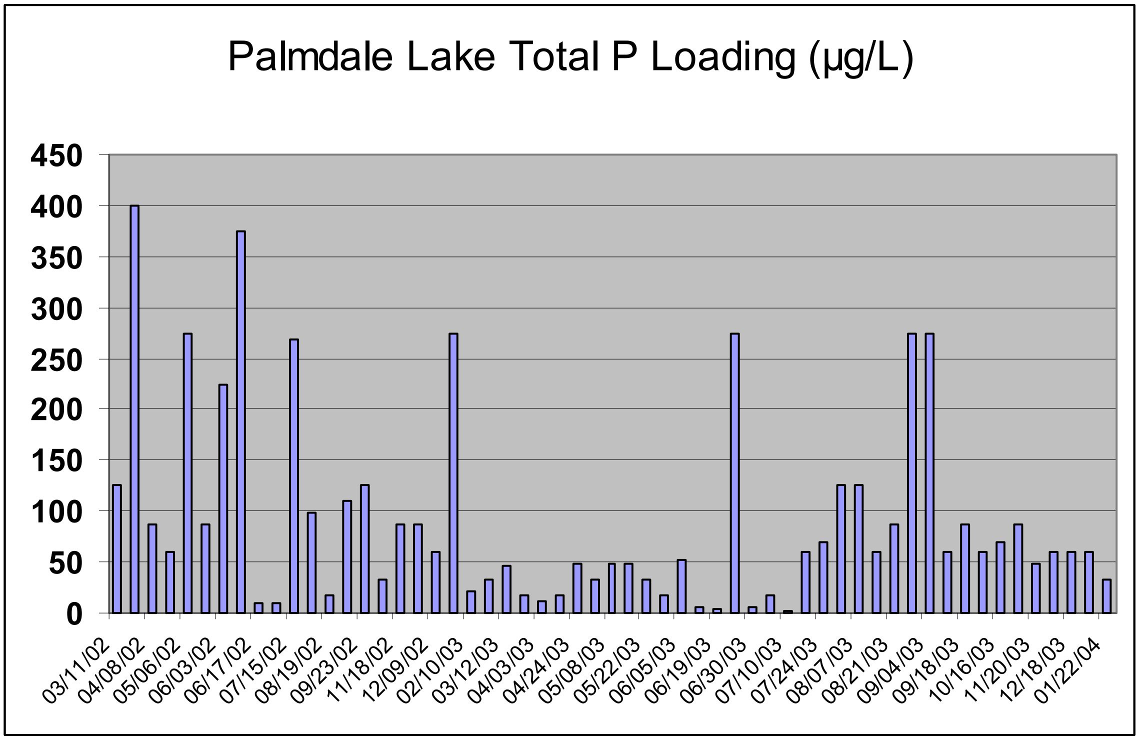

Figure 6: Total Phosphorus loading (µg/L)

