

**PREDICTED EFFECTS OF IN-LAKE TREATMENT ON WATER QUALITY
IN CANYON LAKE**

FINAL REPORT

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Executive Summary

Canyon Lake suffers from poor water quality as a result of both internal and external loading of nutrients. During the frequent periods of limited rainfall in the region, internal recycling dominates the overall loading of nutrients to the lake. In an effort to reduce this internal loading of nutrients, a laboratory assessment of in-lake nutrient control strategies was recently completed (Anderson, 2007a). Nitrogen and phosphorus release from lake sediments treated using oxygenation, aeration and alum was compared with reference (untreated) sediment cores. All 3 techniques significantly lowered nutrient flux from the sediments, with reductions of SRP flux of 37-85%, and approximately 20-35% reductions in $\text{NH}_4\text{-N}$ flux. The treatments varied in their effectiveness in controlling SRP flux, and increased in the order reference < aeration < hypolimnetic oxygenation < alum. Hypolimnetic oxygenation was found to be most effective for controlling N flux, while alum appeared to have lower overall long-term effectiveness (Anderson, 2007a).

This report summarizes results from a modeling study that evaluated the effects of these different in-lake treatment techniques on water quality in the lake. The 1-D hydrodynamic-ecological model DYRESM-CAEDYM was used for these simulations. The model is currently used by researchers and environmental professionals in over 59 countries and has undergone continual development and testing for the past 10 yrs. As the first step, the model was calibrated using water quality data collected biweekly – monthly from June 2006 – June 2007 (Anderson, 2007b). Default model values (Hipsey et al., 2006) were used for all model parameters except those explicitly quantified in recent laboratory studies or field measurements (Anderson, 2007a,b). Initial water column conditions were taken from the June 12, 2006 sampling (Anderson, 2007b). Daily inflow to Canyon Lake was taken from USGS gaging stations on the San Jacinto River at Sun City and on Salt Creek (USGS, 2007). Withdrawal volumes from the lake were provided by Elsinore Valley Municipal Water District (J. Ma, pers. comm.). Sufficient meteorological data to drive the hydrodynamic model (DYRESM) was not available at the lake, so CIMIS data from the meteorological station at UC Riverside was used. Sediment oxygen demand, $\text{NH}_4\text{-N}$ and SRP flux from the sediments were taken from laboratory measurements (Anderson, 2007a).

The model adequately reproduced the main features of observed water quality trends for the past year. For example, it correctly described strong thermal stratification

through the summer, followed by weakening during the fall until mixing occurred in late November, with anoxia in the hypolimnion that persisted until fall mixing. The model also quite accurately predicted pronounced increases in concentrations of $\text{NH}_4\text{-N}$, SRP, total N and total P in the hypolimnion through the summer and fall of 2006. Mixing in late November distributed nutrients throughout the water column, triggering a fall algal bloom that yielded predicted chlorophyll concentrations exceeding $60 \mu\text{g/L}$ in excellent agreement with measured chlorophyll levels. The model did deviate from observed chlorophyll concentrations in January-February 2007, however, predicting an algal bloom that persisted through this period in contrast with the observed strong reduction in chlorophyll concentrations and improvements in clarity found in January (Anderson, 2007b). The model also missed a smaller algal bloom in late August 2006, but correctly predicted reductions in chlorophyll levels below $20 \mu\text{g/L}$ later in the spring of 2007. The model also correctly described onset of stratification, rapid depletion of DO in the hypolimnion, and accumulation of $\text{NH}_4\text{-N}$ and SRP to levels similar to those found in June 2006 (Anderson, 2007).

Given the overall reasonable agreement between predicted and observed water column properties and water quality, the model was then used as parameterized to predict water quality for the lake following implementation of the in-lake restoration alternatives. An alum treatment, hypolimnetic oxygenation and aeration were all simulated by using the nutrient flux values and sediment oxygen flux values derived from laboratory core experiments. Hypolimnetic oxygenation was simulated by assigning a positive oxygen flux value that slightly exceeded the sediment oxygen demand value; hypolimnetic oxygenation thus provided DO that was used to also help meet oxygen demand within the lower water column due to decomposition reactions. Aeration was simulated using the mixing algorithm within DYRESM assuming an air flow rate of $0.04 \text{ m}^3/\text{s}$ at the diffuser through a single diffuser line with 160 diffuser ports located just above the sediments in the deepest part of the lake. Three year simulations were conducted under an idealized drought condition, where it was assumed for this scenario that no inflows nor withdrawals occurred. This allowed one to consider effects due solely to internal processes, without the complicating factors of mass inputs from inflows or mass removal due to withdrawals. Scenarios in which large volumes of runoff and concomitant external loading of nutrients were also evaluated.

Results of these simulations highlighted the benefits of aeration and hypolimnetic oxygenation on water quality, especially in the late fall, when predicted peak chlorophyll

concentrations were lowered from 60-100 $\mu\text{g/L}$ for the reference (no treatment) case to concentrations of approximately 30-40 $\mu\text{g/L}$ for hypolimnetic oxygenation and about 20 $\mu\text{g/L}$ with aeration. Predicted summer chlorophyll concentrations were also about 35% lower for the main basin of the lake with aeration and hypolimnetic oxygenation when compared with the reference (no treatment) case and with alum applied (approximately 20 $\mu\text{g/L}$ vs. 30 $\mu\text{g/L}$ after 2 yrs of operation).

The different in-lake treatments also varied in their effect on water column temperature and DO concentrations. The reference (no treatment) case and alum treatment both yielded temperature and DO conditions representative of the current condition of the lake, with thermal stratification in place from approximately March – November and strong anoxic conditions present in the hypolimnion. Hypolimnetic oxygenation maintained thermal stratification in the main basin of the lake while providing oxic conditions in the hypolimnion, with DO levels >4 mg/L through the summer. Increased oxygen supply to the hypolimnion could readily increase DO levels to 5 mg/L or greater throughout the water column. Aeration altered quite dramatically the temperature profile relative to the other treatment techniques, yielding essentially isothermal conditions throughout the year, with bottom temperatures reaching 27-28°C during July-August. Thus, hypolimnetic oxygenation and aeration differ in this important aspect. Specifically, although the anoxia currently present in the hypolimnion limits use of the lower water column by aerobic organisms, hypolimnetic oxygenation would offer thermal refugia that is important for many fishes and other organisms. Such habitat would be absent using an aeration system.

Predicted nutrient concentrations varied across these different in-lake treatments as well; aeration and hypolimnetic oxygenation both yielded very similar total N and total P concentrations (approximately 1.2 and 0.4 mg/L, respectively) that exhibited little seasonal or interannual differences. In contrast, total N concentrations were predicted to edge up in the reference and alum treatment scenarios, exceeding 2 mg/L after 3 yrs of no inflow or withdrawal, due to both recycling and evapoconcentration effects. Total P levels for the alum treatment were predicted to be quite similar to those for hypolimnetic oxygenation and aeration (approximately 0.4 mg/L). Thus, although alum was the most effective at controlling SRP release from the sediments, its limited effect on $\text{NH}_4\text{-N}$ flux had little effect on algal production due to the lake's strong N-limitation. Very dramatic declines in P availability would be necessary to overcome the lake's strong N-limitations and induce P-limitation to algal production.

It is useful to compare predicted water quality in the lake with the final numeric targets provided in the TMDL (SWRCB, 2005). In the absence of external loading to (or withdrawals from) the lake, annual average chlorophyll concentrations in the epilimnion met the target concentration of 25 $\mu\text{g/L}$ after 1 year of operation of both the aeration and hypolimnetic oxygenation systems (annual average concentrations of 18.1 and 22.7 $\mu\text{g/L}$, respectively). This compares with annual average values of 33.8 and 32.2 $\mu\text{g/L}$ for the reference condition and the alum treatment. As simulated, none of the in-lake treatments met the daily DO target of 5 mg/L in the hypolimnion, although DO concentrations near the center of the hypolimnion met or exceeded 5 mg/L on 270 out of 365 days during the 2nd year of operation, with minimum concentrations of 2.8 and 3.7 mg/L for aeration and hypolimnetic oxygenation, respectively. The annual average hypolimnetic concentrations exceeded by a fairly wide margin 5 mg/L however (6.1 and 6.4 mg/L, respectively, vs. an average value for the reference condition of 0.6 mg/L). Increased air or oxygen flows should allow aeration and hypolimnetic oxygenation to meet this target. Predicted annual average total N concentrations (in the epilimnion) for all of the in-lake treatment techniques did exceed the numeric target of 0.75 mg/L, however (1.26, 1.29 and 1.60 mg/L for aeration, hypolimnetic oxygenation and alum, respectively, vs. 1.64 for the reference case). Predicted annual average total P concentrations (in the epilimnion) exceeded by a factor of 3-4x the numeric target of 0.1 mg/L, although treatment lowered predicted value by 25-50% that for the reference (no treatment) condition.

Allowing for significant external loading of nutrients to Canyon Lake from the San Jacinto River and Salt Creek generally reduced the effectiveness of the in-lake treatment techniques, with the magnitudes dependent upon the mass loadings, presence of overflows to Lake Elsinore, and timing and volumes of water withdrawn by EVMWD for treatment. This was especially true for the alum treatment, where its effectiveness would be dramatically reduced following a single large runoff event that would also import an extensive amount of suspended solids that would bury the alum layer. The effectiveness of aeration and hypolimnetic oxygenation would generally also be reduced, but these techniques would be less substantively affected and moreover would ensure oxic conditions persisted through the water column (although increased flow rates may be needed to offset additional productivity and oxygen demand).

While marked improvements in water quality are predicted to result from installation and operation of a diffused aeration system or a hypolimnetic oxygenation

system in Canyon Lake, it appears unlikely any of the in-lake treatment alternatives will fully meet all of the final numerical targets set for the lake without reductions in external nutrient loading as well. At the same time, simulations suggest that plausible controls on external loading of nutrients alone will also be insufficient to meet numeric targets for the lake. Model results thus indicate that aeration or hypolimnetic oxygenation in conjunction with watershed projects that reduce external nutrient loading will be necessary to meet the numeric targets set for the lake.

1.0 Introduction

Canyon Lake has been listed on the federal Clean Water Act section 303(d) list due to excessive levels of nutrients since 1998. More recently, the Santa Ana Regional Water Quality Control Board adopted Resolution R8-2004-0037 to incorporate a nutrient TMDL for the control of nitrogen and phosphorus in the lake. Final numeric targets specified in the TMDL include an annual average total phosphorus concentration of 0.1 mg/L, an annual average total nitrogen concentration of 0.75 mg/L, an annual average chlorophyll concentration not greater than 25 µg/L, and daily average dissolved oxygen concentrations in the hypolimnion of not less than 5 mg/L (SWRCB, 2005).

Water quality monitoring conducted at the lake indicates that significant effort will be needed to meet these numeric targets. For example, monitoring conducted at Canyon Lake from June 2006 – June 2007 yielded an annual average total P concentration from 5 sites (in the epilimnion during the summer and the whole water column when mixed) of 0.276 mg/L (Anderson, 2007b), a concentration that exceeds the numeric target by 2.7x. Similarly, the total N concentration averaged 1.283 mg/L, and the annual average chlorophyll concentration exceeded 38 µg/L (Anderson, 2007b), levels that exceed by 50% or more the final numeric target values. Dissolved oxygen concentrations in the hypolimnion also fell far short of the target of 5 mg/L, attaining this concentration only during the winter, with summer values routinely <0.1 mg/L and hydrogen sulfide present (Anderson, 2007b).

