PREDICTED EFFECTS OF EXTERNAL LOAD REDUCTIONS AND IN-LAKE TREATMENT ON WATER QUALITY IN CANYON LAKE – A SUPPLEMENTAL SIMULATION STUDY

FINAL REPORT

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Executive Summary

A previous modeling analysis evaluated effects of aeration, hypolimnetic oxygenation and alum treatments on the water quality in Canyon Lake (Anderson, 2007). Results from that study indicated 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 of these in-lake treatment alternatives was capable of meeting all of the prescribed water quality goals. In contrast, an alum treatment was predicted to have little effect on overall water quality. Since none of the simulated in-lake treatments were able to meet all of the numeric targets, it was suggested that reductions in external loading of nutrients would also be necessary (Anderson, 2007).

In light of these findings, additional simulations were conducted to assess the effectiveness of management strategies that include both watershed-based reductions in external loading and in-lake treatment. The DYRESM-CAEDYM model previously developed, calibrated and used for the in-lake treatment analysis for Canyon Lake served as the basis for these additional simulations. A total of 21 additional sets of simulations evaluated the effects of nutrient load reductions (0%, 25%, 50% and 75%) and in-lake treatment (no treatment, aeration, alum, and hypolimnetic oxygenation) on water quality in Canyon Lake. Three-year simulations were conducted using meteorological data for 2002-2004; this period was selected since it represents a wide range in runoff and external loading to the lake. Additional simulations considered the case where runoff volumes were increased by an additional 50%.

The results of this modeling analysis indicate that external nutrient load reductions in combination with in-lake treatment will improve water quality beyond that achievable with in-lake treatment or watershed improvements alone, and more effectively meet numeric targets set for the lake. For example, a 50% reduction in nutrient concentrations in runoff to Canyon Lake in combination with hypolimnetic oxygenation was predicted to meet numeric targets for chlorophyll (<25 μg/L), total N (<0.75 mg/L), and hypolimnetic DO (>5 mg/L). Aeration, in conjunction with a 50% reduction in external nutrient loading, was predicted to also meet the chlorophyll and total N targets, but just miss the 5 mg/L numeric target for DO, although increased air flow rates at the diffuser would allow aeration to also meet the DO target. In contrast, a 50% reduction in external loading alone or with an alum application, were both predicted to exceed the total N target, and miss the DO numeric target by a wide margin. Aeration or hypolimnetic oxygenation is necessary to meet the DO numeric target for Canyon Lake irrespective of external nutrient load reductions. Total P was predicted to be the most difficult numeric target to meet; out of the 21 different scenarios evaluated, only hypolimnetic oxygenation in combination with a 75% reduction in external nutrient loading met the total P and all other numeric targets.

Additional simulations evaluated effects of a 50% increase in runoff volume from that used in the 2002-04 simulations. These simulations yielded average annual nutrient, chlorophyll and DO concentrations within 10-20% of those predicted for 2002-04, indicating that improvements in water quality from external loading control and in-lake treatments will only be moderately affected by typical variations in hydrologic conditions, and not dramatically alter attainment of numeric targets, subject to the assumptions used in these simulations.

Model results also demonstrated a marked benefit of watershed external nutrient load reductions and in-lake treatment for Lake Elsinore. These two efforts lowered total N and total P concentrations in outflow to Lake Elsinore, with in-lake treatment more effectively lowering total P concentrations delivered downstream when compared with total N. This is an important consideration since Lake Elsinore is generally P-limited.

1.0 Introduction

The Santa Ana Regional Water Quality Control Board adopted in 2004 Resolution R8-2004-0037 that developed a nutrient TMDL for the control of nitrogen and phosphorus in Canyon Lake. Final numeric targets specified in the TMDL include an annual average total phosphorus concentration not to exceed 0.1 mg/L, an annual average total nitrogen concentration of 0.75 mg/L or less, 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, 2004).

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 of 0.276 mg/L (Anderson et al., 2007), 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 was over 38 μg/L (Anderson et al., 2007), 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 et al., 2007).

To evaluate the capacity of in-lake treatment strategies to improve water quality and meet the numeric targets of the TMDL, a modeling study was recently conducted (Anderson, 2007). The DYRESM-CAEDYM model was found to reasonably reproduce observed water quality in June 2006 – June 2007 (Anderson et al., 2007). The model was then reparameterized to predict water quality in Canyon Lake with (i) aeration, (ii) hypolimnetic oxygenation and (iii) alum addition. Model simulations demonstrated substantial benefits of aeration and hypolimnetic oxygenation on water quality, lowering chlorophyll and nutrient concentrations and increasing hypolimnetic DO concentrations. (Anderson, 2007). A simulated alum treatment effectively suppressed total P release from bottom sediments, but had little effect on total N, DO or chlorophyll concentrations in the water column. Despite marked improvements in water quality, however, in-lake treatments were not able to meet all of the numeric targets set for the lake. It was thus concluded that controls on external loading from the watershed would also be needed to meet water quality goals.

The purpose of this study was to evaluate the effects of external nutrient load reductions, in conjunction with in-lake treatment alternatives, on predicted water quality in Canyon Lake.

2.0 Methods

The DYRESM-CAEDYM model (Hipsey et al., 2006) developed and used in the previous modeling study (Anderson, 2007) was also utilized in this analysis. Model calibration and simulation results are detailed in Anderson (2007). Interested individuals are encouraged to review that document for details.