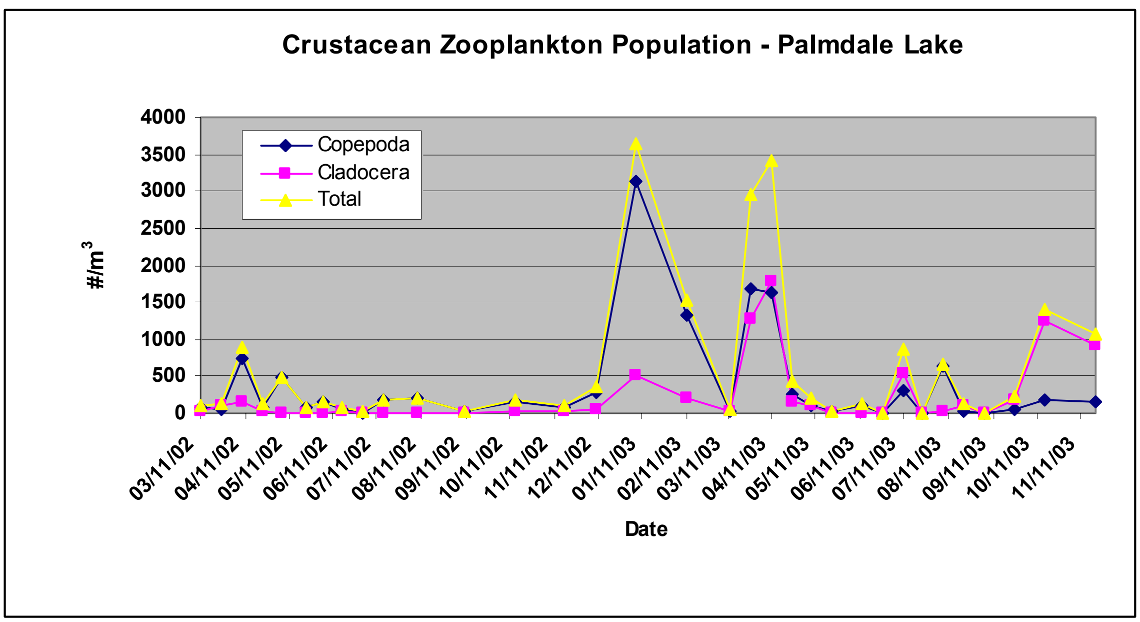

Figure 7: Crustacean zooplankton population – Lake Surface (units/m^3)

pH, Temperature, Secchi Transparency depth and turbidity.

Average lake surface pH between March and August 2002 was 8.79, the minimum was 8.24 and the maximum was 9.12. For the same period in 2003, these numbers were 8.46, 8.13, and 8.97 respectively. When pH reaches 8.9 and above, it gets difficult for aluminum sulfate, the coagulant used in treatment, to perform effectively especially at flow rates near the plant design capacity (28MGD) prevalent in summer months. pH peaked at >8.9 several times between May and July in 2002 while there was just one such incidence in 2003 (March 27, 2003) (Fig 8). Lower pH level in 2003 is tied to less algal activity because of lake circulation despite higher average lake temperature in 2003 (Table 3).

Table 3 – pH and Temperature (March - August), Turbidity and Secchi depth (March – October), Trophic State.

	Average	**Minimum**	**Maximum**
2002 – No lake circulation			
pH	8.79	8.24	9.12
Temperature ^oC	19.1	12.6	24.8
Turbidity, NTU	6.66	2.7	9.3
Chlorophyll a	13.5	5.3	24.9
TSI (Chl a)	56	47	62
Trophic State	Eutrophic	Mesotrophic	Eutrophic
Secchi depth, ft	3	3	4
2003 – Lake circulation			
pH	8.46	8.13	8.97
Temperature ^oC	20.3	13.6	25.6
Turbidity, NTU	5.21	0.7	12
Chlorophyll a	6.6	2	20.1
TSI (Chl a)	49	37	60
Trophic State	Mesotrophic	Oligotrophic	Eutrophic
Secchi depth, ft	6	3	14

High summer temperature and light penetration are known to promote algae bloom in lakes and open reservoirs but secchi disc transparency depth decreases as algae population increases. Algal mass decreases water clarity thereby reducing transparency depth and increasing turbidity. Increased secchi transparency depth in 2003 (Table 3) enhances light penetration but the algal activity normally encouraged by photosynthesis and high temperature is curtailed by limited amount of nutrient forced by lake circulation. There is also a reduction in lake average turbidity in 2003 compared to 2002. Observed incidences of high turbidities always coincided with high wind conditions. Wind speed up to 30mph occurs normally in the valley.