A study was recently conducted to evaluate potential in-lake treatment alternatives and their capacity to improve water quality in the lake (Anderson, 2007a). Three treatment alternatives were evaluated in laboratory studies: (i) aeration, (ii) hypolimnetic oxygenation, and (iii) alum. While all 3 techniques were found to reduce nutrient release from sediments collected from the lake, they varied in their effectiveness at controlling N and P. Alum achieved >85% reduction in SRP flux through irreversible

binding and precipitation of Al-P phases (Anderson, 2007a). Hypolimnetic oxygenation also achieved very good control of internal phosphorus loading, reducing SRP flux by an average of 71% relative to untreated sediment cores. Aeration was somewhat less effective, lowering SRP flux by 37%. These techniques were generally less effective at controlling internal N loading, with aeration and hypolimnetic oxygenation lowering N flux by approximately 35%, and alum lowering long-term N release from sediments by about 20% or so (Anderson, 2007a).

Questions remain about the effect of these treatment techniques on water quality in Canyon Lake, however. In particular, what is the potential for these treatments to meet the numeric targets set forth in the nutrient TMDL for the lake? To address this and related questions, information from the recent lake monitoring and in-lake treatment studies was used in a water quality modeling study.

2.0 Methods

Water quality conditions in Canyon Lake under current conditions and with the different in-lake treatment technologies in place were simulated using the 1-D hydrodynamic-lake ecosystem model DYRESM-CAEDYM (CWR, 2007). The model is currently in use in over 59 countries for a wide array of studies by environmental professionals, researchers and others. The model has undergone essentially continual development over the past decade and is generally considered as state-of-the-art. Available lake monitoring data (Anderson, 2007b), information from sediment nutrient flux and in-lake treatment effectiveness studies (Anderson, 2007a), meteorological and flow data were used in the simulation study.

2.1 Model Calibration

The model was calibrated against water column data collected at Canyon Lake from June 2006 – June 2007 (Anderson, 2007b). Samples were collected biweekly, except during the winter (December 2006 -March 2007) when sampling was conducted approximately monthly. Hydrolab casts were made at 5 sites on the lake (3 in the main basin and 2 in east bay), providing vertical profile measurements of temperature, DO, pH, electrical conductance, oxidation-reduction potential, and turbidity. Depth-integrated surface samples were analyzed for chlorophyll, total and dissolved nutrients, and other constituents. Discrete samples were also collected at the thermocline, and composited discrete samples from 2-3 depths within the hypolimnion were also collected (except

during the winter when the water column was well-mixed vertically, when a single depth-integrated sample was collected from each site). The results from this monitoring campaign thus yielded a rich dataset with which the model could be calibrated against.

The model requires sufficient meteorological data to calculate instantaneous heat budgets for the lake and mixing due to wind shear and convective processes. Meteorological data from the CIMIS station located near UCR was used to drive the thermodynamic model. The model also requires information for inflows and withdrawals to account for turbulent kinetic energy inputs to the water column via these mechanisms. Flow data for the calibration period (June 2006 – June 2007) were taken from the USGS gaging stations on the San Jacinto River near Sun City (USGS gage #11070365) and on Salt Creek (USGS gage #11070465). Water quality measurements for the (limited) flows entering the lake over this period were not available, so average values from previous sampling conducted on the San Jacinto River and Salt Creek were used as inputs (Dyal and Anderson, 2003). Information on volumetric withdrawals from the lake over this period were provided by EVMWD (J. Ma, pers. comm.).

Rates of internal loading of nitrogen and phosphorus to the water column over the calibration period were separately measured in laboratory core-flux studies (Anderson, 2007a). Rates of $\text{NH}_4\text{-N}$ release averaged $43.3 \text{ mg/m}^2/\text{d}$ for the 3 main basin sites, with similar average flux rates also found for the 2 east bay sites ($45.0 \text{ mg/m}^2/\text{d}$). Average SRP flux from the sediments was lower than that of N (15.3 and $16.0 \text{ mg/m}^2/\text{d}$ for the main basin and east bay sites, respectively). Model calibration focused on adequately describing the temperature, DO, chlorophyll and nutrient concentrations in the main basin, so the average nutrient flux rates from the main basin were used. Sediment oxygen demand was also determined in these studies. Measurement conducted in July 2006 found SOD values of about $0.3 \text{ g/m}^2/\text{d}$, with very little difference between any of the sites (Anderson, 2007a). Additional measurements made in April 2007 found slightly higher short-term SOD values ($0.36\text{-}0.38 \text{ g/m}^2/\text{d}$), although longer-term SOD values were somewhat lower ($0.22\text{-}0.25 \text{ g/m}^2/\text{d}$). An average SOD value of $0.3 \text{ g/m}^2/\text{d}$ was used for the model calibration.

2.2 Simulation of In-Lake Treatment Alternatives

Following model calibration, simulations were conducted to assess the influence of aeration, hypolimnetic oxygenation and alum treatments. For this assessment, 3-yr simulations were conducted, with separate scenarios representing a drought condition

with no flows to the lake, typical conditions that involve moderate rainfall and runoff, and an El Nino type event of substantially above-average rainfall and runoff.

2.2.1. Meteorological and Runoff Conditions

Meteorological conditions (shortwave radiation, wind speed, air temperature and relative humidity) for the drought scenario were taken from the UCR CIMIS station for the period January 2006 – October 2007; the balance of 2007 was spliced in from the same period in 2006, while the final year of the simulation used the same meteorological conditions as for the 2nd year. For this particular assessment, all inflows from the San Jacinto River and Salt Creek were set to zero and withdrawals from the lake by EVMWD were also suspended. The purpose of this scenario was to isolate the lake from external loading (excluding atmospheric deposition) and focus on internal recycling and the effects of aeration, hypolimnetic oxygenation and alum on water quality.

The typical condition for the lake was taken as 2002-2004 in part because lake and watershed water quality data were available for this time period and because it reflected both drought conditions (2002 and 2004) as well as an intervening year with moderate rainfall and runoff. Nutrient concentrations in runoff entering the lake were taken from streamflow samples collected and analyzed from the San Jacinto River and Salt Creek over this time period (specifically, in the winter of 2003) (Dyal and Anderson, 2003).

The effects of El Nino-type conditions on water quality, in which very large volumes of runoff and substantial external loading are delivered to Canyon Lake, was also evaluated through model simulations. For this analysis, the 2004-2006 period was selected; although rainfall and runoff were limited in the winter of 2004, significant precipitation events occurred late in the year and continued through the winter of 2005, yielding near-record rainfall and runoff for the region. Meteorological and runoff information were again taken from CIMIS and USGS gaging station databases. As with the “nominal” condition described above, nutrient concentrations were assumed to be the same as found in streamflow samples collected and analyzed from the San Jacinto River and Salt Creek in winter 2003 (Dyal and Anderson, 2003).

2.2.2. Modeling In-Lake Treatment Processes

In addition to the reference (no treatment) case for each of the 3 weather conditions, simulations were conducted to evaluate the effect of aeration, hypolimnetic oxygenation and alum on predicted water quality.

Aeration was simulated by activating the diffused aeration subroutine within DYRESM. For these simulations, air flow at the diffuser was set at 0.04 m³/s. Aeration was simulated using the mixing algorithm within DYRESM assuming air flow through a single diffuser line with 160 diffuser ports at a rate of 0.04 m³/s at the diffuser. This flow rate was chosen based upon scaling of other reported air flow rates found to be successful at lake mixing (Ashley et al., 1987). The diffuser line was placed just above the sediments in the deepest part of the lake, and the system was assumed to be operated continuously. The rates of nutrient release from the sediments were adjusted downward from reference values, by 37% for SRP flux (to a value of 0.0096 g/m²/d) and by 35% (0.028 g/m²/d) for NH₄-N based upon previously described sediment core-flux measurements made during active aeration (Anderson, 2007a).

Hypolimnetic oxygenation was simulated by assigning a positive oxygen flux value that slightly exceeded the sediment oxygen demand value; hypolimnetic oxygenation thus provided DO that was used to also help meet oxygen demand within the lower water column due to decomposition reactions. SRP flux from the sediments were reduced by 71% (0.0044 g/m²/d), while NH₄-N flux was reduced by 35%, as done for aeration, based upon laboratory core-flux measurements (Anderson, 2007a).

Alum, shown to be even more effective than hypolimnetic oxygenation at controlling SRP release from sediments, was simulated by lowering SRP by 85% of the reference value, while the average NH₄-N flux rate was lowered by 20% (to 0.0023 and 0.0346 g/m²/d, respectively). The pH and alkalinity of the lake water were not changed in these simulations since the main basin of the lake was shown to have sufficient alkalinity to limit acidification associated with alum treatments (Anderson, 2007a).

3.0 Results

3.1 Model Calibration: 2006-2007

The model reasonably reproduced observed trends in temperature and thermal stratification in the lake (Fig. 1). The model correctly predicted the main features of the field data, e.g., a deepening of the epilimnion through summer of 2006, with surface temperatures near 30 °C in July and August, rapid cooling in late September – November and weakening of thermal stratification, with mixed conditions in place by

December (Fig. 1). Well-mixed, cool winter conditions were present through January 2007, although both field (Fig. 1a) and model-predictions (Fig. 1b) indicated that stratification began setting up in late February. The epilimnion continued to warm through the spring while the hypolimnion remained quite cool (10-12 °C). The contour plots developed from observed data were based upon 20 measured profiles, while the contour plot from simulation results were developed from over 365 profiles; as a result, the observed plot suggested short-term features that are principally a result of interpolation across a sparse dataset, rather than significant short-term features. Overall, these results indicate that the model reasonably reproduced the heating, cooling, stratification and mixing processes (i.e., the physics) of Canyon Lake.

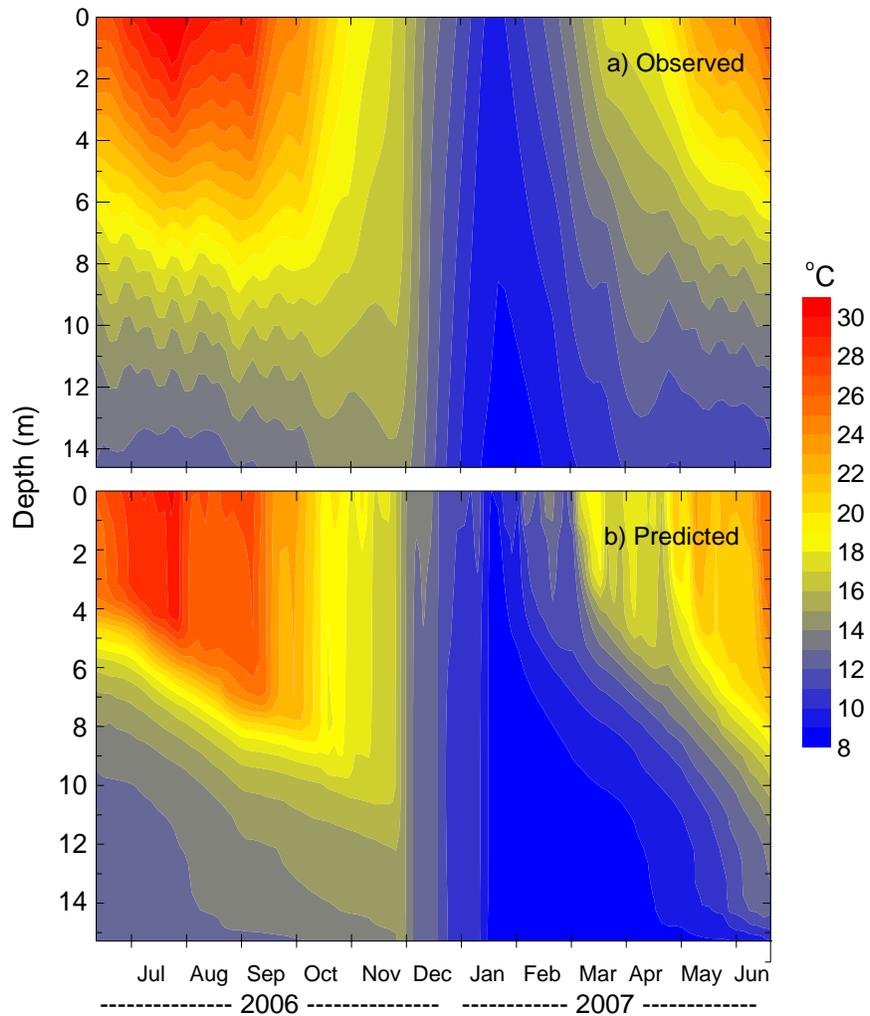


Fig. 1. Temperature profiles over time: a) observed and b) predicted.

