LABORATORY AND LIMNOCOSM-SCALE EVALUATIONS OF RESTORATION ALTERNATIVES FOR LAKE ELSINORE

Final Report to:

Lake Elsinore & San Jacinto Watersheds Authority

Prepared by:

Michael A. Anderson
Dept. of Environmental Sciences
University of California, Riverside

Summary

A series of laboratory and limnocosm-scale studies were conducted to evaluate the impacts of recycled water addition, aeration, and metal salt additions on water quality in Lake Elsinore. Specifically, studies were conducted to quantify (i) algal response to nutrient and recycled water additions, (ii) the influence of aeration and metal salt additions on nutrient concentrations and release from the sediments, and (iii) lake response to recycled water additions and in-lake treatments through use of limnocosms.

Chlorophyll *a* concentrations were found to increase significantly following PO_4-P and recycled water additions in laboratory incubation studies. Concentrations were not influenced by N additions as either NO_3-N or NH_4-N, however. Chlorophyll concentrations increased from ~10 µg/L to approximately 45 and 62 µg/L after 4 days following PO_4-P additions to 0.1 and 0.3 mg/L, respectively. Recycled water additions at rates of 1:30, 1:10 and 1:3 yielded final chlorophyll concentrations of 50, 105 and 115 µg/L, respectively. Based upon these findings, one can conclude that Lake Elsinore is P-limited in the late summer. Moreover, recycled water inputs, in the absence of prior nutrient removal or other mitigation measures, have the potential to significantly increase chlorophyll concentrations and algal biomass in the lake.

Laboratory studies of nutrient flux from sediments revealed a high rate of internal loading of PO_4-P under low dissolved oxygen (DO) conditions (8.8±0.7 mg/m^2/d). Commonly used restoration techniques significantly reduced PO_4-P loading rates. Alum was the most effective treatment for reducing P internal loading, completely stopping release from the sediments over the duration of the study. Calcium treatment reduced PO_4-P flux to 2.9±0.1 mg/m^2/d (67% reduction) under low DO conditions, while aeration

(DO ~7 mg/L) reduced PO_4-P release to 5.4±0.7 mg/m^2/d (39% reduction). Flux rates for sediment treated with calcium+alum, with and without aeration, were not substantially different than that for alum alone. Similarly, nutrient flux from sediment cores treated with alum+aeration was not significantly different than that for alum alone, although aeration did favorably reduce the measured PO_4-P flux rate for the Ca treatment relative to non-aerated cores. The flux of NH_4-N from the sediment under low DO conditions (86±11 mg/m^2/d) was an order of magnitude higher than that for PO_4-P. Rates of NH_4-N flux were not substantially influenced by aeration (78±19 mg/m^2/d) or metal salt additions (*e.g.*, 82±11 mg/m^2/d with alum).

Water quality response to aeration, alum, Ca and recycled water additions in the limnocosms was varied. In general, transparencies increased and chlorophyll a concentrations decreased in all of the limnocosms, regardless of treatment, due to the development of an attached algae population. Nutrient concentrations in the limnocosms without recycled water addition were all quite low, while those with recycled water additions increased sharply following the additions and then decreased rapidly over the next 7 days to levels comparable to control and treated limnocosms.

Introduction

Lake Elsinore is a large, shallow lake that has been plagued by poor water quality, including low transparencies, high chlorophyll concentrations, low DO, and periodic fish kills. The lake is also subject to substantial evaporative losses, with an average annual water deficit of about 3,600 af (~7% of total lake volume), and annual deficits as large as 15,000 af (30%) in dry years. Lake restoration and provisions for maintenance of the lake level with recycled water additions are currently under consideration.

In an effort to understand the potential impacts of various lake management and restoration strategies on water quality in Lake Elsinore, a series of laboratory and field experiments were conducted. Specifically, studies were conducted to quantify (i) algal response to nutrient and recycled water additions, (ii) the influence of aeration and metal salt additions on nutrient concentrations and release from the sediments, and (iii) lake response to recycled water additions and in-lake treatments through use of limnocosms.

Algal Response to Nutrient Additions

Algal response to nutrient inputs was quantified in laboratory studies in which solutions of known N, P and/or recycled water volumes were added to surface water

samples from Lake Elsinore. Approximately 25 L of surface water from Lake Elsinore was sampled on August 24 and immediately brought to the lab. Macroscopic algae and zooplankton were removed by sieving through a 0.053 µm sieve. Approximately 0.6 L of the treated water was decanted into a series of clear plastic vessels. The solutions were spiked to known concentrations of N, P and recycled water (Table 1).

Table 1. Summary of treatments for nutrient addition study.

Treatment	— Concentration (mg/L) —		
	Low	Medium	High
Control	-	-	-
PO_4-P	0.03	0.1	0.3
NO_3-N	0.3	1.0	3.0
NH_4-N	0.3	1.0	3.0
N+P	0.03, 0.3, 0.3[a]	0.1, 1, 1	0.3, 3, 3
Recycled water	1:30[b]	1:10	1:3

[a]concentration of PO_4-P, NO_3-N and NH_4-N, respectively
[b]ratio of recycled water to Lake Elsinore water

Solutions were then placed in a temperature- and humidity-controlled growth chamber. An illumination profile approximating that of natural conditions, with a 12-h illumination/12-h darkness cycle was used. Samples were taken daily for 4 days and analyzed for chlorophyll a using the 10200 H.3 (fluorescence) method (APHA, 1989).

Chlorophyll concentrations in the control solutions were unchanged at ~10 µg/L for the duration of the culture experiment, while concentrations in the PO_4-P spiked samples increased by up to 6x that of the control samples at the end of 4 days incubation (Fig. 1).