The simulation period from 2002-2004 was selected for detailed analysis. This period was chosen in part because lake and watershed water quality data were available for this time period and because it reflected both strong drought conditions (water year 2002) as well as water years with low (2004) to large (2003) rainfall and runoff. Flow data were taken from the USGS gaging stations on the San Jacinto River near Sun City (USGS gage #11070365) and on Salt Creek (USGS gage #1107465). Runoff volumes from these two gaging stations used in simulations totaled 1,039, 11,291 and 3,108 af for water years 2002, 2003 and 2004, respectively. 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 (Dyal and Anderson, 2003). While concentrations varied somewhat within as well as between storms, total N concentrations averaged 1.93 mg/L in San Jacinto River, with approximately 1.2 mg/L in labile particulate organic N forms, 0.25 mg/l as NH_4-N and 0.48 mg/L as NO_3+NO_2-N. These values were used in simulations as done previously. Total P in San Jacinto River inflow (0.37 mg/L) was comprised principally of PO_4-P (0.32 mg/L) and a lower concentration of labile particulate organic P (0.05 mg/L) (Dyal and Anderson, 2003). Quite similar concentrations and forms of N and P were also used for Salt Creek (total N of 2.0 mg/L and total P of 0.4 mg/L) (Dyal and Anderson, 2003). At these concentrations, annual total N loading to Canyon Lake varied by more than an order of magnitude, from 2,475 kg in water year 2002 to 27,060 kg N in water year 2003. An intermediate total N loading was present in water year 2004. A similar range in annual external loading of P was present (475 – 5,231 kg).

In addition to these baseline external loading rates, loading rates were reduced by 25%, 50% and 75% from these values in separate simulations to represent implementation of watershed-based nutrient BMPs. As a result, a total of four different levels of external load reductions were evaluated in this study: 0% (no reductions from the concentrations and external loads described above), 25%, 50% and 75%. The four different in-lake treatment strategies were also incorporated into this analysis (no in-lake treatment, aeration, alum and hypolimnetic oxygenation). A total of 16 three-year simulations were thus conducted to evaluate external loading and in-lake treatment (Table 1). Separate simulations were conducted that evaluated 50% reductions in external loading of only N and only P (with no in-lake treatment), and with a 50% increase in runoff volumes.

Table 1. Simulation scenarios evaluated: shown as matrix of in-lake treatment x external load reduction.

External Load	No Treatment	Aeration	Alum	Oxygenation
0%	X	X	X	X
25%	X	X	X	X
50%	X	X	X	X
75%	X	X	X	X

3.0 Results

3.1 Predicted Water Column Concentrations in Canyon Lake

3.1.1 Effects of External Load Reductions

The first year of the simulation period (2002) had minimal inflows to the lake (Fig. 1a). Water was imported to Canyon Lake via the San Jacinto River for 2 weeks in late March at about 85 af/d that was predicted to increase the lake level by about 1.1 m. Most of the added water was subsequently lost to evaporation over the summer and fall (Fig. 1b). A storm in mid-December restored the lake level to near 15 m (maximum depth), although subsequent large storms in the winter of 2004 resulted in water levels that overtopped the spillway (16.5 m above minimum bottom elevation) and released about 9,000 af of water downstream to Lake Elsinore (Fig. 1c). Storms in late 2004 also contributed significant flows to Canyon Lake that also subsequently spilled to Lake Elsinore. Since there was little natural external loading to Canyon Lake in 2002, discussion will focus on 2003-2004.

Total N concentrations varied considerably over the simulation period and decreased in response to greater external loading controls (Fig. 2). Maximum concentrations were generally found each winter, with levels generally decreasing in the spring. Total N concentrations in the epilimnion of the water column decreased in response to reduced runoff concentrations, although water column concentrations decreased by less than the influent concentration reductions (Fig. 2). For example, a 50% reduction in influent concentrations yielded an average of about 35% reduction in TN concentration in the water column. This difference reflects the contribution of internal nutrient loading and to a lesser extent direct atmospheric deposition on the lake surface to the overall nitrogen budget to the lake.