Dissolved oxygen concentrations in 2006-2007 were generally also adequately reproduced by the model, although the model did fail to predict the very low DO concentrations present throughout the water column immediately following mixing in the fall (Fig. 2). The water quality part of the model (CAEDYM), does not explicitly simulate hydrogen sulfide production (or the oxygen demand that results during mixing in the fall); moreover, the model does not include the oxygen demand that results from the oxidation of reduced forms of metals (Fe^{2+} and Mn^{2+}) (Hipsey et al., 2006). Notwithstanding this deviation between predicted and observed DO concentrations, the model reproduced the oxic conditions present through the water column during December-January and the onset of anoxia in the hypolimnion beginning in February 2007 (Fig. 2).

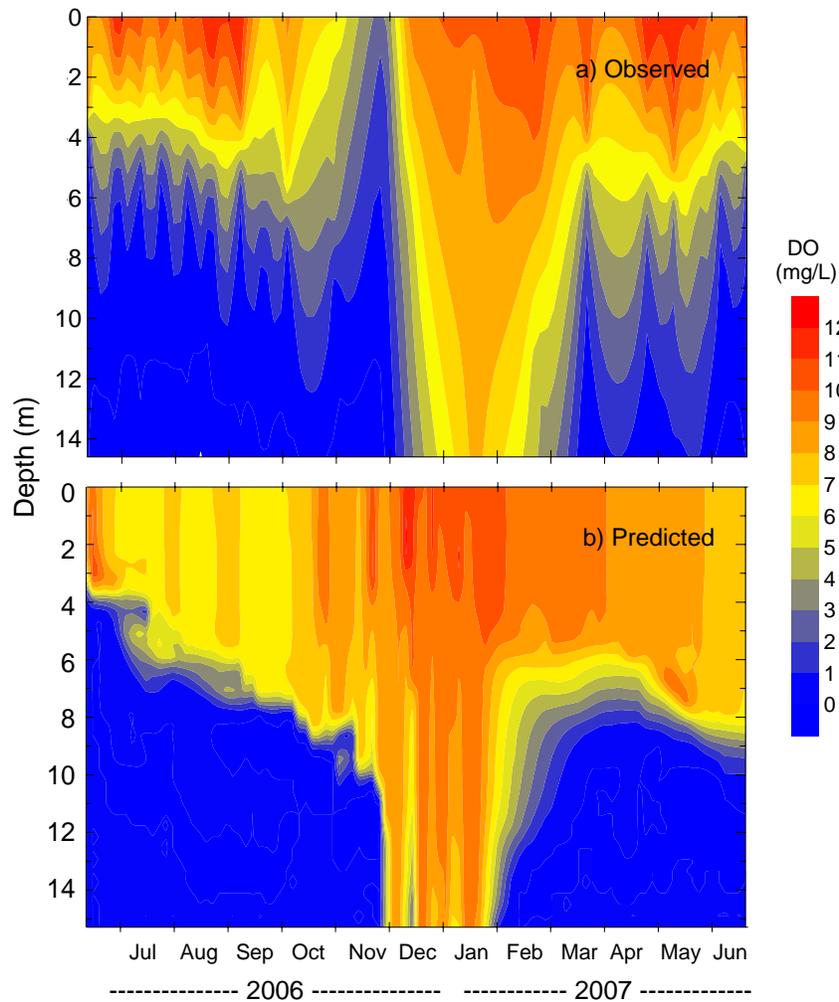


Fig. 2. Dissolved oxygen profiles over time: a) observed and b) predicted.

DYRESM-CAEDYM also predicted chlorophyll concentrations and total and dissolved nutrients within the water column. Monitoring at the lake yielded chlorophyll concentrations in depth-integrated epilimnion samples that varied significantly during the year (Fig. 3, open circles). Concentrations declined from about 30 $\mu\text{g/L}$ in June 2006 to about 15 $\mu\text{g/L}$ in July and early August, followed by an apparent algal bloom that briefly yielded chlorophyll levels near 40 $\mu\text{g/L}$, and a stronger algal bloom at the onset of fall mixing (Fig. 3, open circles). The model adequately reproduced these trends, including the sharp increase in chlorophyll concentration during mixing, although it did miss the algal bloom in September (Fig. 3, line). A more substantive difference between predicted and observed chlorophyll concentrations was present in January, when the model predicted that the winter bloom continued through this time period, while laboratory analysis yielded very low chlorophyll concentrations present (Fig. 3). The low chlorophyll levels were corroborated by Secchi depth measurements at this time, when a marked increase in transparency was found (Anderson, 2007b). The reason for this discrepancy is not entirely clear, although it is hypothesized that the rapid increase in transparency was due to a “clearing” event triggered by precipitation of CaCO_3 and rapid settling of phytoplankton (Wetzel, 2001). Although the model does account for changes in dissolved inorganic carbon (i.e., alkalinity) and the effects of increased or decreased CO_2 concentrations in the water column due to biological processes and atmospheric exchange, the precipitation of calcite is not included in the model (Hipsey et al., 2006).

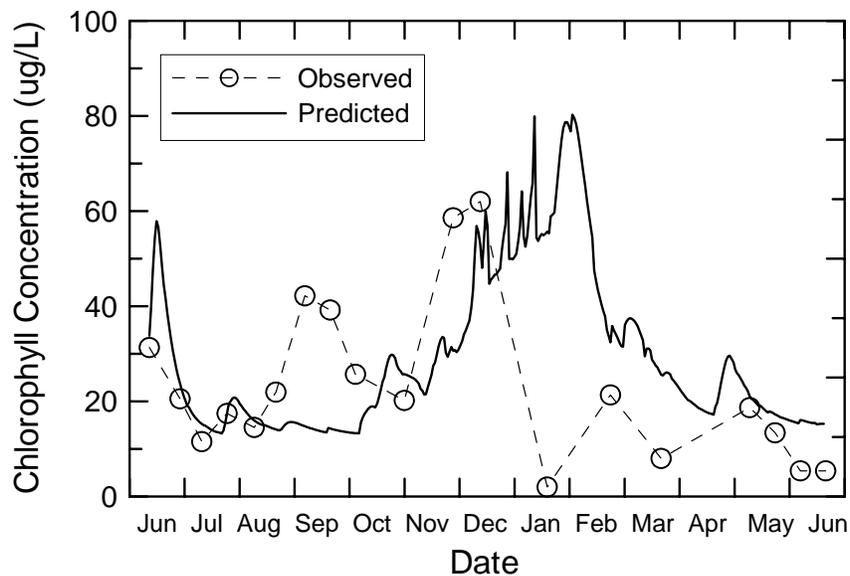


Fig. 3. Chlorophyll concentration in epilimnion over time: a) observed and b) predicted.

Total N concentrations predicted by the model were also available for comparison with measured values. The model did quite a good job of reproducing observed concentrations in both the epilimnion and hypolimnion (Fig. 4). Observed and predicted concentrations in the epilimnion both edged down during the summer, increased during mixing in December, and gradually declined the following spring, although comparatively modest changes in total N concentrations overall were found (Fig. 4, solid circles and line). Much more dramatic changes in total N were found in the hypolimnion (Fig. 4, open circles and dashed line). Observed concentrations that increased from about 1.8 mg/L in June 2006 increased to 4 mg/L by late October were very well reproduced by the model; the model also captured the timing and extent of the dramatic decline in concentrations present following mixing and the subsequent increase in total N in the spring of 2007 (Fig. 4).

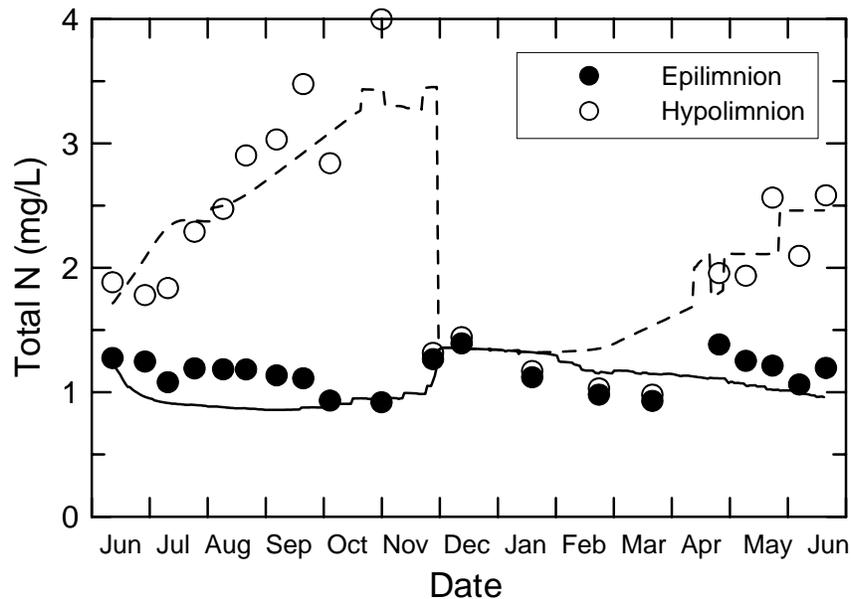


Fig. 4. Predicted and observed total N concentrations over time.

Ammonium-N accounted for most of the increased total N in the hypolimnion in the summer and fall of 2006 and again in the spring of 2007, as indicated in both lake monitoring and model predictions (Fig. 5). Very low predicted and observed concentrations of this readily available form of N were present in the epilimnion (<0.04 mg/L), except following mixing, when concentrations approach 0.5 mg/L were found (Fig. 5). The increase in $\text{NO}_3\text{-N}$ concentrations at this time is attributed to nitrification of $\text{NH}_4\text{-N}$ and to a lesser extent, some $\text{NO}_3\text{-N}$ inputs from the limited runoff over this period.

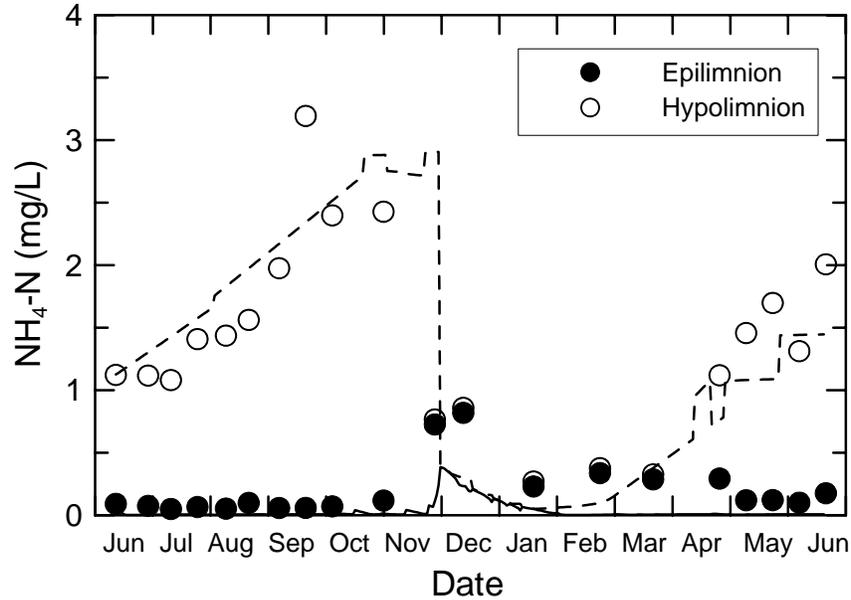


Fig. 5 Predicted and observed NH_4-N concentrations over time.