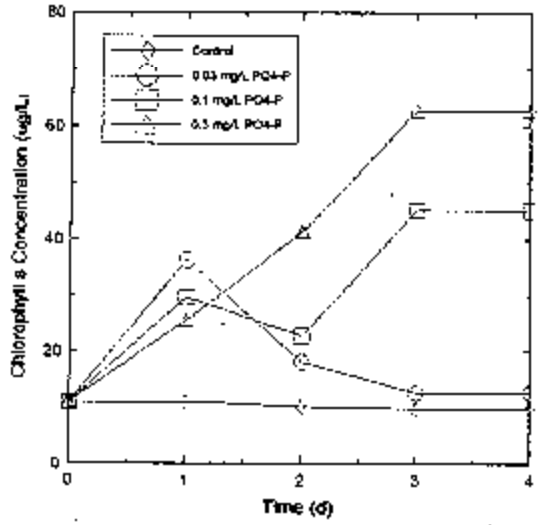

Fig. 1. Chlorophyll a concentrations vs. time following known PO_4-P additions.

Chlorophyll a concentrations followed PO_4-P concentrations and increased with increasing PO_4-P concentration (Fig. 1). Some difficulty was experienced in maintaining a viable culture after 4 or 5 days, thus limiting the duration of the experiment; however it seems plausible that additional increases in chlorophyll a concentration may be witnessed in a lake setting, especially at high PO_4-P additions.

Nitrate-N and NH_4-N were found to exert negligible influences on final chlorophyll a concentration in the cultured samples, yielding chlorophyll a concentrations at or below that of the control after 4 days (data not shown). Based on the relative response to PO_4-P, NO_3-N and NH_4-N, the algal community present in Lake Elsinore at the time of sampling was strongly P-limited.

Simultaneous addition of N and P yielded evidence for a positive growth response relative to the control (Fig. 2). A rapid increase in chlorophyll a was observed for all treatments over the first 2 days, although concentrations declined after 3 days for the lowest and highest treatment levels.

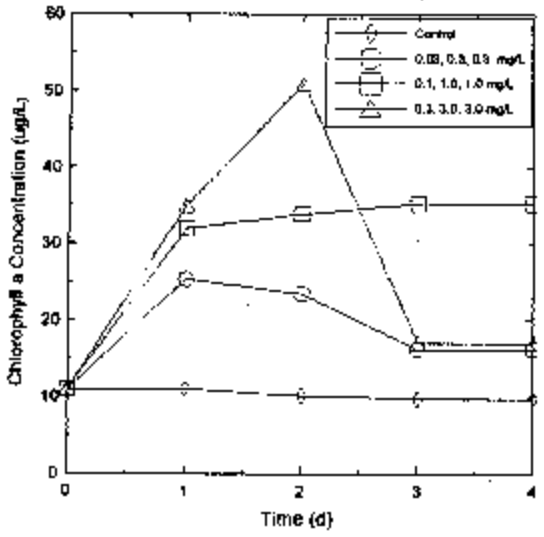

Fig. 2. Chlorophyll a concentrations vs. time following known N+P additions.

Recycled water additions had the most substantial impact on chlorophyll a production in the culture experiments, where concentrations exceeded 100 µg/L after only 3 days at the 1:10 and 1:3 ratios (Fig. 3). Even the lowest addition (1:30) resulted in chlorophyll a concentrations that were 5x higher than the control (Fig. 3). Concentrations in the recycled water used in these experiments were 2.09 mg/L PO_4-P, 8.20 mg/L NO_3-N, and

0.15 mg/L NH_4-N. Thus, PO_4-P concentrations in the final culture solutions ranged from 0.07 – 0.7 mg/L and NO_3-N ranged from 0.27 - 2.73 mg/L.

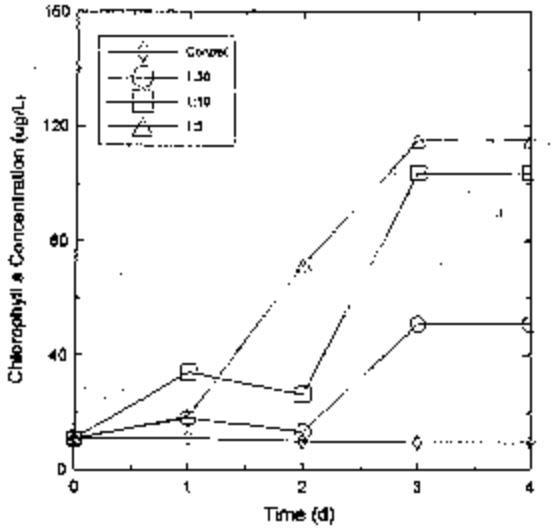

Fig. 3. Chlorophyll a concentrations vs. time following recycled water additions.

Nutrient Release from Sediments

In separate studies, nutrient flux from intact sediment cores (Moore *et al.*, 1998) was evaluated following aeration, alum addition, calcium treatment and combined alum/calcium additions. A series of intact cores were collected October 10 following Beutel (2000) from the deepest portion of the lake (approximately 7.3 m depth) (Fig. 4).

The sediment was a finely textured material with 4.6% organic carbon, 9.8% $CaCO_3$, and 850 µg/g total P. Cores were collected using 30.5 cm by 6.3 cm diameter Lucite tubes with approximately 10 cm sediment and 20 cm overlying water. Cores were promptly sealed with #13 rubber stoppers upon sampling. A total of 24 cores were collected and transported back to the lab, where 10 mL of overlying water from each of the cores were filtered through a 0.45 µm polycarbonate filter and acidified to pH<2 with H_2SO_4. Following sampling, triplicated cores were then treated with alum (at a rate of ~100 g Al/m^2), calcium (~50 g Ca^{2+}/m^2), or alum+calcium under aerated or non-aerated (sealed) conditions. The cores were incubated at room temperature (~22°C) in the dark. Samples were then collected daily for 7 days, filtered and acidified for nutrient analysis. Dissolved O_2 measurements were made using a YSI Model 55 DO meter.