Palmdale lake Secchi disc transparency or Secchi depth averaged 6ft. (1.83m) in 2003. Therefore based on SD,

$$TSI = 60 - 14.4 \ln(1.83) = 51$$

Palmdale lake choloropyll a level ranged from 2 to 20.1μg/L in 2003 with an average of 6.6μg/L. Therefore based on CHL,

$$TSI\ (minimum) = 9.81 \ln(2) + 30.6 = 37$$
$$TSI\ (average) = 9.81 \ln(6.6) + 30.6 = 49$$
$$TSI\ (maximum) = 9.81 \ln(20.1) + 30.6 = 60$$

From Table 3, TSI indicates that Palmdale Lake ranged from oligotrophic to eutrophic in 2003 compared to ranging between mesotrophic and eutrophic in 2002.

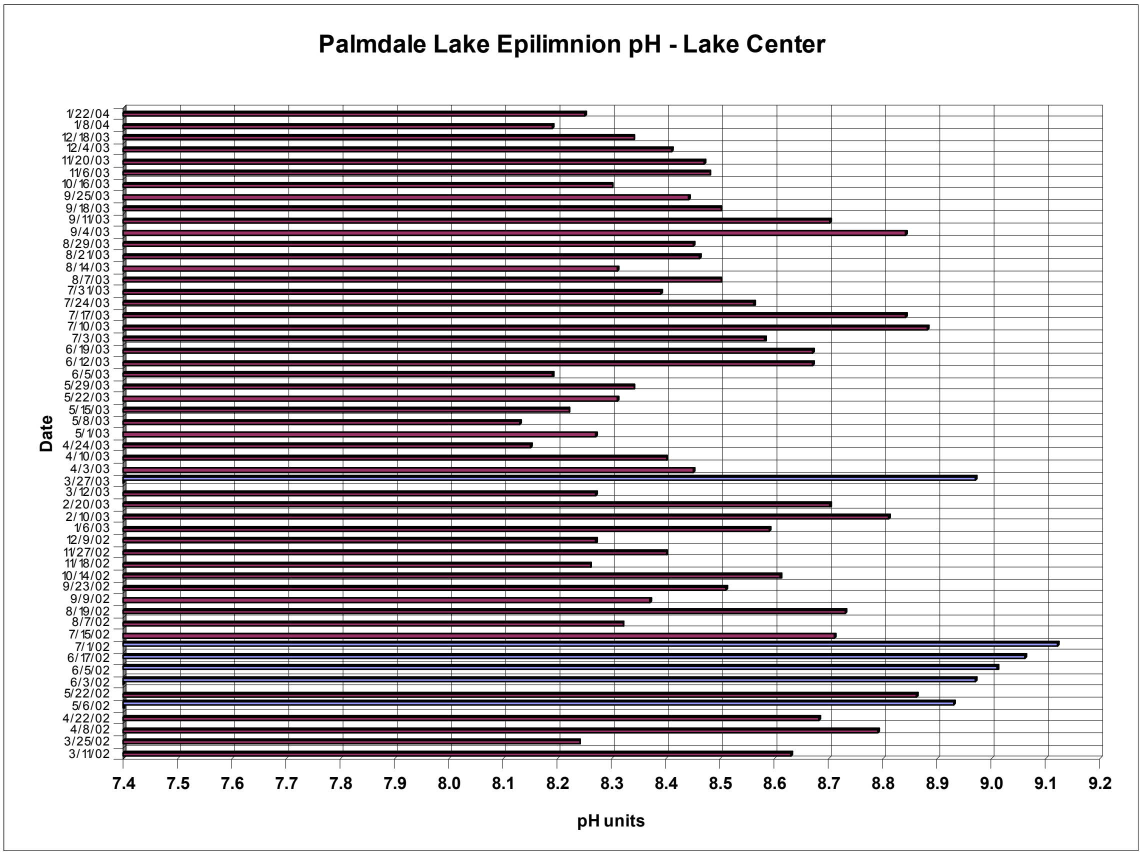

Figure 8: Epilimnion pH – Lake Center

Lake Stratification and Dissolved Oxygen

Summer ambient temperature fluctuates widely between day and night because of the desert climatic conditions of the Antelope Valley. This pattern reflects in the lake, making the daily summer temperature difference between the epilimnion and hypolimnion above 1^oC on a regular basis (Fig 9). Since the circulation device cannot operate without solar energy, there is virtually no circulation at night. In essence, lake stratification always occurs in the summer months when daytime ambient temperature can be as high as 110^oF (29^oC) and epilimnion temperature can reach 26.5^oC. However, the adverse effect of lake stratification is mitigated when circulation begins because the thermocline (at a depth of about 10 feet) will always be disturbed (Fig 10) resulting in continuous stratification/de-stratification of the lake. Thermocline, the depth at which an abrupt change in temperature stratifies the lake into two distinct temperature zones with the warmer zone on top, promotes algal activities. It is evident from figures 9 & 10 that the thermocline persisted during spring and summer of 2002, but became inconsistent in 2003 when lake circulation was in place.