Total P concentrations also exhibited strong season trends that were well-captured by the model (Fig. 6). Epilimnetic concentrations near 0.2 mg/L in the summer of 2006 increased to about 0.6 mg/L following mixing in December before declining through the spring of 2007 (Fig. 7). Predicted and observed total P levels in the hypolimnion increased from 0.8 to over 1.6 mg/L in the summer before declining sharply during mixing (Fig. 6, open circles and dashed line). As with total N, total P levels in the hypolimnion increased during the spring, returning to levels seen the prior June.

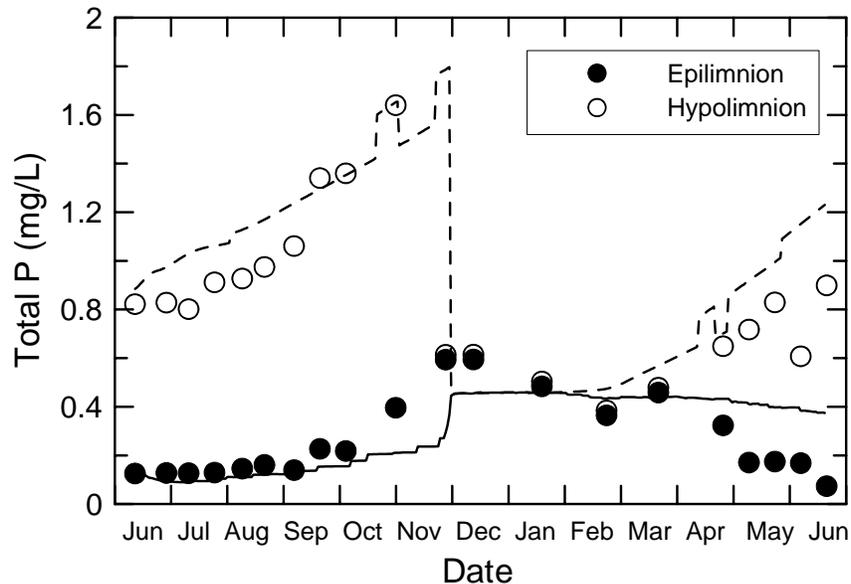


Fig. 6. Predicted and observed total P concentrations over time.

Much of the total P in the epilimnion and most of it in the hypolimnion was in the soluble-reactive form, with SRP concentrations following trends noted for total P (Fig. 7). That measurable free SRP was found in the epilimnion suggests that N was likely limiting algal growth in the lake; total N:total P ratios support this (Anderson, 2007b). The model did a very good job reproducing observed SRP concentrations in the hypolimnion and generally did an adequate for the epilimnion as well (Fig. 7).

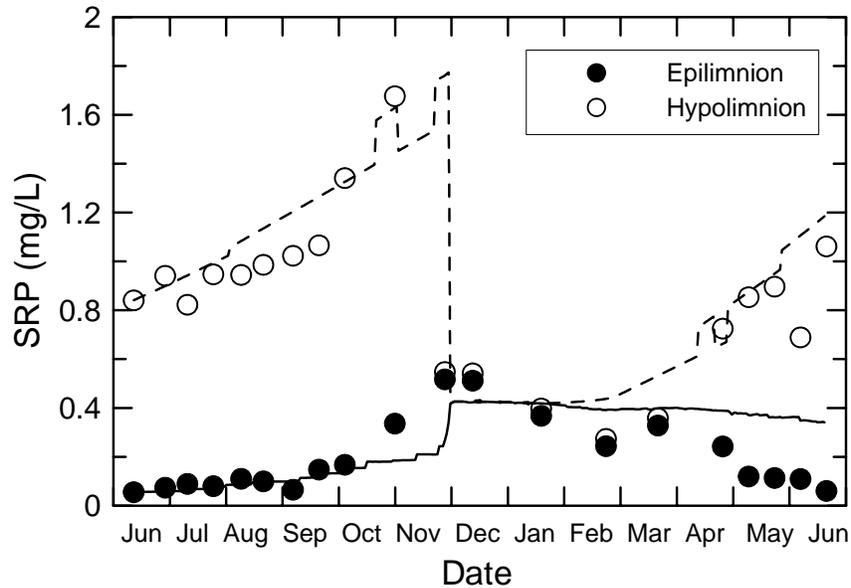


Fig. 7. Predicted and observed SRP concentrations over time.

The overall good agreement between predicted and observed water column properties (temperature and DO profiles, chlorophyll concentrations, dissolved and total nutrient levels) provides some reasonable basis for using the model to predict effects of in-lake treatment alternatives on water quality and to quantitatively evaluate predicted water quality against the numeric targets set forth in the TMDL for Canyon Lake.

3.2 Evaluation of In-Lake Treatments

3.2.1 Predicted Water Quality Under Drought Conditions

For these simulations, the ability of aeration, hypolimnetic oxygenation and alum to control internal loading was evaluated under an idealized drought condition with no significant external loading of nutrients due to runoff from the San Jacinto River and Salt Creek. Simulations were conducted for a 3-yr time period to assess the moderate-term effects of in-lake treatment on water quality and is thought to represent a fairly typical

interval of drought for the region. Simulation results for in-lake treatment were compared with the reference (no treatment) scenario.

The temperature profiles under the no-treatment scenario were essentially identical to those shown in Fig. 1, with cool well-mixed conditions present during the short winters, and very warm surface water temperatures and strong stratification present during the summer (Fig. 8a). (Note that the y-axis is taken here as height above the bottom; this convention allows one to also inspect the changes in lake surface elevation, due in this case to evaporation.) Aeration resulted in temperature profiles that deviated markedly from the reference condition (and the other in-lake treatments), yielding uniform temperatures present throughout the water column (i.e., no thermal stratification present) (Fig. 8b). Temperatures during the summer were very similar to those found in the epilimnion in the reference condition.

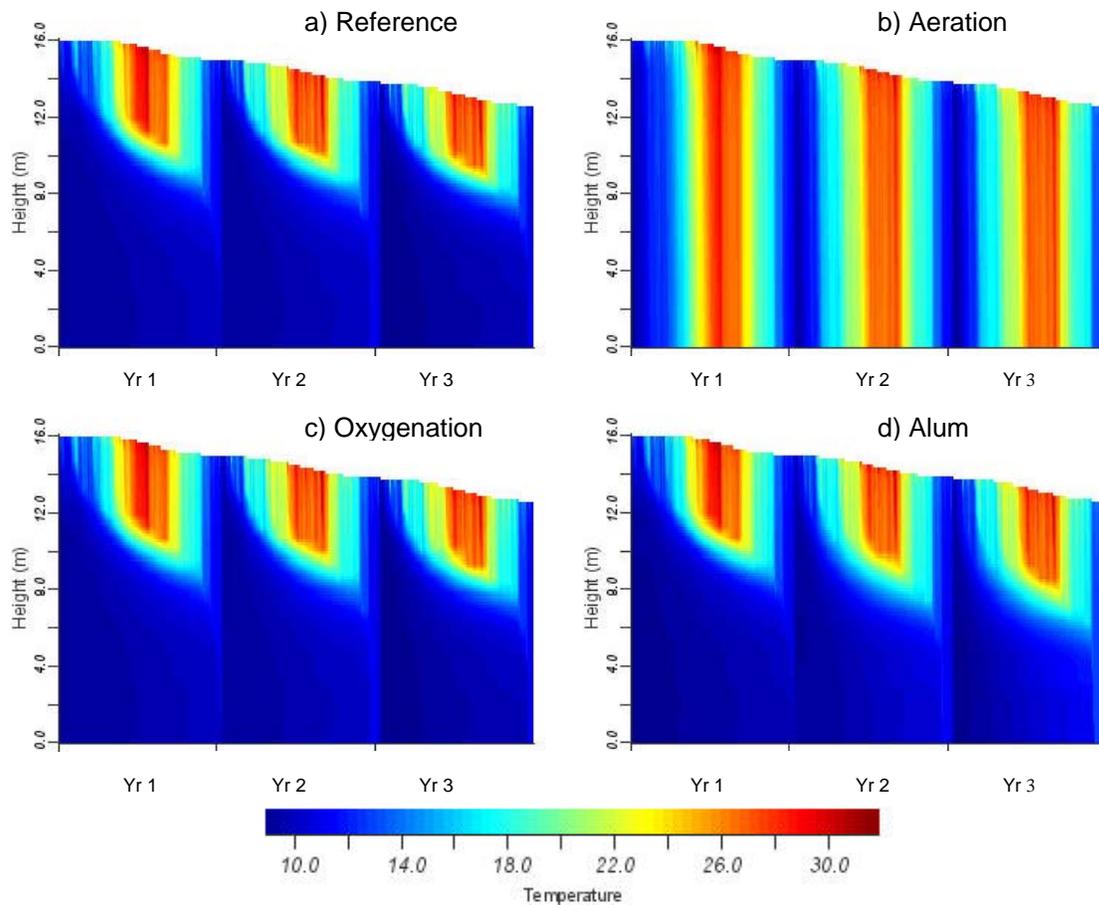


Fig. 8. Predicted temperature profiles for the different in-lake treatment alternatives (drought scenario).

The predicted temperature profiles under oxygenation and alum treatment were essentially identical to that for the reference case (Fig. 8), since (unlike aeration) these techniques do not impart additional turbulent kinetic energy to the water column.

The predicted DO profiles for the reference case were also similar to those found in 2006-2007, with chronic anoxia (represented by the deep blue color on the contour plots) present in the hypolimnion for about 10 months of the year (Fig. 9). Supersaturation of DO was predicted to be present in winter following mixing, with DO maxima above the thermocline present in the spring (i.e., a heterograde DO profile).