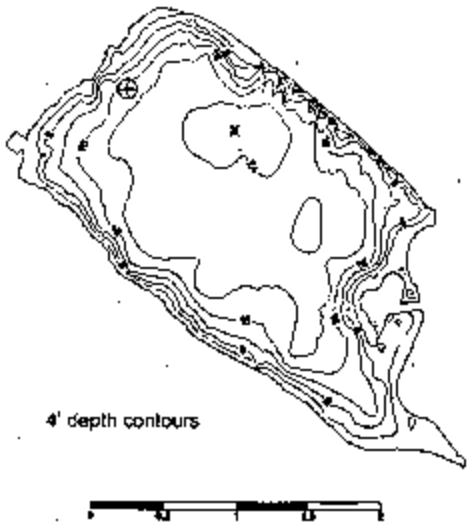

Fig. 4. Lake Elsinore showing approximate location of core samples (x) and limnocosms (⊕).

All of the treatments were found to have a significant effect on PO_4-P release from the sediments relative to the control (no treatment) (Fig. 5). In the absence of oxygen inputs or metal salt additions, the mean dissolved PO_4-P concentration in the water overlying the sediments increased linearly to more than 0.4 mg/L after 7 days. For comparison, after 1 week of aeration, PO_4-P concentration reached approximately 0.27 mg/L, while its concentration actually decreased slightly following alum treatment (Fig. 5).

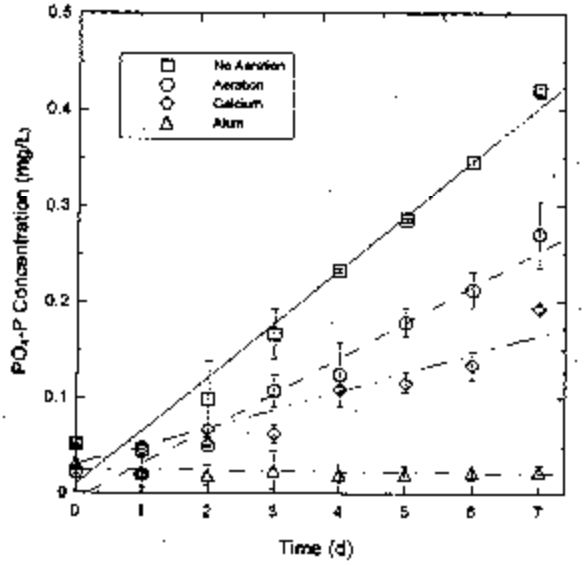

Fig. 5. PO_4-P concentrations (mean ± 1 s.d) above the sediment following treatments.

Ammonium release from the sediments was not substantially influenced by any of the treatments, although variability tended to be higher than that observed for PO_4-P (Fig. 6). Nitrate-N concentrations remained low (generally <0.05 mg/L) for all samples, although concentrations were observed to increase slightly under aerated conditions after 7 days, suggesting the onset of nitrification.

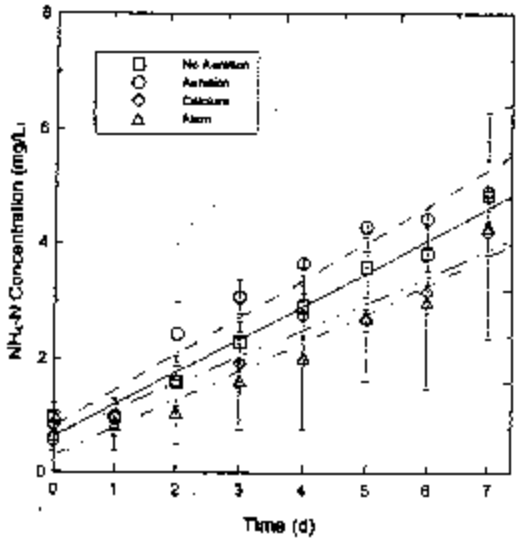

Fig. 6. NH_4-N concentrations (mean ± 1 s.d.) above the sediment following treatments.

The data in Figs. 5 and 6 were used to calculate nutrient flux rates from the sediment following the different treatments (Table 2).

Table 2. Nutrient flux from sediments.

Treatment	— PO_4-P —		— NH_4-N —	
	Flux (mg/m^2/d)	% Reduction[a]	Flux (mg/m^2/d)	% Reduction
Control	8.8 ± 0.7	-	86 ± 11	-
Alum	-0.2 ± 0.3	100	82 ± 28	5
Ca^{2+}	2.9 ± 0.1	67	71 ± 1	17
Alum+Ca^{2+}	-0.5 ± 0.5	100	92 ± 14	0
Aeration	5.4 ± 0.7	39	78 ± 19	9
Aeration+Alum	-0.2 ± 0.2	100	50 ± 5	42
Aeration+Ca^{2+}	1.1 ± 1.0	88	93 ± 29	0
Aeration+Alum+Ca^{2+}	-0.3 ± 0.4	100	78 ± 17	9

[a]Percent reduction relative to control

Limnocosm Study

Field limnocosm experiments were conducted to evaluate lake response, including transparency and chlorophyll a concentrations, to different treatment strategies and to recycled water additions. A set of 20 limnocosms, each ~17' tall and 3' in diameter, were constructed using an aluminum frame-transparent film design. The limnocosms were placed at the northwest end of the lake in approximately 14' of water (Fig. 4).