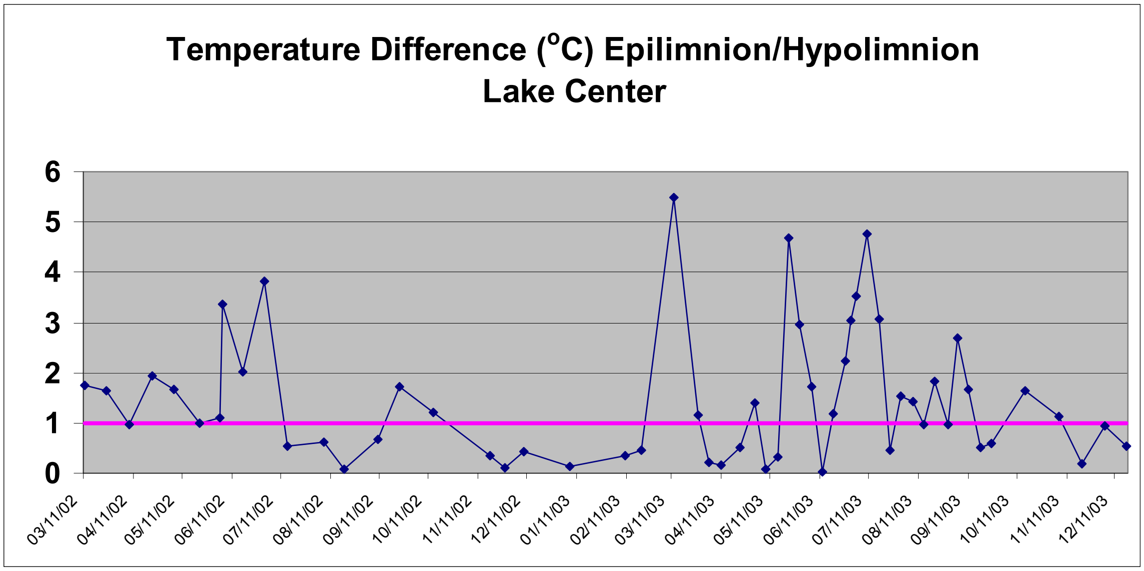

Figure 9: Temperature difference – Epilimnion/Hypolimnion – Lake Center

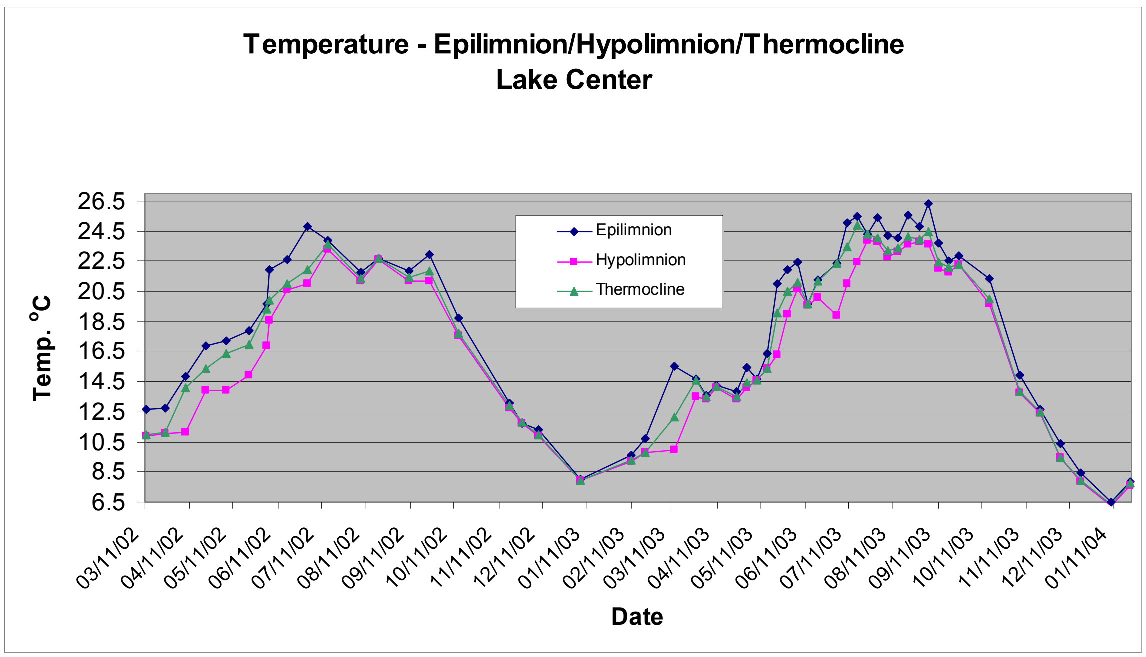

Figure 10: Temperature – Epilimnion, Hypolimnion and Thermocline at Lake Center.

Dissolved oxygen (DO) distribution in the lake column is more uniform during the lake circulation period. The average difference and maximum difference in DO between the epilimnion and the hypolimnion pre-circulation (March – October 2002) were 2.74mg/L and 7.56mg/L respectively compared to 1.65mg/L and 5.99mg/L during lake circulation (March – October 2003). This is shown by the downward trend in DO difference in Fig 11. While there is no difference in average hypolimnion DO with or without circulation since there is no aeration, the minimum DO recorded without circulation was 2.67mg/L compared to 3.86mg/L with circulation.