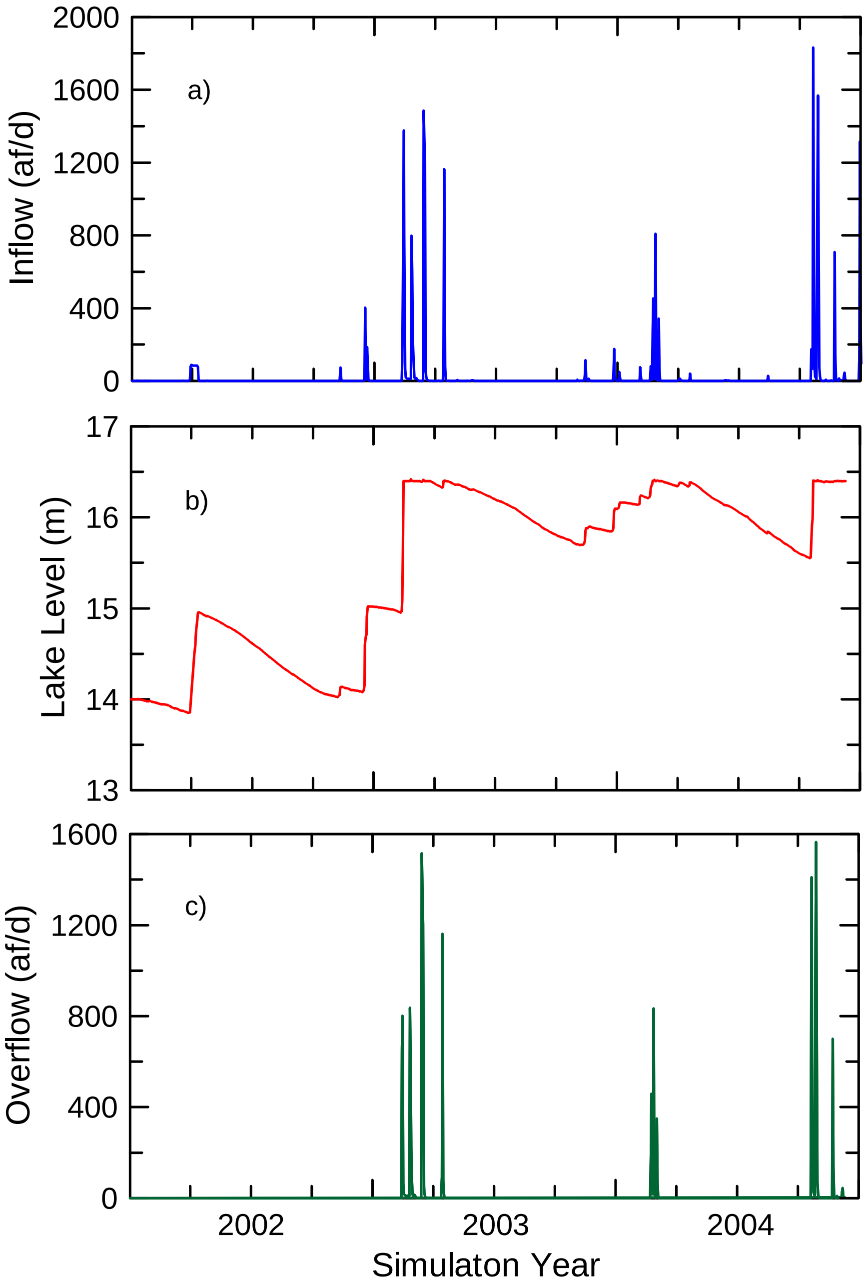

Fig. 1. a) Inflows to Canyon Lake (from USGS gaging stations on San Jacinto River and Salt Creek) and predicted b) lake level and c) overflow to Lake Elsinore.

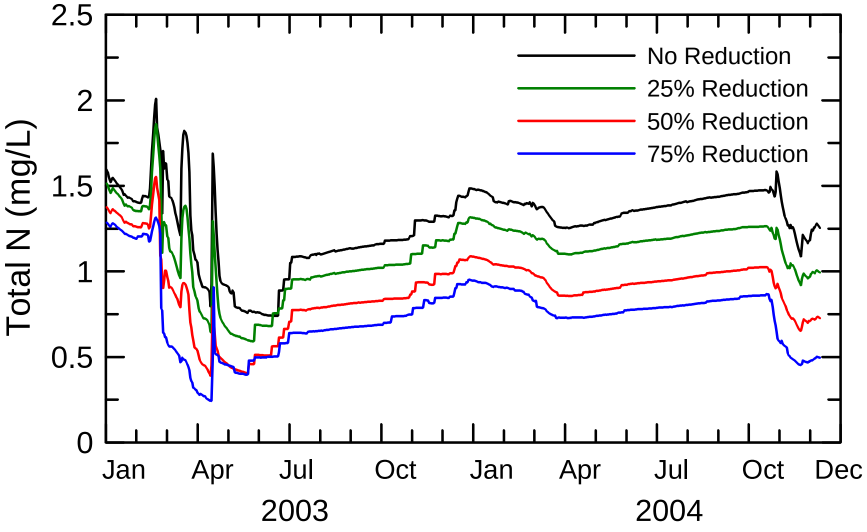

Fig. 2. Predicted epilimnetic total N concentrations in Canyon Lake assuming no in-lake treatment and reductions in external loading of 0 – 75%.

Total P concentrations also varied over time and in response to external load reductions (Fig. 3). Water column concentrations increased as a result of internal loading over much of the simulation period, although marked reductions were found in February-March 2003 and October-November 2004 due to rainfall and runoff that added water at lower P concentrations than often present in the lake (especially when large reductions in nutrient concentrations were assumed). The increase in total P concentrations in late 2003 resulted from fall turnover that mixed hypolimnetic waters with high SRP concentrations into the surface waters (Fig. 3).