A summary of the different treatments in the limnocosm study is given in Table 3. Recycled water additions were chose to reflect approximate volumes needed to offset low, typical and high net annual evaporative losses (1:100, 1:20, and 1:4, respectively). The limnocosms were sampled at varying intervals over a period of about 30 days. Samples were collected every 2 or 3 days during the beginning of the experiment, and approximately once a week near the end. Measurements included transparency, as measured by Secchi disk, and temperature, DO, pH, and EC measured using a HydroLab. Water samples for nutrient and chlorophyll determinations were collected at 1 m depth using a van Dorn sampler. As a reference, measurements were also made and samples were also collected for the water column adjacent to the limnocosms.

Table 3. Treatment and replication for the limnocosm study.

Treatment	Replication
Control (No aeration)	2
Aeration	2
Alum + Aeration	2
Alum/Ca + Aeration	2
Zooplankton + Aeration	2
Recycled water at 1:100 + Aeration	2
Recycled water at 1:20 + Aeration	2
Recycled water at 1:4 + Aeration	2
Alum/Recycled water at 1:20 + Aeration[a]	2
Alum/Ca/Recycled water at 1:20 + Aeration[a]	2

[a]Alum was added and allowed to settle out prior to recycled water addition to simulate recycled water addition to an alum-treated lake.

The Secchi depth for the water column was largely unchanged over the ~30 day sampling period, and averaged about 80 cm (Fig. 7). In contrast, mean Secchi depths increased over time for all the limnocoms, with transparencies more than doubling after about 30 days.

Recycled water addition at a rate of about 1:20 with aeration yielded transparencies that were broadly comparable to those for the control (*i.e.*, no aeration and no recycled water addition). Alum addition with aeration did not yield Secchi depths significantly different than that for recycled water alone, although alum+Ca with aeration resulted in substantial gains in transparency after about 2-3 weeks (Fig. 7). Mean chlorophyll a concentrations for these same limnocosms showed generally decreasing levels over time, although variability was high (Fig. 8).

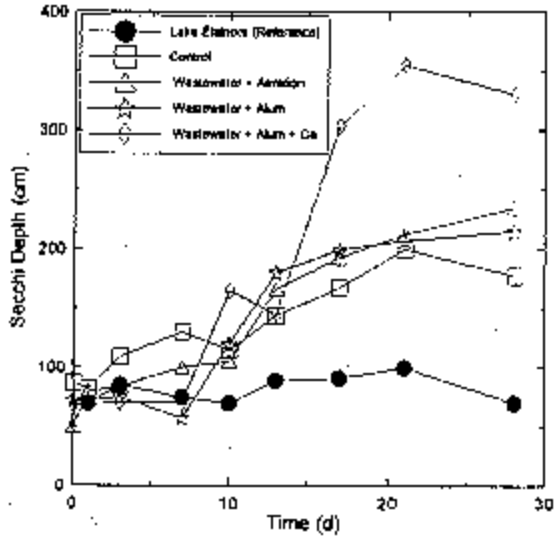

Fig. 7. Mean Secchi depths for selected limnocosms.

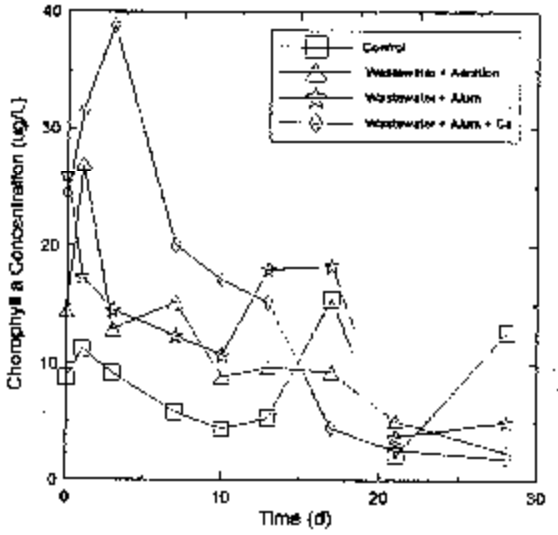

Fig. 8. Mean chlorophyll a concentrations for selected limnocosms.

The observed trends in Secchi depth and chlorophyll a over time follow qualitatively the emergence of a substantial attached algae community in the limnocosms (*e.g.*, Fig. 9). That is, as the ecology moved from a phytoplankton-dominated to a periphyton-dominated system within the limnocosms, water clarity increased. While an unfortunate development in the context of this study, it does underscore the benefits of a macrophyte and attached algae-based ecosystem as compared to the phytoplankton-dominated system presently in place in the lake. Attached algal biomass was greatest near the surface and decreased with increasing depth. Biomass also varied between some of the treatments. For example, attached algae growth in the alum-treated limnocosm (Fig. 9b) was noticeably lower than that in the control (Fig. 9a).

Fig. 9. Photographs showing attached algae growth in limnocosms: a) control and b) alum + aeration.

Mean algal biomass at the water surface (0-10 cm) ranged from 1.41 – 39.7 g/m^2 and tended to increase with increased recycled water additions and decreased with alum additions, although considerable variability between duplicates was observed (Table 4).

Table 4. Algal biomass in limnocosms (0-10 cm depth, after 60 days).