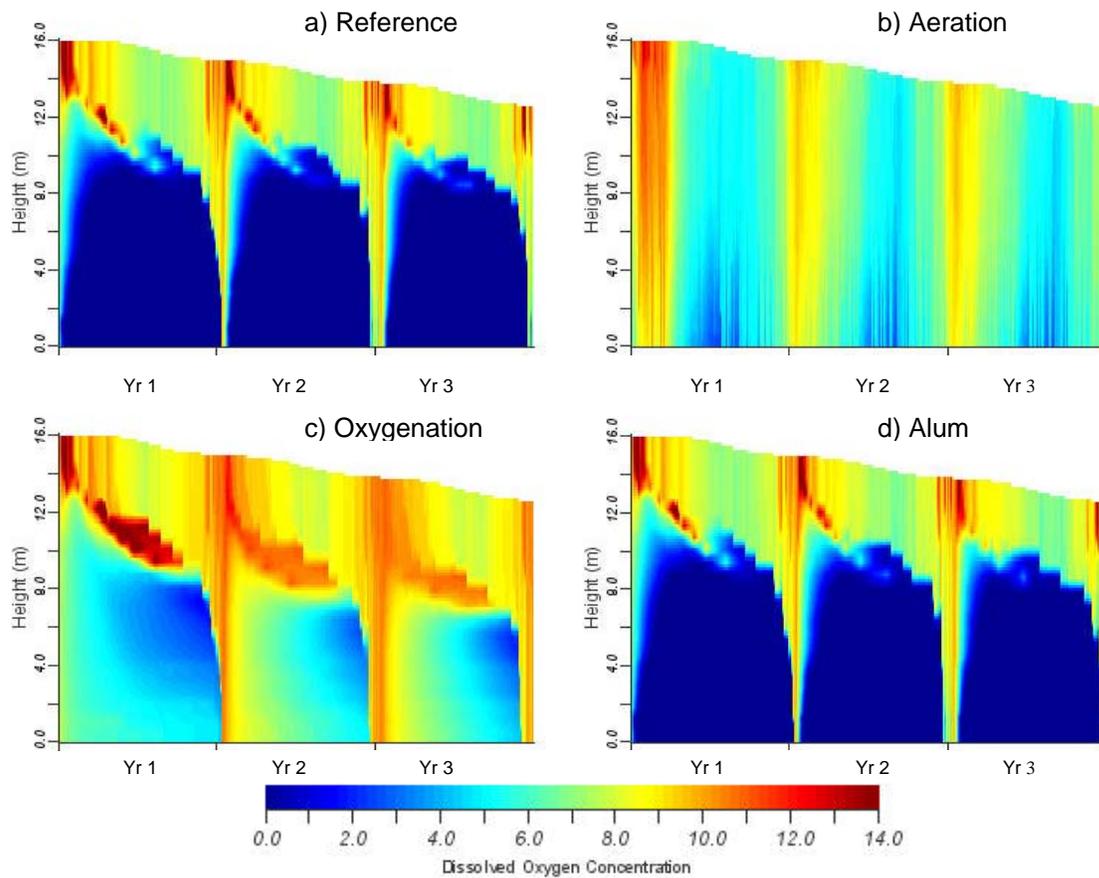


Fig. 9. Predicted DO profiles for the different in-lake treatment alternatives.

Operation of the diffused aeration system dramatically altered the DO profiles in the lake when compared with the reference condition (Fig. 9b). DO concentrations remained comparatively high throughout the water column even during the summer, with concentrations only briefly dropping below 4 mg/L a short distance above the sediments. Hypolimnetic oxygenation dramatically altered the DO profiles in the lake as well (Fig.

9c). DO concentrations were generally highest above the thermocline, with the lowest levels a short distance below the thermocline. The overall volume-weighted DO concentrations in the water column were higher during hypolimnetic oxygenation than aeration, although DO concentrations did slowly drop to about 4 mg/L above the sediments just before mixing (Fig. 9c). Alum treatment did not alter in any substantial way the predicted DO levels in the hypolimnion; as found in the reference condition, strong anoxia was in place in the lower water column for most of the year (Fig. 9d).

Chlorophyll concentrations were predicted to vary with depth and over time in the lake. Under reference conditions, high concentrations were predicted in the winter each year following mixing as nutrients that were previously accumulating within the hypolimnion are brought into the surface photic zone (Fig. 10a). Chlorophyll levels were then predicted to decline in the epilimnion during the spring, with maximum chlorophyll concentrations present above the thermocline. This behavior was well-characterized at the lake by Davis et al. (2005). The accurate prediction by the model of this complex feature speaks to the sophistication of the model in predicting water column properties.

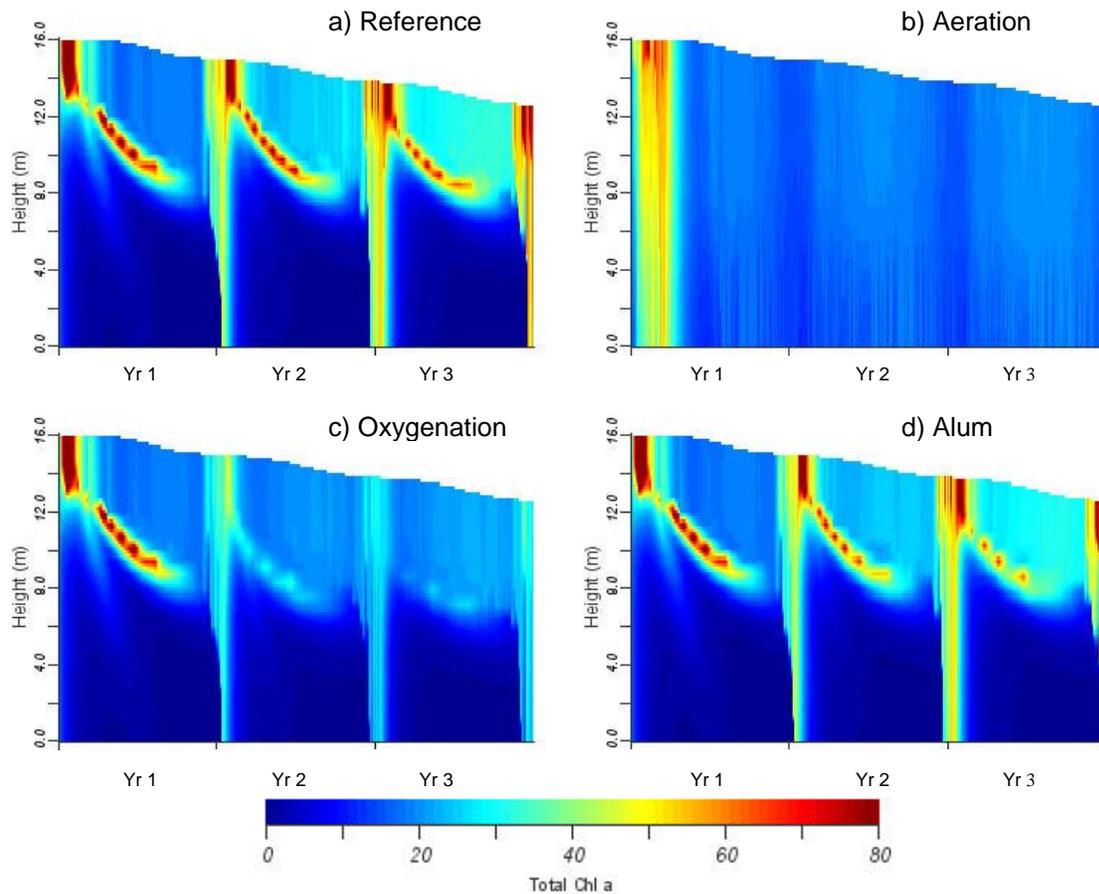


Fig. 10. Predicted chlorophyll profiles for the different in-lake treatment alternatives.

Higher overall chlorophyll concentrations were predicted in each successive year of the reference simulation, due to accelerated rates of nutrient recycling and lower lake levels (Fig. 10a). Predicted chlorophyll concentrations were markedly different with aeration (Fig. 12b). As with temperature and DO, the mixing of the water column with aeration also eliminated the generally strong vertical gradient in chlorophyll concentrations present under other alternatives. Thus, lower chlorophyll concentrations were present near the surface of the lake with aeration, although the depth-averaged chlorophyll concentration was actually higher than for the reference condition (e.g., 17.3 vs. 12.5 $\mu\text{g/L}$ on day 200 of year 1 of the simulation). Hypolimnetic oxygenation yielded chlorophyll concentrations similar to those found for the reference condition in year 1 (Fig. 10a), although concentrations were much lower in 2nd and 3rd years of the simulation (Fig. 10c). Control of N and P recycling reduced the availability of nutrients in subsequent years, even lowering algal production near the thermocline. Alum had no substantial effect on predicted chlorophyll levels, yielding profiles that were very similar to those found in the reference condition (Fig. 10d).

Total P concentrations also varied with depth and seasonally for the reference condition and the 3 treatment alternatives (Fig. 11). High concentrations of total P (principally as SRP) accumulated above the sediments as a result of the rapid rate of internal recycling there and the persistent stratification that limited exchange with the rest of the water column (Fig. 11a). Concentrations reached almost 4 mg/L immediately above the sediments shortly before mixing occurred in December in each of the three simulation years. Concentrations declined dramatically following mixing, however, as the modest hypolimnetic volume was mixed into the larger volume surface waters. This redistribution of nutrients into the upper, well-lit portion of the water column upon hypolimnetic entrainment and mixing is responsible for the pronounced increase in chlorophyll concentrations seen during this time (e.g., Fig. 10a). Aeration yielded uniform and generally much lower total P concentrations within the water column that nevertheless did increase over time (from about 0.25 mg/L at the beginning of year 1 to about 0.6 mg/L by the end of the 3rd year of the simulation) (Fig. 11b). Hypolimnetic oxygenation maintained thermal stratification, but because of its more effective control of P internal loading than aeration, yielded lower water column concentrations (Fig. 11c); predicted concentrations did reach about 0.5 mg/L by the end of the 3rd simulation year. Alum yielded total P concentrations very similar to those found for hypolimnetic oxygenation (Fig. 11d).

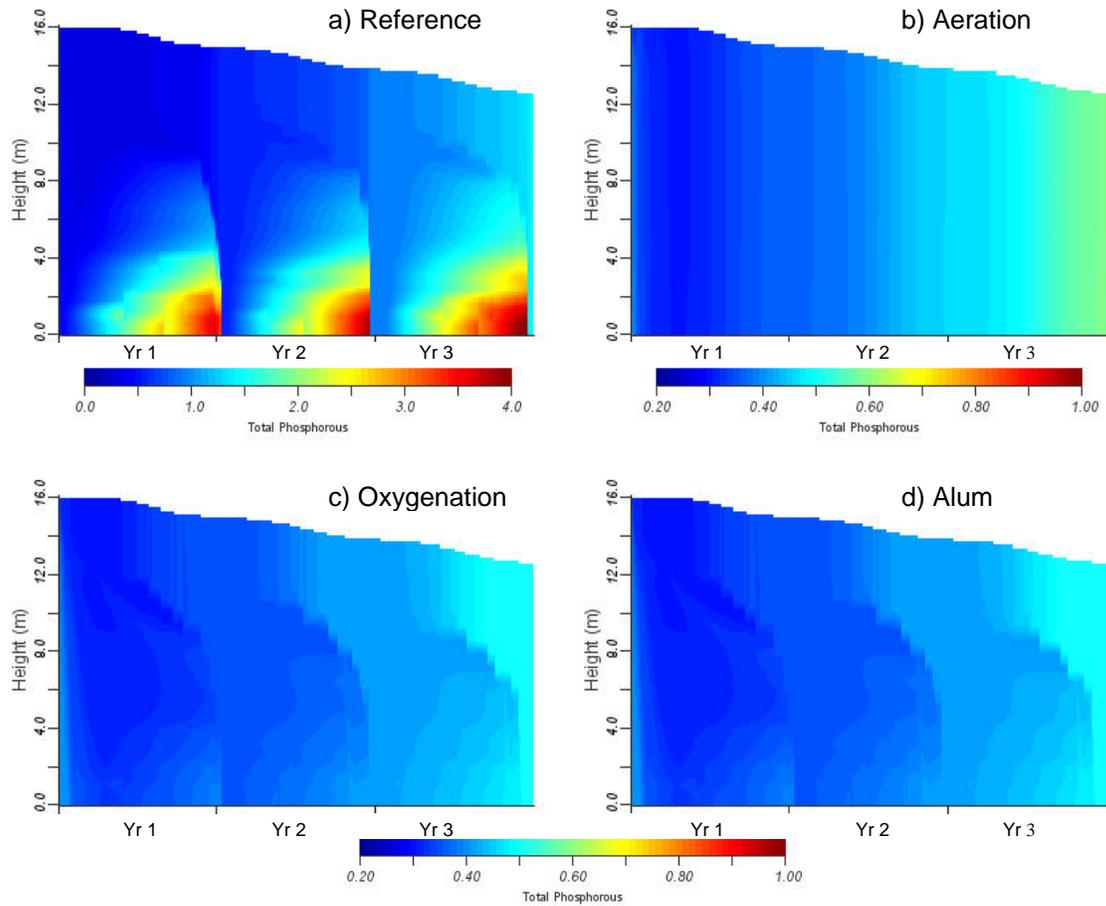


Fig. 11. Predicted total P profiles for the different in-lake treatment alternatives.