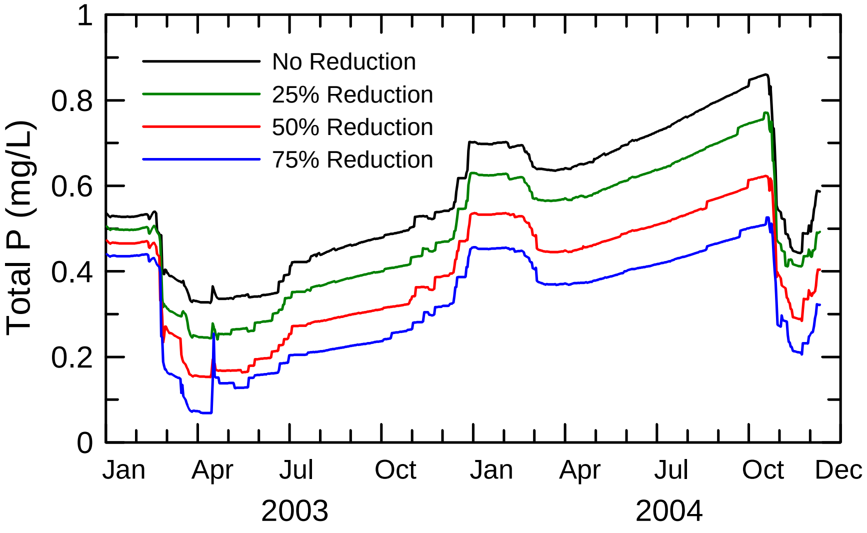

Fig. 3. Predicted epilimnetic total P concentrations in Canyon Lake assuming no in-lake treatment and reductions in external loading of 0 – 75%.

Predicted chlorophyll concentrations varied over time and in response to reductions in total N and P concentrations in the runoff from the watershed into the lake (Fig. 4). The reference (no reduction) case yielded chlorophyll concentrations in the epilimnion that varied from about 20 μg/L in late summer to 40-160 μg/L during the fall-spring periods (Fig. 4, no reduction).

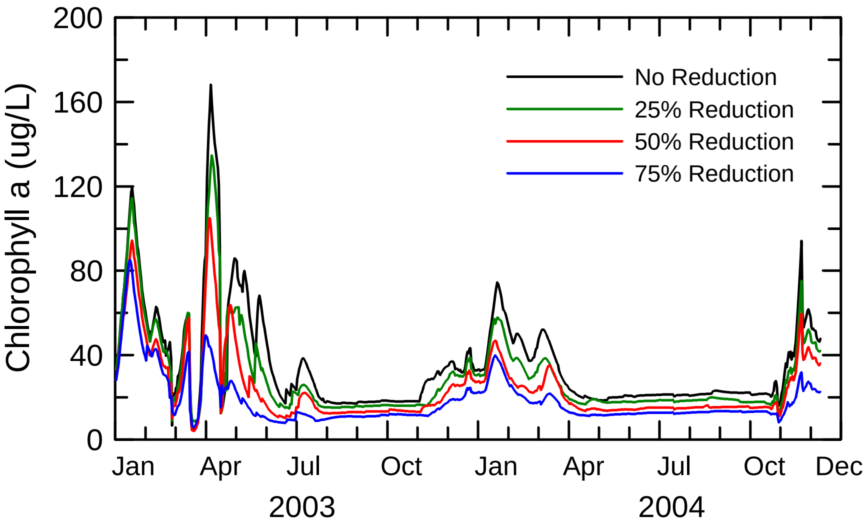

Fig. 4. Predicted epilimnetic chlorophyll a concentrations in Canyon Lake assuming no in-lake treatment and reductions in external loading of 0 – 75%.

Assuming BMPs in the watershed can achieve a 25% reduction in both N and P concentrations, somewhat lower chlorophyll concentrations were predicted through most of the simulation period, although peak concentrations in April 2003 were still predicted to approach 140 μg/L (Fig. 4, 25% reduction). Higher reductions in nutrient concentrations in inflows to the lake lowered predicted chlorophyll concentrations, although comparatively little impact was predicted in early 2003.

The TN:TP ratio for the lake (often near 2) indicates that strong N-limitation would be expected. Thus, is seems likely that it is the reduction in N inputs to Canyon Lake, rather than reductions in P inputs, that are regulating chlorophyll concentrations. To test this, additional simulations were conducted comparing predicted chlorophyll concentrations assuming no external load reductions, and 50% reductions in only N, only P and N+P (Fig. 5.). Predicted chlorophyll concentrations assuming 50% reduction in external P concentrations followed essentially exactly the reference (no reduction) case, indicating no effect at these concentrations on algal production in the lake. On the other hand, a 50% reduction in N yielded essentially an identical chlorophyll response to that found when both N and P loading were reduced by 50%. Thus, reductions in N, rather than P, appear to have the greatest beneficial effect on chlorophyll levels, at least up to 75% reductions from ambient levels in runoff within the watershed.

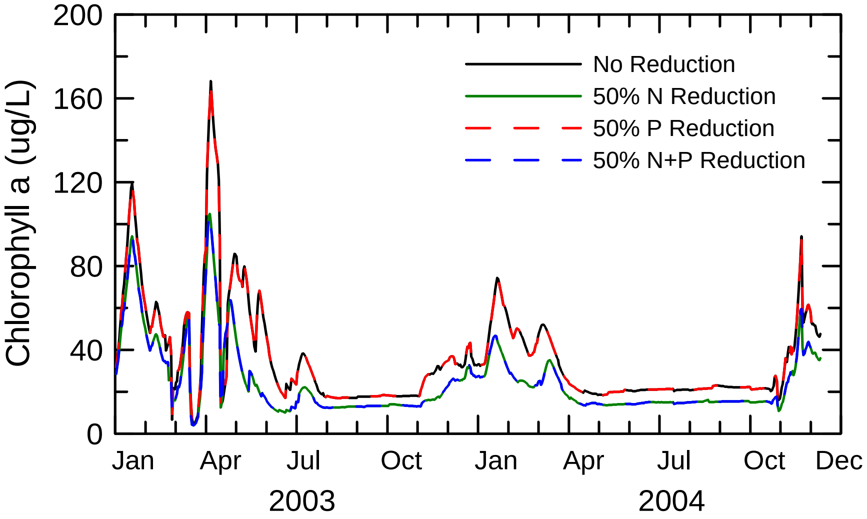

Fig. 5. Predicted epilimnetic chlorophyll a concentrations in Canyon Lake assuming no in-lake treatment and reductions in external loading of 0%, as well as 50% N, 50% P and 50% N+P.