Treatment	Biomass (g/m^2)
Control (No aeration)	18.7 ± 21.1
Aeration	39.7 ± 35.5
Alum + Aeration	9.4 ± 9.6
Alum/Ca + Aeration	6.4 ± 2.8
Zooplankton + Aeration	23.6 ± 29.6
Recycled water at 1:100 + Aeration	5.4 ± 3.2
Recycled water at 1:20 + Aeration	19.4 ± 17.9
Recycled water at 1:4 + Aeration	41.5 ± 20.7
Alum/Recycled water at 1:20 + Aeration	1.4 ± 1.9
Alum/Ca/Recycled water at 1:20 + Aeration	37.8 ± 32.3

Concentrations of NO_3-N in the limnocosms increased from about 0.05 mg/L to ~0.15 – 0.2 mg/L upon recycled water addition at the intermediate (estimated 1:20) rate, but decreased rapidly over the next week or so (Fig. 10). After one week, the NO_3-N levels in the limnocosms with recycled water added were very similar to the control.

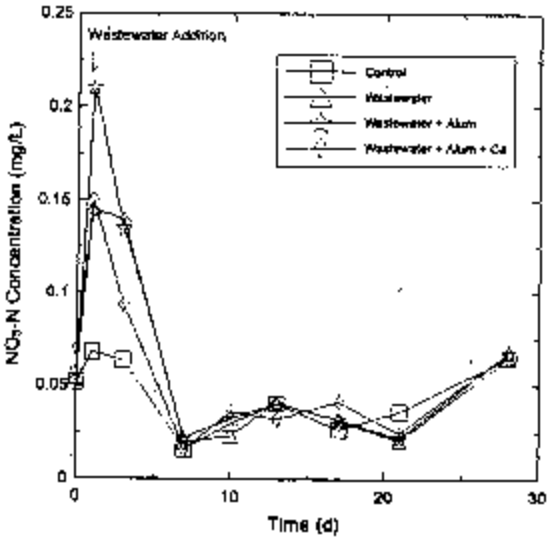

Fig. 10. Mean NO_3-N concentrations vs. time: limnocosms.

Phosphate-P concentrations did not exhibit any clear long-term trends over time. Concentrations generally increased following recycled water addition, but then decreased before increasing again after about 3 weeks (Fig. 11). The reasons for these oscillations in P concentrations are unclear, but it can be shown that the measured P concentrations are consistent with levels expected resulting from the intermediate levels of recycled water addition used in the study.

Assuming a target 1:20 mixture of recycled water and Lake Elsinore water and an initial NO_3-N concentration in the recycled water of about 8 mg/L (the concentration previously measured for EVMWD treatment plant effluent), one predicts an NO_3-N concentration of about 0.4 mg/L in the limnocosm. The concentrations in the limnocosms following recycled water addition were ~0.15 – 0.2 mg/L (Fig. 10), so it appears that the mixing ratio was closer to 1:50. With a recycled water concentration of approximately 2 mg/L PO_4-P, a 1:50 dilution (based upon NO_3-N) should yield a limnocosm PO_4-P concentration of about 0.040 mg/L. Since concentrations were 0.02 - 0.03 mg/L (Fig. 11), it may be that the PO_4-P level in the recycled water added to the limnocosms was somewhat less than 2 mg/L, although rapid PO_4-P removal might also be possible.

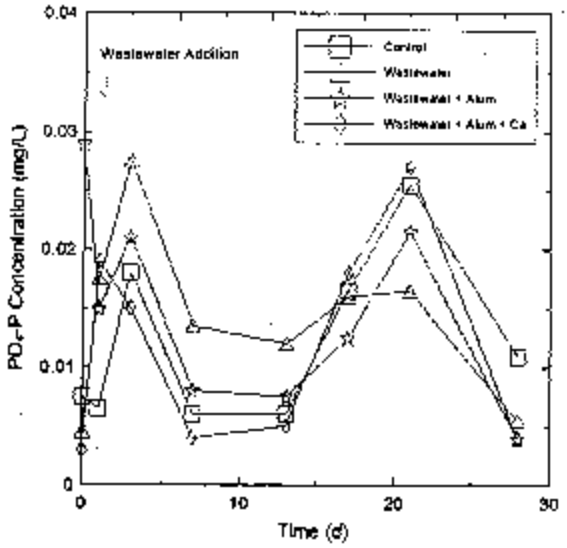

Fig. 11. Mean PO_4-P concentrations vs. time: limnocosms.

The highest recycled water addition rate (estimated 1:4) yielded the highest dissolved nutrient levels of any of the limnocosms immediately following addition, although the concentrations rapidly decreased over time (Fig. 12).

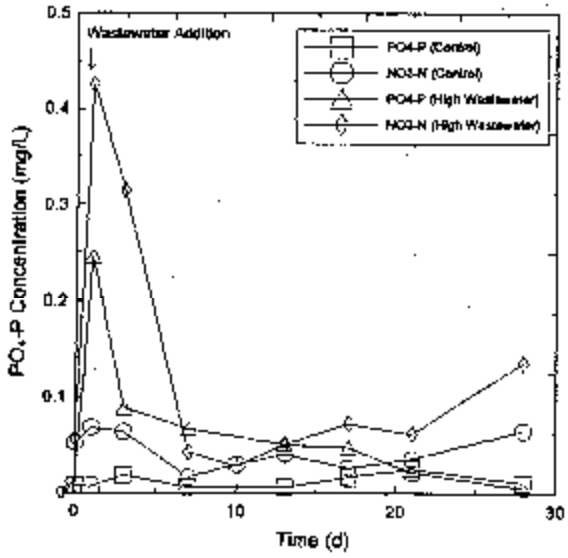

Fig. 12. Mean NO_3-N and PO_4-P limnocosm concentrations: high recycled water vs. control.