Finally, the concentration of total N within the lake varied even more dramatically than total P or most of the other constituents evaluated (Fig. 12). Under the reference condition, very high concentrations of total N (principally as $\text{NH}_4\text{-N}$) above the sediments were predicted during the 1st year as the high initial concentrations of labile N within the water column settled and was mineralized; much lower concentrations were predicted in the hypolimnion in the 2nd and 3rd year of the simulation (Fig. 12a). Aeration yielded its characteristic uniform concentrations vertically, with values that edged up from about 1.2 mg/ in the 1st simulation year to about 1.4 mg/L by the end of the 3rd year (Fig. 12b). Hypolimnetic oxygenation yielded a much more complex vertical and seasonal distribution, with concentrations approaching 1.6 mg/L above the sediments and somewhat lower concentrations near the thermocline and in the epilimnion (Fig. 12c). Up to about 50% of the total N here was in the form of $\text{NO}_3\text{-N}$, so this differs from the reference (and alum) cases where strongly reducing conditions resulted in $\text{NH}_4\text{-N}$

accumulation in the hypolimnion. The alum treatment was predicted to yield total N concentrations slightly lower but otherwise very similar to those found for the reference condition (Fig. 12d). Increased availability of DO with aeration and hypolimnetic oxygenation promoted nitrification, with subsequent denitrification and exchange with the atmosphere serving to ventilate some N₂ to the atmosphere during aeration as well.

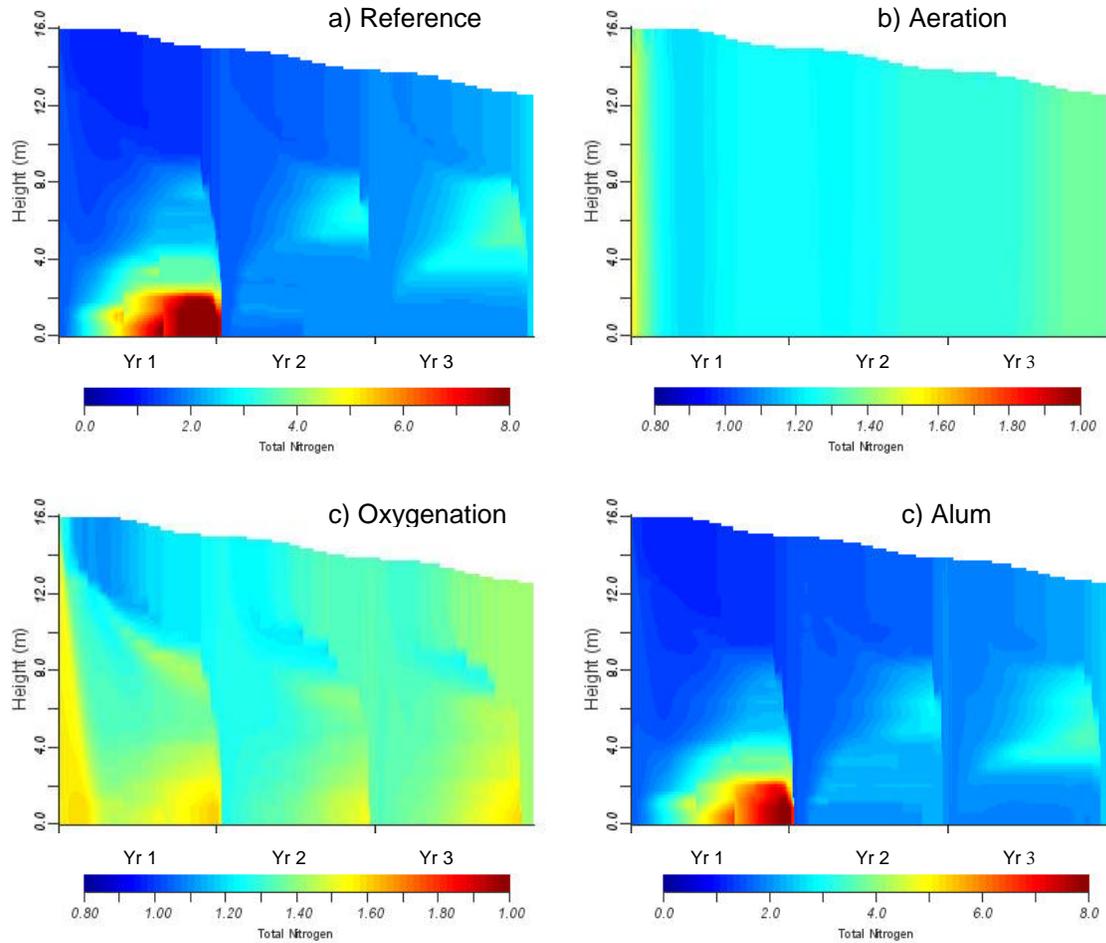


Fig. 12. Predicted total N profiles for the different in-lake treatment alternatives.

The predicted water quality can be compared with the numeric targets set forth in the TMDL for Canyon Lake (SWRCB, 2006). Results are presented for the 2nd year of the simulations; the lake level remained high and the in-lake treatments had one full year to help offset and assimilate the external load of nutrients present in the water column at the beginning of the simulations. The predicted annual average concentration of chlorophyll (in the epilimnion) for the reference condition was 33.8 µg/L, a value that was

35% higher than the target concentration of 25 µg/L (Table 1). Aeration was predicted to lower the surface chlorophyll concentrations by 46% relative to the reference condition (18.1 µg/L) and handily meet the chlorophyll target. Hypolimnetic oxygenation also met the chlorophyll target (22.7 µg/L) and yielded a predicted annual average concentration that was 33% lower than the reference (no treatment) condition (Table 1). Alum had a negligible effect on predicted chlorophyll concentrations and failed by a relatively wide margin to meet the chlorophyll target value of 25 µg/L.

Table 1. Comparison of predicted water quality with numeric targets: drought scenario (second year of operation). Predicted chlorophyll and total N and P concentrations for epilimnion; DO reported as number of days where DO concentrations >5 mg/L at 2 m above sediments.					
Criteria	Target	Reference	Aeration	Oxygenation	Alum
Chlorophyll	<25 µg/L	33.8	18.1	22.7	32.2
DO	>5 mg/L	24 (6.6%)	271 (74.2%)	271 (74.2%)	27 (7.4%)
Total N	<0.75 mg/L	1.64	1.26	1.29	1.60
Total P	<0.1 mg/L	0.67	0.40	0.38	0.41

While aeration and hypolimnetic oxygenation both met the chlorophyll target, none of the in-lake treatments fully met the DO target of daily hypolimnetic concentrations >5 mg/L (Table 1). Notwithstanding, aeration and hypolimnetic oxygenation helped the lake meet this challenging target 74% of the time, with each yielding 271 days exceeding 5 mg/L. This stands in sharp contrast to the reference (no treatment) condition and alum in which this target was met only 6.6 and 7.4 % of the time. Moreover, the minimum DO concentrations varied widely for these 4 conditions (<0.1, 2.8, 3.7 and <0.1 mg/L for reference, aeration, hypolimnetic oxygenation and alum, respectively). While fairly standard operational conditions were used for aeration and oxygenation in these simulations, it is expected that increased airflow would allow these two in-lake treatments to fully meet this numeric target for DO.

Meeting the nutrient targets looks to be a more difficult endeavor. Aeration and hypolimnetic oxygenation had the best success, e.g., lowering predicted annual average total N concentrations from 1.64 mg/L for the reference case to 1.26 and 1.29 mg/L, respectively for reductions of 20-25%, but predicted concentrations remain 65-70% above the target total N concentration of 0.75 mg/L (Table 1). Comparable reductions were predicted for total P levels, with alum also lowering total P concentrations, although

all three in-lake treatment techniques were predicted to exceed the total P target by a factor of 4x (Table 1).

3.2.2 Predicted Water Quality Under High Runoff Conditions

The model was also used to simulate water quality during a period of high runoff and external loading to the lake. The 3-yr period from January 1, 2004 – December 31, 2006 was selected for this analysis. The winter of 2005 was the 2nd highest rainfall totals for the region on record, with more than 48,000 af of water delivered to the lake (USGS, 2007). The model developed numerical instabilities dealing with this large of flow into such a small reservoir, however, so it was necessary to reduce the flows by about 2/3rd (Fig. 13a) Importantly, this flow this still substantially exceeded the total lake volume, met the “wet year” case with inflows of approximately 17,000 af (SWRCB, 2006), and resulted in large outflows to Lake Elsinore (Fig. 13b). The lake was also predicted to spill a small amount in year three.

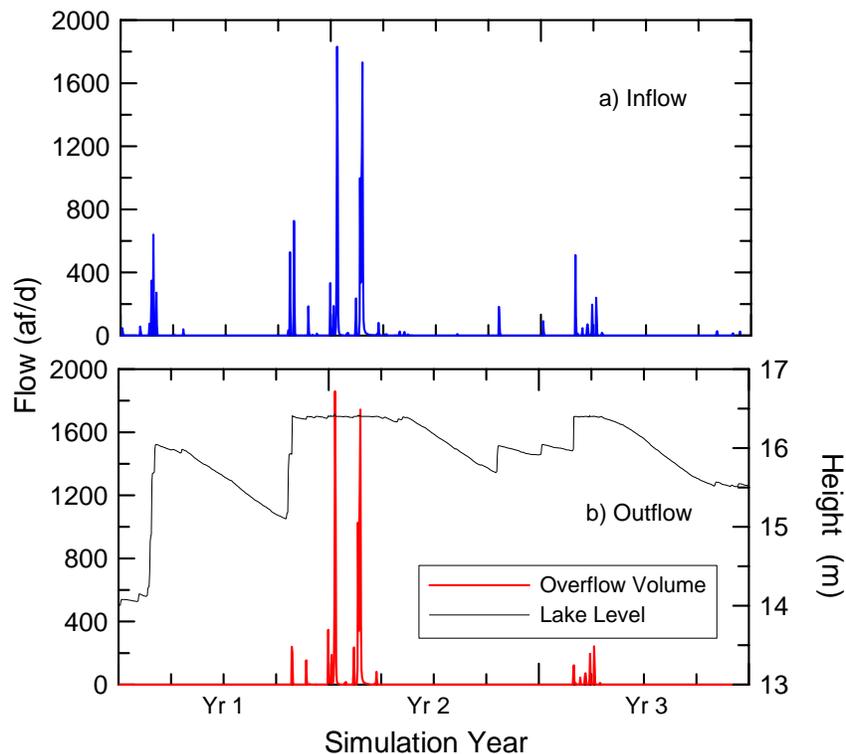


Fig. 13. Hydrologic conditions for high runoff scenario: a) inflow and b) outflow.

External loading of total N and total P to the lake in the 2nd water year under this scenario was 30,625 and 6,030 kg, respectively. For comparison, internal loading over

the approximately 7 months with some inflow to the lake was about 10,160 kg N and 3,530 kg P. Although significant amounts of the external loads of N and P were quickly exported from the lake via overflow, about 2/3rd of the externally loaded nutrients remained in Canyon Lake during this simulation (Table 2). Water quality results from this flow scenario, especially for year 2 of the simulation, in contrast to the drought scenario are thus expected to be strongly influenced by external loading.