3.1.2 Effects of External Load Reductions and In-Lake Treatment

These time series demonstrate the beneficial effect of control of external nutrient loading on predicted water quality in Canyon Lake. In-lake treatment strategies were also found to substantially improve water quality (Anderson, 2007a). Combining these strategies would be expected to further improve water quality in the lake. Subsequent simulations evaluated this wherein mean annual chlorophyll, nutrient and DO concentrations were calculated from data like that shown in Figs. 2-4. Only modest (<5-10%) differences between 2003 and 2004 were generally found, so two-year average values were calculated for each of the 16 different combinations of external and in-lake controls (Table 1) and compared with numeric targets for the lake.

The RWQCB has set a annual average numeric target of 25 μg/L chlorophyll a. One sees that this target can be met in a number of different ways. As previously noted, aeration and oxygenation both effectively lower chlorophyll concentrations relative to the no-treatment conditions (Anderson, 2007). The average chlorophyll concentration predicted for 2003-2004 met the numeric target with aeration alone (i.e., with 0% reduction in external loading), while oxygenation only slightly exceeded the target, although interannual variation was evident (Fig. 6). No-treatment and alum yielded predicted average chlorophyll concentrations that exceeded the target by 10 μg/L or more. A 25% reduction in external loading lowered predicted average chlorophyll levels by about 5 μg/L, with both aeration and hypolimnetic oxygenation below the 25 μg/L numeric target. An external loading reduction of 50% lowered average chlorophyll concentrations for all treatments to <25 μg/L, while annually averaged chlorophyll concentrations of about 11-18 μg/L were predicted when 75% of N and P were removed from runoff entering the lake (Fig. 6).

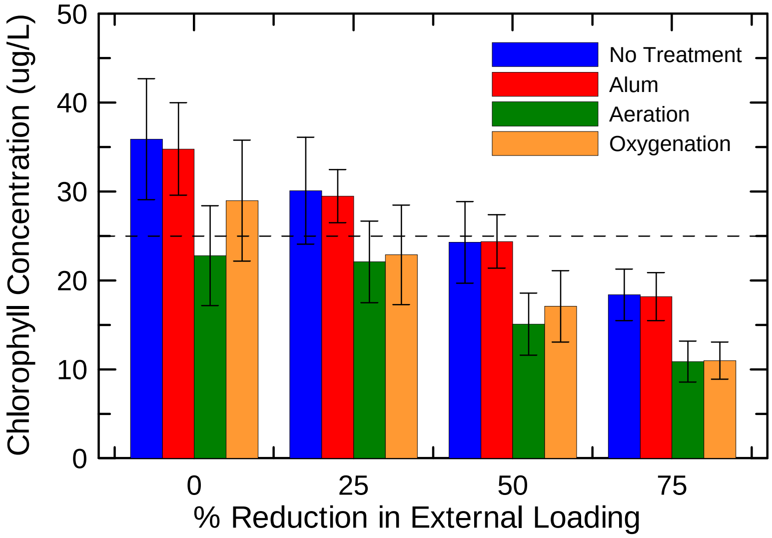

Fig. 6. Annual average chlorophyll concentrations as function of % external nutrient load reduction and in-lake treatment. Dashed line represents numeric target for chlorophyll.

Annual average total N concentrations in the lake were also favorably influenced by reductions in external loading and by in-lake treatments. Aeration and oxygenation both consistently yielded lower predicted average total N concentrations when compared with no-treatment or alum (Fig. 7). The numeric target of 0.75 mg/L N was not as readily achieved as that for chlorophyll, requiring at least 50% reductions in external loading and either aeration or hypolimnetic oxygenation, although a 75% reduction in external loading was predicted to meet, on average, the annual numeric target for N for all in-lake treatments, including the reference (no-treatment) case (Fig. 7).

Total P was found to be the most challenging water quality target to meet (Fig. 8). With an objective of 0.1 mg/L, concentrations in the lake were predicted to exceed this value by a fairly wide margin under most external loading and in-lake treatments, although a 75% reduction in external loading combined with hypolimnetic oxygenation was predicted, on average, to (just) meet this target, although year-to-year variation is predicted to yield some annual exceedances (Fig. 8). Reductions in external loading exceeding 75% would be necessary to meet this numeric target with either alum or aeration.