The observed decreases in dissolved N and P over time were used to calculate uptake/removal rate coefficients for NO_3-N and PO_4-P. Both N and P removal increased with increasing initial concentration (Figs. 10 and 12), and in fact reasonably fit first order kinetics (Table 5).

Table 5. Nitrate-N and PO_4-P uptake/removal rate coefficients and half-lives.

Nutrient	k (d^{-1}) ± 1 s.d.	$t_{1/2}$ (d)
NO_3-N	0.16 ± 0.02	4.3
PO_4-P	0.11 ± 0.02	6.3

Total P concentrations followed the same temporal trends as PO_4-P, although total P concentrations were generally about 0.1 mg/L higher (Fig. 13). Total P in the water column, collected at the time of limnocosm sampling, was about 0.15 mg/L, while soluble reactive PO_4-P averaged 0.014 mg/L. Total P in the untreated (control) limnocosms averaged approximately 0.10 mg/L (Fig. 13), considerably higher than the soluble PO_4-P levels found (Fig. 12). Total P concentration increased approximately 4x immediately after recycled water addition at the highest rate to 0.28 mg/L although, like soluble PO_4-P, subsequently decreased over time (Fig. 13). The decrease in total P in the recycled water-treated limnocosms is consistent with decreased chlorophyll (Fig. 8), increased Secchi depth (Fig. 7), and development of significant attached algal biomass (Fig. 9, Table 4).

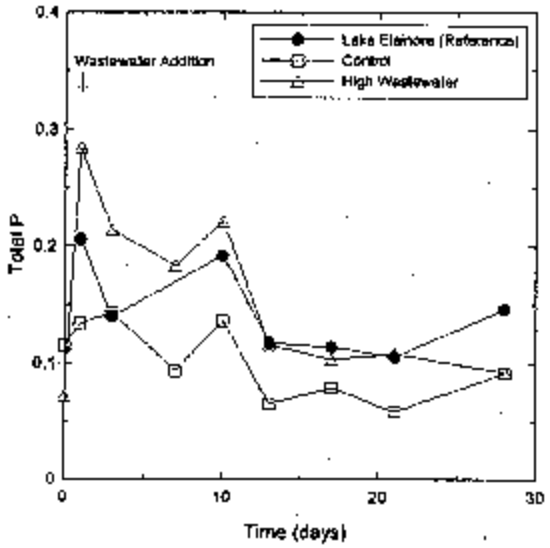

Fig. 13. Mean total P limnocosm concentrations: high recycled water vs. control

Discussion

Results from these studies indicate that the proposed restoration and management practices will have a significant effect on water quality in Lake Elsinore. Recycled water addition to water samples resulted in substantial (5-12x) increases in chlorophyll concentrations over 4 days incubation when compared to an unamended control. In separate nutrient addition experiments, chlorophyll production was associated with PO_4-P additions. Nitrate-N and NH_4-N additions were not found to have any substantive effect on chlorophyll levels. These results indicate that the lake is P-limited in the late summer, and further suggest that recycled water supplementation to the lake, in the absence of prior nutrient removal or other mitigation measures, will likely result in potentially chronic algal blooms and further degradation of the water quality in Lake Elsinore.

Column experiments demonstrated significant PO_4-P and NH_4-N release from the fine organic sediments dominating the lake bottom. Under low DO conditions (<1 mg/L), flux of PO_4-P and NH_4-N averaged 8.8±0.7 and 86±11 mg/m^2/d, respectively. Internal loading of PO_4-P from the sediments was significantly reduced with aeration and with metal salt additions. Alum was the most effective treatment for reducing P internal loading, completely stopping release from the sediments over the duration of the study (flux rate of -0.2 mg/m^2/d). Calcium treatment reduced PO_4-P flux to 2.9±0.1 mg/m^2/d (67% reduction) under low DO conditions, while aeration (DO ~7 mg/L) reduced PO_4-P release to 5.4±0.7 mg/m^2/d (39% reduction). Alum treatments were effective regardless of aeration state, while calcium additions were more effective under aerated conditions (1.1±1.0 mg/m^2/d) than non-aerated. Aeration may decrease CO_2 accumulation near the sediments and thus decrease local $CaCO_3$ solubility. There were no additional benefits from addition of calcium and alum when compared with alum treatment alone. Ammonium flux was high (86±11 mg/m^2/d under low DO conditions) and largely unaffected by aeration (78±19 mg/m^2/d) and metal salt additions (*e.g.*, 82±28 mg/m^2/d with alum).

The measured rates of PO_4-P and NH_4-N release from sediments can be compared with rates determined in other studies. For example, preliminary measurements of anoxic nutrient flux conducted by this investigator in March, 2000 yielded flux rates of 19.2±9.3 and 62.2±13.5 mg/m^2/d for PO_4-P and NH_4-N, respectively (Table 6). More recently, Beutel (2000) reported PO_4-P release rates under anoxic conditions that ranged from 7.7 – 26.6 mg/m^2/d (mean value of 17.0±6.5 mg/m^2/d). Beutel (2000)

observed a strong seasonal trend in PO_4-P flux, with flux decreasing from an average value of 24.1 mg/m^2/d in July to 9.5 mg/m^2/d in September. The PO_4-P release rate of 8.8 mg/m^2/d measured in this study for samples collected in October is below the values from other studies (Table 6), but is consistent with the seasonal trend noted by Beutel (2000). NH_4-N release rates were generally in good agreement across all studies (Table 6).

Table 6. Nutrient release rates under anoxic conditions.