Table 2. Loading of nutrients to Canyon Lake: high runoff scenario.				
Nutrient	Gross External Load (kg)	Exported (kg)	Net External Load (kg)	% Retained
Total N	30,625	9,498	21,127	69.0
Total P	6,030	2,324	3,706	61.5

Predicted chlorophyll concentrations in the epilimnion varied over the 3-yr simulation period and with in-lake treatment (Fig. 14). The reference condition yielded peaks in predicted chlorophyll concentrations that exceeded 100 µg/L in the spring of years 1 and 2, although lower concentrations were predicted in the spring of year 3 (Fig. 14). Summer chlorophyll concentrations were much lower, near 20 µg/L.

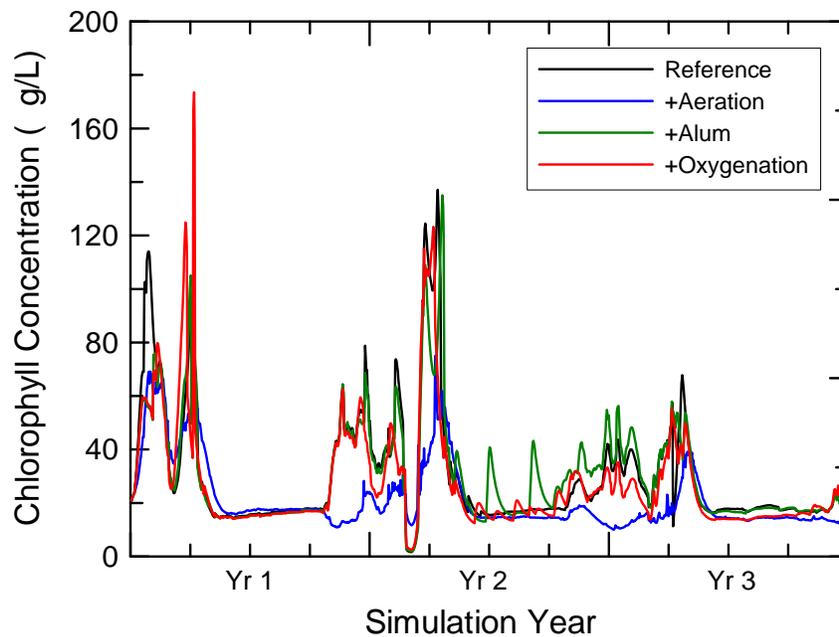


Fig. 14. Predicted chlorophyll concentrations in epilimnion: high runoff scenario.

The different in-lake treatments did alter the predicted chlorophyll concentrations somewhat, although aeration, hypolimnetic oxygenation and alum all yielded fairly sharp increases in the spring. Aeration typically yielded lower surface chlorophyll levels during the spring bloom when compared with the others (Fig. 14), although as noted previously, this is due in part to the mixing of chlorophyll throughout the entire water column; in contrast, chlorophyll concentrations were generally much lower in the hypolimnion of the other treatments. The annual average chlorophyll concentration for the high runoff year (year 2 of the simulation) was 31.6 µg/L for the reference (no-treatment) condition (Table 3), a value similar to that found for the drought scenario (Table 1). Aeration was able to achieve a 33% reduction and meet the chlorophyll target, although hypolimnetic oxygenation was less successful under high external loading (Table 3). As was found for the drought scenario, alum yielded chlorophyll levels similar to the reference.

Table 3. Comparison of predicted water quality with numeric targets (second year of operation): High runoff scenario. Predicted chlorophyll and total N and P concentrations for epilimnion; DO reported as number of days where DO concentrations >5 mg/L at 2 m above sediments.					
Criteria	Target	Reference	Aeration	Oxygenation	Alum
Chlorophyll	<25 µg/L	31.6	21.1	28.4	34.1
DO	>5 mg/L	8 (2.2%)	148 (40.5%)	172 (47.1%)	7 (1.9%)
Total N	<0.75 mg/L	1.10	0.99	0.94	1.07
Total P	<0.1 mg/L	0.29	0.15	0.17	0.18

Total N concentrations in the epilimnion also varied over time and with the different in-lake treatments (Fig. 15). The strong external loading events are evident in late year 1 and early year 2 of the simulations. Here, hypolimnetic oxygenation appeared to perform somewhat better than the other in-lake treatments, generally yielding lower total N concentrations (Fig. 15; Table 3), although only about a 15% reduction in total N was achieved (compared with a 23% under the drought scenario; Table 1).

In contrast, total P concentrations were much more favorably affected by in-lake treatments under this scenario when compared with the drought scenario (Fig. 16; Table 3). All 3 in-lake treatments substantially lowered the predicted total P levels in the surface waters relative to the reference conditions, from concentrations near 0.4 mg/L at the beginning of the simulation to around 0.1 mg/L (Fig. 16). For the high external

loading year (year 2), total P concentrations were 38 – 48% lower for the in-lake treatments compared with the reference, although levels did remain above the numeric target (Table 3).

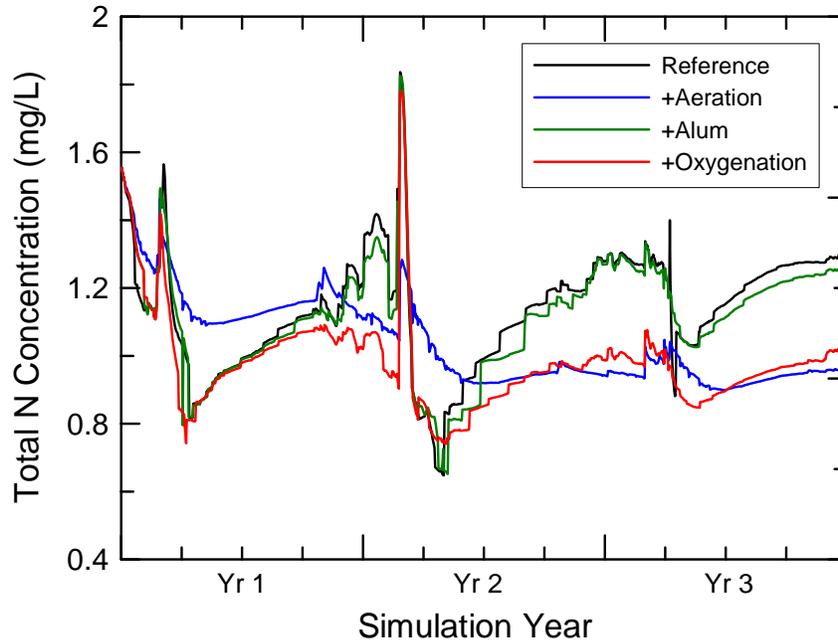


Fig. 15. Predicted total N concentrations in epilimnion: high runoff scenario.

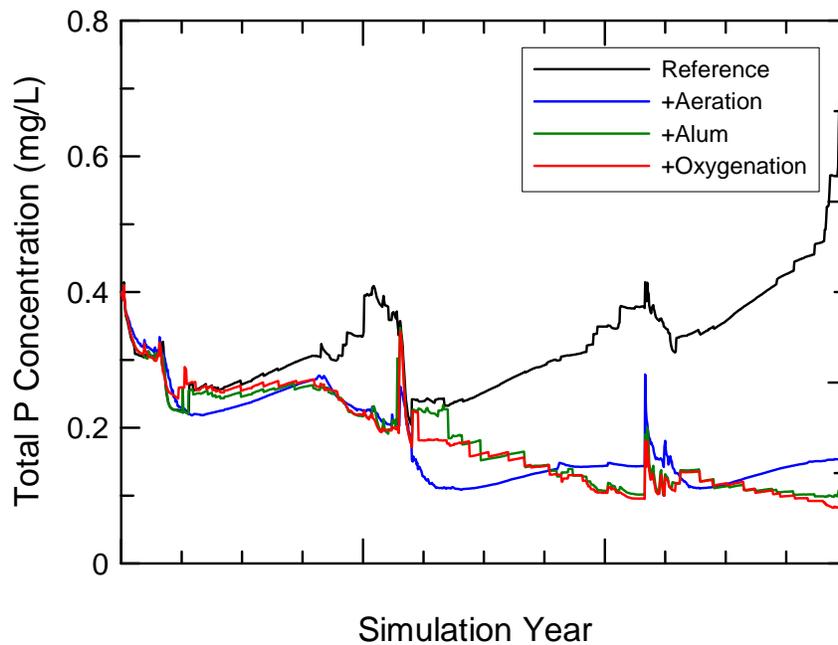


Fig. 16. Predicted total P concentrations in epilimnion: high runoff scenario.

Dissolved oxygen in the hypolimnion proved to be more difficult to maintain when compared with the drought scenario. The number of days in which DO concentrations were 5 mg/L or greater in the reference condition edged down from 24 in year 2 of the drought scenario to 8 days in the high runoff scenario (Table 3). Aeration and hypolimnetic oxygenation substantially improved DO levels, although the frequency of compliance declined from 74% (Table 1) to only 40-47% (Table 3). The greater lake depth and higher oxygen demand is though to be responsible for the poorer DO conditions present in the lake.

3.2.3 Predicted Water Quality Under Nominal Conditions

Water quality was also evaluated under the meteorological regime present from 2002-2004 (Fig. 17). The first year of the simulation (2002) was very dry, with negligible flows into the lake, although more significant flows were present in the 2nd year (2003). A total of 12,200 af entered the lake in late year 1 and early year 2; these flows were sufficient to fill the lake under this scenario (assumed starting lake surface was 2.4 m below the spillway of the dam). These flows delivered in these simulations 29,335 kg of N and 5,671 kg of P (Table 4). The model predicted that 73% of the inflow was released as overflow, exporting 10,971 kg of N and 3,085 kg of N. These calculations support the notion that Canyon Lake serves as a net sink for nutrients, since a smaller relative proportion of N and P were exported (Table 4). That is, although only 27% of the runoff remained in the lake, about 2x as much N and P were retained.

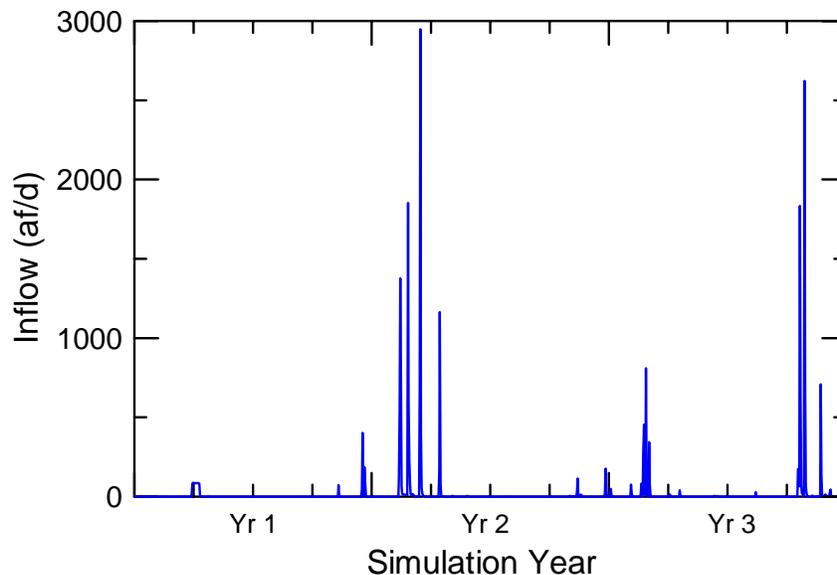


Fig. 17. Inflows based upon 2002-2004 for nominal runoff scenario.

Nutrient	Gross External Load (kg)	Exported (kg)	Net External Load (kg)	% Retained
Total N	29,335	10,971	18,364	62.6
Total P	5,671	3,085	2,586	45.6

Predicted water quality over this period was somewhat poorer than found in previous scenarios, with an annual average chlorophyll concentration of just under 40 µg/L in the reference case. Aeration and hypolimnetic oxygenation were able to lower this value by 20-35 %, while alum had a much smaller effect, although none of the in-lake treatments met the numeric target of 25 µg/L (Table 5). Predicted total N concentrations were modestly reduced by aeration and somewhat more so by hypolimnetic oxygenation, but again remained about the N numeric target. Total P levels were not reduced as substantially in this scenario as in the previously discussed high runoff scenario (Table 5).