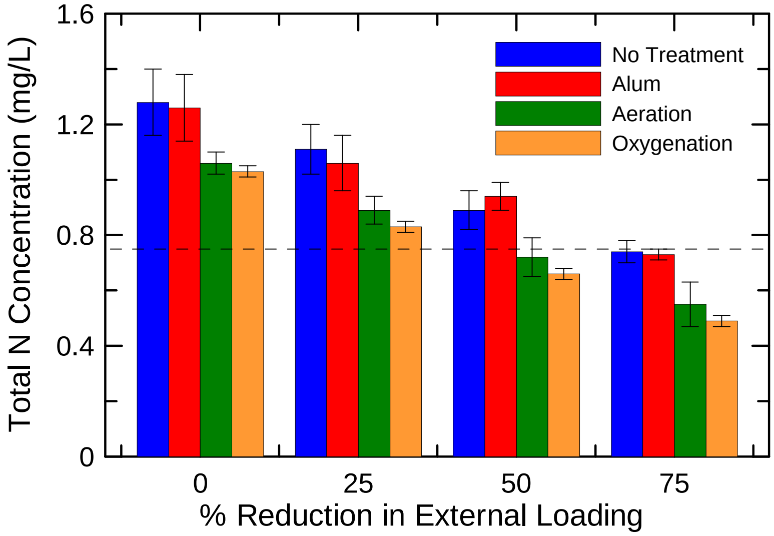

Fig. 7. Annual average total N concentrations as function of % external nutrient load reduction and in-lake treatment. Dashed line represents numeric target for total N.

Given the strong N-limitations in the lake, total P is probably the less critical water quality goal for the lake, at least in the near term, although it may be that with continued nutrient management, the lake might eventually evolve to a P-limited system.

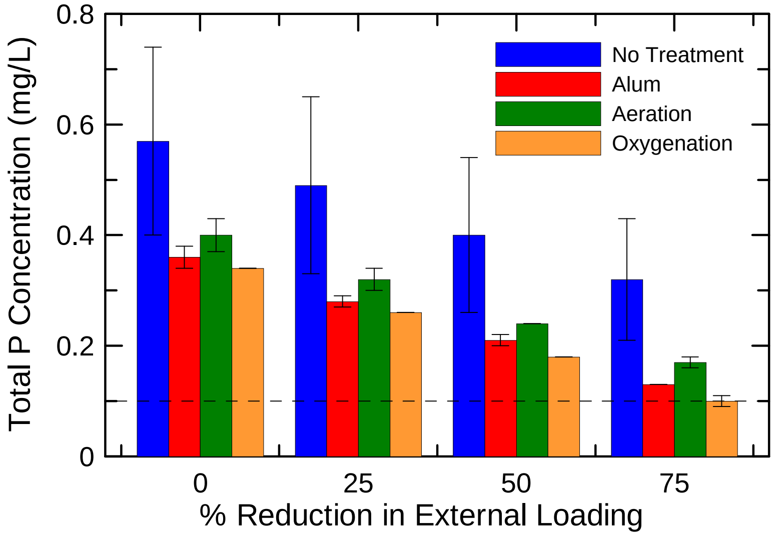

Fig. 8. Annual average total P concentrations as function of % external nutrient load reduction and in-lake treatment. Dashed line represents numeric target for total P.

The average dissolved oxygen concentrations, taken here at 2 m above the bottom sediments, were also calculated from the simulation results (Fig. 9). Quite dramatic differences in predicted DO levels were found; reductions in external loading had no meaningful effect on DO concentrations in the no-treatment and alum-treatment scenarios, with annual average concentrations <0.3 mg/L in all cases (Fig. 9).

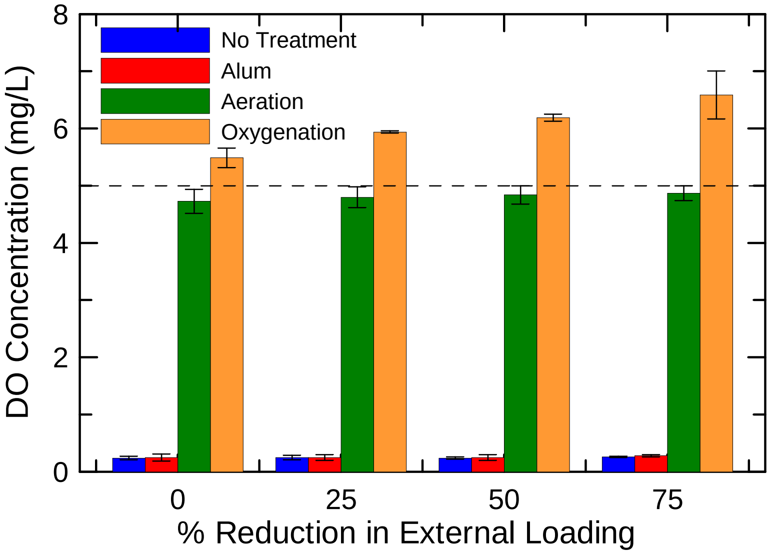

Fig. 9. Annual average hypolimnetic dissolved oxygen concentrations as function of % external nutrient load reduction and in-lake treatment. Dashed line represents numeric target for DO.

In contrast, much higher concentrations of DO were predicted with aeration and hypolimnetic oxygenation. Aeration fell just short of meeting the target of 5 mg/L, while hypolimnetic oxygenation yielded DO levels that exceed this target, and increased with greater reductions in external loading (Fig. 9).