Source	PO_4-P	NH_4-N
	— mg/m^2/d —	
This study	8.8 ± 0.7	86 ± 11
Anderson (2000)	19.2 ± 9.3	62 ± 14
Beutel (2000)	17.0 ± 6.5	90 ± 27
Montgomery-Watson (1997)[a]	15.9 ± 4.8	79 ± 15

[a]Taken from Fig. C-8, 4-8 days

In addition to temporal variation in nutrient flux, some of the differences in measured nutrient release rates in Table 6 may also be due to spatial variation. Beutel (2000) reported release rates for three sites within Lake Elsinore that varied by up to 20 – 30%. Spatial variability in sediment properties has been explicitly evaluated as part of the Lake Elsinore TMDL project sponsored by the SARWQCB. Sediment sampling conducted July 27 - August 2, 2000 demonstrated significant spatial variability in porewater N and P concentrations (Fig. 14a, b). Work is ongoing to better define the spatial and temporal variations in porewater chemistry and impacts on internal loading of nutrients.

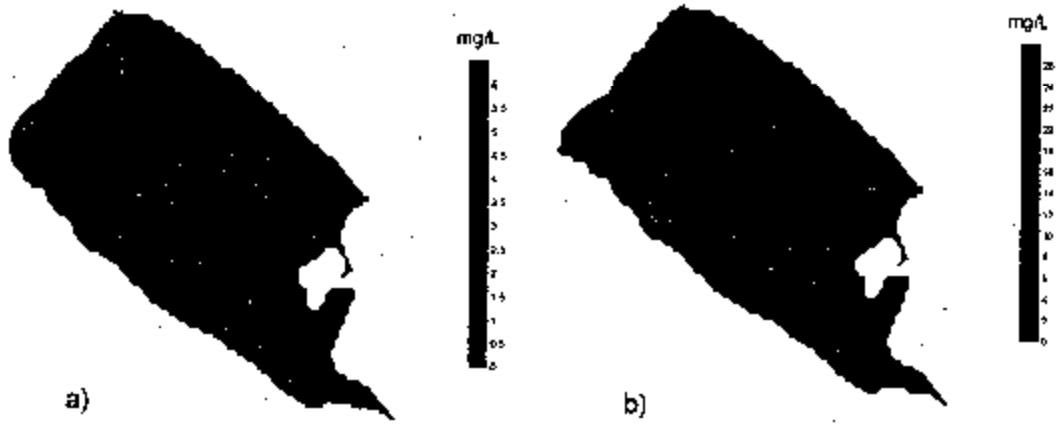

Fig. 14. Porewater concentrations (mg/L) on samples collected 7/27- 8/2/2000: a) PO_4-P, and b) NH_4-N

Aerated conditions decreased the rate of PO_4-P release relative to anaerobic conditions, although N release was largely unaffected (Table 2). This can also be compared with recent findings of Beutel (2000) (Table 7), although it is important to consider differences in experimental design. Following Moore *et al.* (1998), Beutel initially aerated fresh samples for 12 days, then scrubbed O_2 out of the system by purging with N_2 for 9 days, and followed with a subsequent 6 day aeration. In this study, a series of cores were collected, with triplicate sets of cores subjected to various treatments (*e.g.*, aeration, alum addition) and referenced against a set of triplicated cores that were sealed against O_2 invasion that quickly reached DO concentrations <1 mg/L. The appropriate comparison between Beutel (2000) and this study, then, is during the initial phase when fresh core samples were brought into the lab and aerated. During this period, PO_4-P concentrations increased (Beutel, 2000, Fig. 7), yielding flux rates of 0.1 – 5.44 mg/m^2/d, with an average value of 2.23 mg/m^2/d (Beutel, 2000). Jar tests conducted by Montgomery-Watson (1997) also revealed PO_4-P release under oxic conditions (Table 7).

Table 7. Nutrient release rates under oxic conditions.

Source	PO_4-P	NH_4-N
	— mg/m^2/d —	
This study	5.4 ± 0.7	78 ± 19
Beutel (2000)	2.2 ± 2.0	85[a]
Montgomery-Watson (1997)[b]	4.4 ± 1.4	NA

[a]Taken from Fig. C-8, 4-8 days
[b]Taken from Fig. C-6, 4-8 days

Ammonium-N concentrations increased to 3 – 5 mg/L over a period of 5-7 days both in this study (Fig. 6) and in that of Beutel (2000) (Beutel, Fig. 7). Subsequent decreases in NH_4-N concentration after 5-7 days corresponds with increased NO_3-N concentrations, and are due to nitrification reactions. No evidence for increased NO_3-N production was observed under low DO conditions.

The observation of significantly reduced rates of PO_4-P release following Ca^{2+} addition relative to low DO (control) and even aerated conditions is noteworthy. Although not as effective as alum (Table 2), Ca was applied at a lower rate than Al (50 vs. 100 g/m^2/d). The mechanism of P retention in the Ca treatments is somewhat different than alum, however. In alum addition, PO_4 forms a strong surface complex with the hydrous

oxide formed from Al hydrolysis, specifically displacing surface hydroxyls through a ligand exchange process. In Ca treatment, one shifts the equilibrium such that $CaCO_3$ precipitates out of solution, and PO_4-P then adsorbs or co-precipitates with the $CaCO_3$ solid phase. While the potential for Ca and other metal salts to have beneficial effects on internal loading of P has been suggested, the efficiency and long-term stability of such associations have not been thoroughly investigated. Additional work would be needed before the role of Ca treatment as a P mitigation measure can be fully understood.

Limnocosm experiments demonstrated improved water quality associated with changes from a phytoplankton- to periphyton-dominated ecosystem. Secchi depths (transparencies) increased from ~0.8 m to >2 m with concomitant decreases in chlorophyll a concentrations. Recycled water additions resulted in short-term (<7 d) increases in dissolved and total nutrients, but no quantifiable production of phytoplankton biomass.