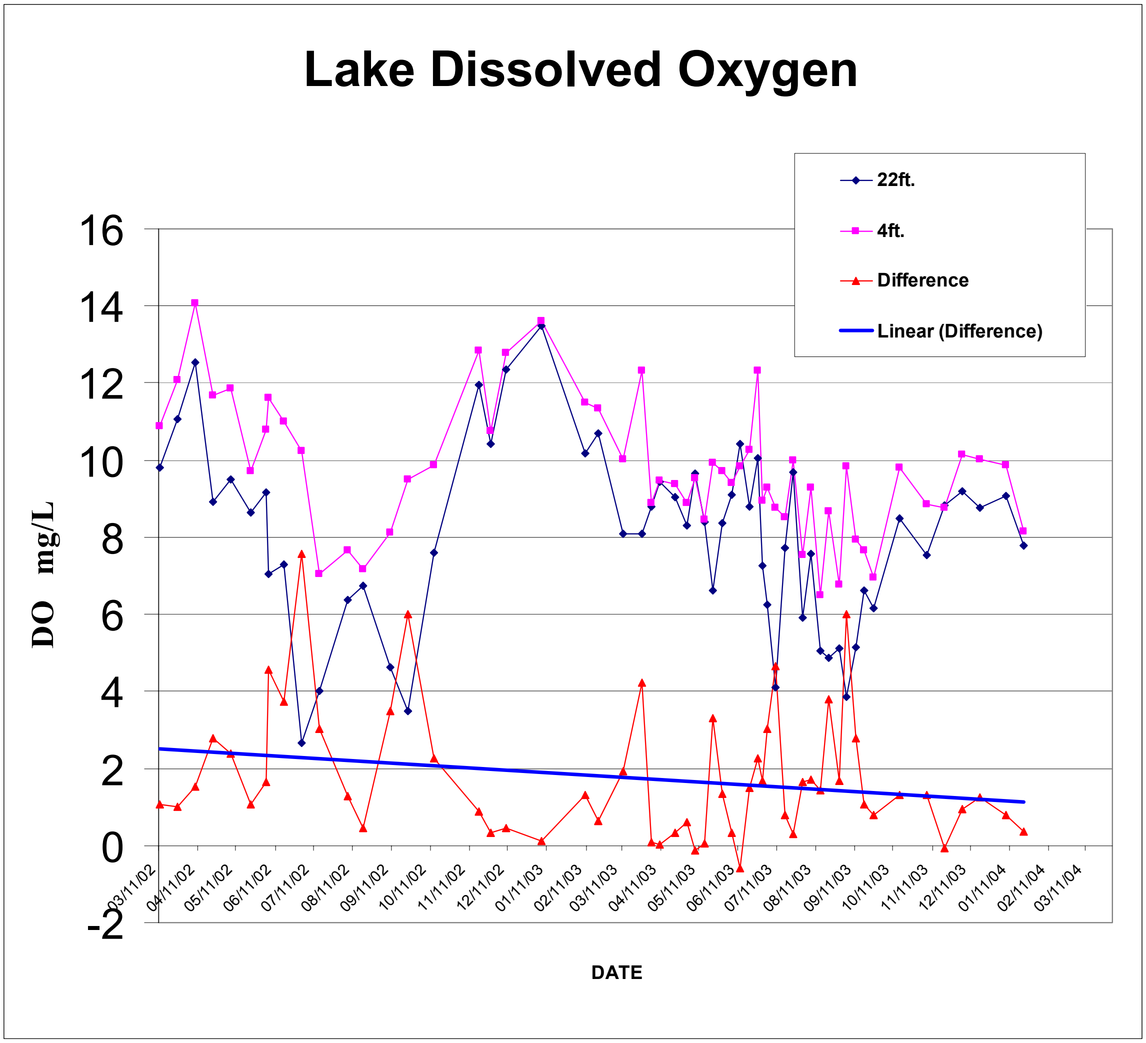

Figure 11: Lake Dissolved Oxygen

Conclusions and Recommendations

Forced lake circulation using solar powered device was effective in controlling the incidence of seasonal algal bloom in Palmdale Lake during the summer of 2003.

The amount of copper sulfate used to limit algal activities in 2003 was substantially less than what was used in 2002 amounting to significant savings regarding chemical treatment of the lake.

Water quality parameters like dissolved oxygen, pH, secchi transparency depth, turbidity and chlorophyll a concentration improved noticeably during forced lake circulation period compared to when lake circulation device was not installed on the lake.

Irrespective of nutrient loading to the lake, algae and zooplankton proliferation was curtailed because circulation exposed available nutrient to all species stimulating much higher food demand than supplied nutrient thereby resulting in quicker die off.

While it typically does not rain in summer in Southern California, the influence of spring showers on summer algal bloom with or without lake circulation could not be assessed for the two-year study period. Total rainfall from February to April 2003 in Palmdale was 5.56 inches while for the same period in 2002, 0.18 inch was recorded*.

Effect of the amount of annual rainfall on algal activities on the lake needs to be investigated however modest improvement in water quality with circulation is expected even in dry years.

*National Oceanic and Atmospheric Administration, National Weather Service (**http://newweb.wrh.noaa.gov/climate/index.php?wfo=lox**)

Reference

1. Water and Wastewater Calculations Manual, Shun Dar Lin: McGraw-Hill-2001. ISBN 0-07-137195-8: 156-159.