These simulation results reflected the average annual concentrations of nutrients, chlorophyll and dissolved oxygen given the meteorological and hydrological conditions that were present over 2002-2004. Relatively large standard deviations in predicted annual concentrations for this period were often present however, reflecting some year-to-year variance. Some of this variance is presumably due to different runoff volumes and thus also differences in loading of nutrients, lake level, and other factors. While it is not possible to simulate all possible runoff conditions in the lake, higher runoff and inflow volumes than found in 2002-2004 are occasionally present. To evaluate the effect of higher runoff inputs to Canyon Lake, runoff volumes were increased by 50% from those in the 2002-2004 simulations. Thus, about 17,000 af of runoff, carrying 40,590 kg total N and 7,846 kg total P, was added to the lake in water year 2003. Lower runoff volumes and nutrient loading was present in the other years (e.g., 1,558 and 4,662 af of runoff for water year 2002 and 2004, respectively). Three different scenarios were evaluated: the reference (no-treatment) condition, as well as oxygenation and oxygenation+50% reduction in runoff nutrient concentrations.

Increasing runoff volume by 50% increased the corresponding nutrient loading to Canyon Lake since average nutrient concentrations were assumed to be unchanged in response to changes in runoff volumes. Increased runoff volume did not meaningfully change predicted annual average chlorophyll, nutrient or DO concentrations in the lake from levels predicted at lower runoff volumes using 2002-2004 data (Table 2). Hypolimnetic oxygenation did favorably lower annual average chlorophyll, total N and total P concentrations, although only the DO numeric target was met (Table 2). Hypolimnetic oxygenation with a 50% reduction in runoff nutrient concentrations (and therefore a 50% reduction in total nutrient loading) had a much more favorable affect on the water column concentrations. The mean chlorophyll concentration was reduced by one-half, to 17.8 ±4.4 μg/L and well below the 25 μg/L numeric target (Table 2). Total N and DO concentrations also met their target values. Total P was reduced to one-third the reference (no-treatment) concentration. Importantly, these predicted annual average concentrations are quite similar to those predicted for 2002-04 when runoff volumes were significantly lower (e.g., Fig. 6-9). Thus, the annual average concentrations of nutrients, chlorophyll and DO do not appear to be dramatically affected by different hydrological regimes, at least within the range of typical runoff volumes found in the watershed. Extreme events were not evaluated since such events are rare and would import vast quantities of sediment into the lake that would change the sediment biogeochemistry, at least in the short term, beyond that parameterized in the model.

Table 2. Predicted nutrients comparing 2002-04 simulation results (no-treatment) to simulation results assuming a 50% increase in runoff with no-treatment, hypolimnetic oxygenation and hypolimnetic oxygenation in conjunction with a 50% reduction in runoff nutrient concentrations.

	Chlorophyll (μg/L)	Total N (mg/L)	Total P (mg/L)	DO (mg/L)
Numeric Target	< 25	< 0.75	< 0.1	> 5
No Treatment	35.9 ± 6.8	1.28 ± 0.12	0.57 ± 0.17	0.24 ± 0.03
1.5x Runoff; No Treatment	37.4 ± 13.1	1.16 ± 0.08	0.52 ± 0.13	0.18 ± 0.03
1.5x Runoff + Oxygenation	31.7 ± 8.1	1.00 ± 0.01	0.33 ± 0.01	5.31 ± 0.15
1.5x Runoff + Oxygenation + 50% Nutrient Reduction	17.8 ± 4.4	0.61 ± 0.02	0.17 ± 0.01	6.09 ± 0.19

3.2 Nutrient Concentrations in Overflow to Lake Elsinore

External nutrient load reductions and in-lake treatment are expected to also improve the quality of water spilled to Lake Elsinore during large runoff events within the watershed. Concentrations of total N released from Canyon Lake during storms was less affected by in-lake treatment than the annual average concentration there, although outflow concentrations did decrease strongly with reductions in external loading for the 2002-04 simulations (Fig. 10). Thus, reductions in external nutrient loads to Canyon Lake, and to a lesser extent in-lake treatment, also benefited Lake Elsinore.

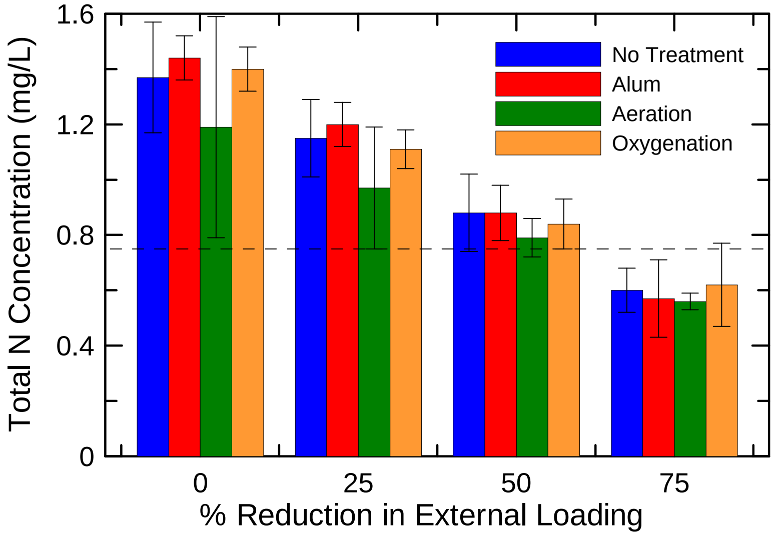

Fig. 10. Total N concentrations in outflow to Lake Elsinore as function of % external nutrient load reduction and in-lake treatment. Dashed line represents numeric target for total N.