Criteria	Target	Reference	Aeration	Oxygenation	Alum
Chlorophyll	<25 µg/L	39.8	25.9	31.6	37.6
DO	>5 mg/L	10 (2.7%)	153 (41.9%)	208 (57.0%)	9 (2.5%)
Total N	<0.75 mg/L	1.20	1.09	1.02	1.17
Total P	<0.1 mg/L	0.45	0.37	0.33	0.33

4.0 Implications and Conclusions

The results of this modeling analysis indicate that aeration and hypolimnetic oxygenation can both significantly improve water quality in Canyon Lake and help bring it closer to meeting the numeric targets set forth by the SWRCB, although neither in-lake treatment alternative appears capable of fully meeting all of the prescribed water quality goals. In contrast, alum had little effect on overall water quality. The improvements in water quality from installation and operation of a diffused aeration or hypolimnetic oxygenation system are a complex function of water column properties, conditions and rates of internal recycling of nutrients, magnitude and timing of external loading events, and other factors.

While aeration and hypolimnetic oxygenation had broadly similar effects on chlorophyll, nutrient and DO concentrations in the epilimnion, hypolimnetic oxygenation had the additional benefit of providing favorable thermal refugia for fish and zooplankton. While the benefit of this was not explicitly evaluated in the modeling study, such conditions would help maintain a cool water fishery in the lake and would also likely promote a better balanced aquatic ecosystem in the lake. The maintenance of thermal stratification and of cooler conditions near the sediments is also thought to offer some benefits with respect to rates of microbial processing of organic matter and nutrients, although aeration may yield slightly higher rates of NH_3 and N_2 loss to the atmosphere.

Importantly however, since none of the in-lake treatments or scenarios evaluated were individually able to meet all of the numeric targets, it appears that significant reductions in external loading of nutrients to the lake will also be needed. Additional modeling could be conducted to quantify the improvements in water quality that would result from load reductions from the watershed. If sufficiently low nutrient concentrations were achieved in the runoff entering the lake, the existing nutrient cycle would be favorably altered. For example, the labile forms of nutrients in the sediments would no longer be enriched with each substantial runoff event, thereby allowing aeration or hypolimnetic oxygenation to more effectively control internal loading. Lower concentrations of nutrients entering the lake would also dilute water column concentrations, and with substantial overflow or withdrawal, export of internally-derived nutrients would also be achieved.

5.0 Acknowledgments

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Friends of Northern San Jacinto Valley
Friends of San Jacinto River
Inland Waterkeeper
Lake Elsinore and San Jacinto Watersheds Authority (LESJWA)
Lake Hemet Municipal Water District
LESJWA TMDL Task Force
Milk Producers Council
National Park Service
Nuevo Development Corporation (Lewis Operating)
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Riverside County Farm Bureau
Riverside County Flood Control & Water Conservation district
Riverside County Regional Park and Open-Space District
San Bernardino Valley Audubon Society
San Jacinto Basin Resource Conservation District
Santa Ana Regional Water Quality Control Board
Santa Ana Watershed Association
Santa Ana Watershed Project Authority
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U.S. Forest Service
Western Municipal Water District
Western Riverside County Ag Coalition
Western Riverside County Regional Conservation Authority

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Appendix

Water Quality in East Bay

The DYRESM-CAEDYM model was also used to evaluate water quality in east bay of Canyon Lake. It is important to note that the 1-D approximation built into this model is not strictly appropriate for this shallow dendritic embayment. A more complex 2-D or 3-D model would be needed to fully simulate east bay. Therefore, with some significant caveats, the model was also used in a semi-quantitative way to evaluate water quality there.

For this analysis, east bay was considered to be functionally isolated from the main basin. Internal $\text{NH}_4\text{-N}$ and SRP loading rates and sediment oxygen demand for east bay were taken from Anderson et al. (2007a). All other model parameters were the same as those used for previously described simulations.

The model was only partially successful in reproducing water quality observed in 2006-2007 (Anderson et al., 2007b) (Fig. A1). The model overpredicted total N concentrations in October-November of 2006, missed the peak concentration in January 2007, and also generally overpredicted concentrations later in the spring (Fig. A1a). The model did marginally better in reproducing total P, but predicted continued increases rather than decreases in spring 2007. The model also missed the peak chlorophyll concentration that exceeded 120 $\mu\text{g/L}$ in late November-December of 2006 (Fig. A1c). The reasons for the overall somewhat disappointing agreement between predicted and observed water quality include the 1-D approximation, the assumption of no hydraulic connection between the main basin and east bay, exclusion of nuisance runoff inputs to this shallow water body, sheltering effects of the steep topography on wind velocities there, and other factors.

Notwithstanding these limitations, some relative trends in water quality may be inferred from possible restoration efforts there. Since much of east bay is only 3-5 m deep, the sediments are generally oxic (Anderson et al., 2007). As a result, no clear advantage would be gained by implementing some sort of aeration or oxygenation system. Moreover, it would be impractical to implement such a system except for the deepest and areally quite limited regions of the bay.

With that in mind, simulations were conducted to represent a conventional alum treatment and dredging. Both of these treatments were represented by assuming lower internal recycling rates and, for dredging, by further assuming slightly greater depths.

Based upon laboratory measurements, alum was assumed to lower SRP flux from the sediments of east bay by 85% and to reduce $\text{NH}_4\text{-N}$ flux by 20% (Anderson, 2007a). Information on reductions in nutrient flux following dredging is not presently available, although based upon previous sediment core analyses and other factors, a reduction of 75% in both SRP and $\text{NH}_4\text{-N}$ flux was assumed.

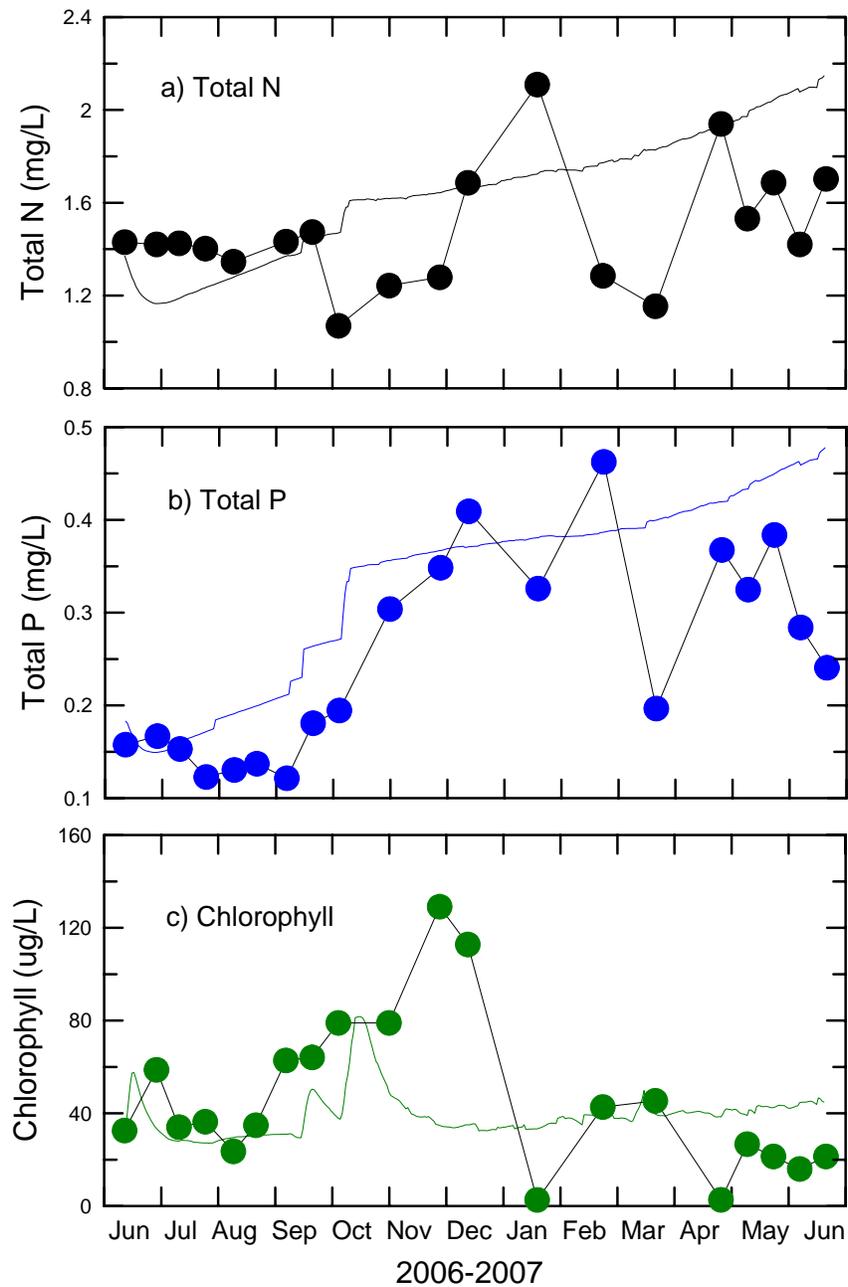


Fig. A1. Predicted and observed concentrations in east bay: a) total N, b) total P and c) chlorophyll.

Results from simulations representing an idealized drought scenario with no external loading of nutrients (excluding atmospheric deposition) indicate that both dredging and alum treatment will offer some improvement in water quality, e.g., lowering predicted annual average chlorophyll concentrations from 28.6 $\mu\text{g/L}$ to 18.2 and 24.7 $\mu\text{g/L}$, respectively (Table 1A). These treatments were also predicted to lower annual average total N and total P concentrations, although values remain well above nutrient targets (Table A1). Dissolved oxygen conditions above the sediments were also favorably affected.

Table A1. Comparison of predicted water quality in east bay with numeric targets (second year following treatment). Predicted chlorophyll and total N and P concentrations for epilimnion; DO reported as number of days where DO concentrations >5 mg/L at 2 m above sediments.				
Criteria	Target	Reference	Dredging	Alum
Chlorophyll	<25 $\mu\text{g/L}$	28.6	18.2	24.7
DO	>5 mg/L	209 (57.3%)	277 (75.9%)	268 (73.4%)
Total N	<0.75 mg/L	1.81	1.40	1.67
Total P	<0.1 mg/L	0.60	0.38	0.33

These concentrations reflect those in the absence of substantial external loading; large runoff events would effectively displace most of the volume in east bay, so that water quality following such an event would be driven by the nutrient concentrations in the runoff. Thus, concentrations of total N and total P could be on the order of 2.0 and 0.4 mg/L, respectively (Dyal and Anderson, 2003). Importantly, a large runoff event would also import a great deal of suspended solids that would lessen the effectiveness of alum and dredging at controlling nutrient flux. It is on this basis that a conventional alum treatment is not considered to be a viable long-term treatment strategy; while dredging suffers from some of these same issues, there remain other benefits, including increased storage capacity for both water and sediment.

An alternative strategy that may be useful for east bay (and north bay) would be microfloc in-stream alum addition (e.g., Harper et al., 1998). The goal would be to add sufficient alum to effectively bind up SRP in the inflowing water so that readily bioavailable water column phosphorus loads would be reduced. Over the long term, such a strategy should also lower sediment SRP release since potentially much less phosphorus would enter the active phosphorus cycle. Any residual sorption capacity of the alum added to the inflow would also be available to suppress internal loading. This

strategy may take some time to achieve significant results however, as the lake will need to be converted from a principally N-limited system to one of P-limitation or co-limitation.

References for Appendix

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