Total P concentrations in outflow to Lake Elsinore were predicted to also be lowered as a result of reductions in external loading and more somewhat more favorably by in-lake treatment than total N (Fig. 11). For example, a 50% reduction in total P concentrations in runoff yielded an average outflow concentration of 0.37±0.03 mg/L (no-treatment), while hypolimnetic oxygenation further lowered total P to 0.21±0.02 mg/L. Average total P concentrations in outflow to Lake Elsinore were further reduced to 0.14±0.03 mg/L with a 75% reduction in concentrations in runoff (Fig. 11).

Increased runoff volume (1.5x that in the above simulations) lowered slightly the average total N concentration in outflow to Lake Elsinore compared with the 2002-04 results, although it increased somewhat total P concentrations (Table 3). The higher runoff simulations yielded average outflow concentrations that were within about 10-20% of those predicted using the 2002-04 conditions.

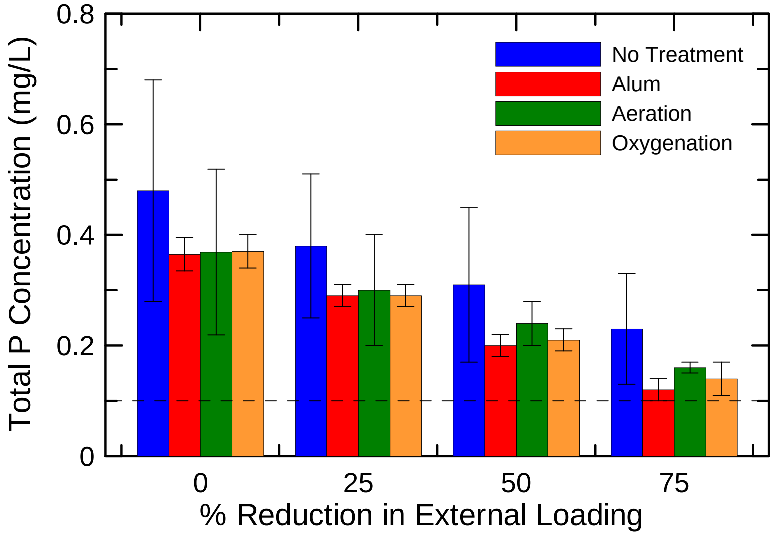

Fig. 11. Total P concentrations in outflow to Lake Elsinore as function of % external nutrient load reduction and in-lake treatment. Dashed line represents numeric target for total N.

Table 3. Predicted nutrient concentrations in outflow to Lake Elsinore.

	Total N (mg/L)	Total P (mg/L)
No Treatment	1.37 ± 0.20	0.48 ± 0.20
No Treatment; 1.5x Runoff	1.20 ± 0.09	0.43 ± 0.13
Oxygenation	0.88 ± 0.14	0.31 ± 0.14
Oxygenation; 1.5x Runoff	1.00 ± 0.13	0.28 ± 0.02
Oxygenation+50% Reduction	0.84 ± 0.09	0.21 ± 0.02
Oxygenation; 1.5x Runoff+50% Reduction	0.67 ± 0.07	0.17 ± 0.03

4.0 Implications and Conclusions

The results of this modeling analysis indicate that external nutrient load reductions in combination with in-lake treatment will improve water quality in Canyon Lake beyond that achievable with in-lake treatment or watershed improvements alone. A 50% reduction in nutrient concentrations in runoff to Canyon Lake in combination with aeration or hypolimnetic oxygenation was predicted to meet numeric targets for chlorophyll and total N, with hypolimnetic oxygenation also meeting hypolimnetic DO target of 5 mg/L. Aeration as modeled in this study was predicted to just miss the 5 mg/L numeric target for DO, although as previously suggested (Anderson, 2007), increasing air flow rates at the diffuser slightly would allow aeration to also meet the DO target. In contrast, no in-lake treatment, or an alum application, were both predicted to miss the total N and especially the DO numeric targets. Total P was predicted to be the most difficult numeric target to meet; out of the 21 different scenarios evaluated, only hypolimnetic oxygenation in combination with a 75% reduction in external nutrient loading met the total P and all other numeric targets.

Simulation results also demonstrated a marked benefit of watershed external nutrient load reductions and in-lake treatment for Lake Elsinore. These two efforts lowered total N and total P concentrations in outflow to Lake Elsinore, with in-lake treatment more effectively lowering total P concentrations delivered downstream when compared with total N. This is an important consideration since Lake Elsinore is generally P-limited.

Total N levels were predicted to control the chlorophyll concentrations in Canyon Lake. Alum, while quite effective at controlling internal recycling of P (Anderson et al., 2007), was consequently predicted to have very little effect on chlorophyll and no effect on DO levels in the lake. Hypolimnetic oxygenation is the preferred in-lake treatment strategy; it has been shown in laboratory studies to lower internal recycling of N and P (Anderson et al., 2007) and lower total N, total P and chlorophyll concentrations in Canyon Lake while preserving thermal structure in the lake (Anderson, 2007). Hypolimnetic oxygenation in combination with at least a 50% reduction in nutrient concentrations in storm runoff to the lake is expected to meet three of the four numeric targets for Canyon Lake, although simulations suggest that at least a 75% reduction in external loading of both N and P will be needed to meet, on average, the numeric target for total P.

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