Recommendations and Conclusions

Based upon the results of these studies, a number of recommendations and conclusions regarding lake restoration can be made. First of all, in the absence of prior nutrient removal or other mitigation measures, addition of significant volumes of recycled water to Lake Elsinore will maintain or exacerbate the water quality problems of the lake. The magnitude of the impact of recycled water addition on water quality can be estimated by comparing internal P loading from the sediments with that resulting from recycled water inputs. Since several different internal loading rates have been reported, the average of the values reported in Table 6 will be used (15.9 mg PO_4-P/m^2/d), with the further assumptions that 60% of the lake sediment releases P to the water column (Fig. 14a), and that most of the release occurs during the warmest 6 months of the year. (It should be recognized that these assumptions are based upon currently available information, and that ongoing work for the SARWQCB will provide additional data defining seasonal and spatial trends.) Subject to these assumptions, one estimates an internal loading of about 23,180 kg P/yr. For comparison, assuming an annual recycled water addition of 3600 af to offset average net evaporative losses, and a recycled water PO_4-P concentration of 2 mg/L, one estimates an external loading of 8860 kg P/yr. Thus, recycled water addition at 3600 af/yr will increase the P loading an additional 38% relative to internal loading. During drought periods where up to 15,000 af might be used,

external loading from recycled water addition can be expected to significantly exceed internal loading. Nutrient removal, especially PO_4-P, from the recycled water and/or other mitigation measures, are thus necessary before significant volumes of recycled water can be added to the lake without further degradation of water quality.

Aeration and metal salt additions can be expected to have significant beneficial impacts on internal loading of PO_4-P and resultant water quality, although N release will not be substantially reduced. Alum addition would be the most effective treatment, and promises to very effectively inhibit internal loading of P, at least in the short term. Calcium addition, while less effective that alum, also holds some promise in reducing P release from sediments. Results from this study indicated that aeration was less effective than alum or calcium additions, although higher PO_4-P removal efficiencies by aeration were reported by Beutel (2000) and Montgomery-Watson (1997). Using the difference between the mean PO_4-P release rate under anoxic conditions (15.9 mg/m^2/d, from Table 6) and oxic conditions (4.0 mg/m^2/d, from Table 7), and the previous assumptions, one estimates a potential offset of 17,400 kg P/year due to aeration. Such an offset is about 2x the P loading that results from recycled water supplementation to the lake under typical conditions. Thus aeration should be able to offset nutrient inputs resulting from recycled water addition under average conditions, although such an offset would fall short of the P-loading from recycled water at the highest additions in the absence of additional mitigation measures. Thus other mitigation measures (*e.g.*, alum addition, wetlands filtration) would be necessary to improve lake water quality (Horne, 2000).

References

Anderson, M.A. 2000. Internal Loadiing and Cycling of Nutrients in Lake Elsinore.. A Grant Proposal to the Santa Ana Regional Water Quality Control Board. 14 pp.

APHA. 1989. Fluorometric Determination of Chlorophyll a. 10200 H.3. In *Standard Methods for the Examination of Water and Recycled water. 17th ed.* p. 10-34.

Beutel, M. 2000. Lake Elsinore Sediment-Water Interface Study. Final Report to Montgomery -Watson. 27 pp.

Horne, 2000. Enhancement of Lake Elsinore: The Seven Component Management Plan. Draft Report.

Montgomery-Watson. 1997. Lake Elsinore NPDES Permit Feasibility Study. Final Phase I Technical Report.

Moore, P.A., K.R. Reddy and M.M. Fisher. 1998. Phosphorus flux between sediment and overlying water in Lake Okeechobee, Florida: Spatial and Temporal Variations. *J. Environ. Qual.* 27:1428-1439.

Appendix

Algal Response to Recycled Water Additions - Winter

The availability of recycled water dictates that any additions to offset the net evaporative losses from Lake Elsinore will occur principally during the winter months. In the main body of the report, results from an evaluation of algal response were presented for recycled water addition during the late summer, where substantial algal growth was observed. Given the lower light intensity, shorter photoperiod, and reduced temperatures present during the winter months, an additional study of algal response to recycled water additions was conducted.

For this study, approximately 25 L of water from Lake Elsinore was collected on Dec. 13, 2000. About 6 L of recycled water was also collected from the effluent of the EVMWD. Samples were treated as described previously, with approximately 0.6 L of lake water decanted into a series of plastic vessels. Samples were spiked to known concentrations of recycled water (1:30, 1:10 and 1:3 v/v) and then placed in a growth chamber at 15 °C with a daily ~9 h illumination period. These conditions reasonably represented the conditions present at the lake at the time of sampling. As before, recycled water concentrations were selected to reflect the range of relative volumes that may be added to the lake, ranging from minimal inputs as would be likely during wet years, to more average conditions (~1:10), and to drought conditions, where up to ~30% of the lake volume could be supplied by recycled water. Duplicate samples were then taken daily for 5 days and promptly analyzed for chorophyll a.

The chlorophyll a concentration at the time of sampling was approximately 70 µg/L; this level was higher than levels found earlier in the fall, and consistent with the visual observation of high algal turbidity at the time of sampling. Chlorophyll a concentrations remained near 70-80 µg/L over the incubation period in the control samples (Fig. A1). Additions of recycled water at the 1:30 ratio resulted in a limited increase in chlorophyll a concentrations relative to the control, while the chlorophyll a concentration increased to over 150 ug/L when recycled water was added at a ratio of 1:10. At the highest addition, chlorophyll a concentration increased by more than 5x its initial level and exceeded 350 µg/L after 5 days.

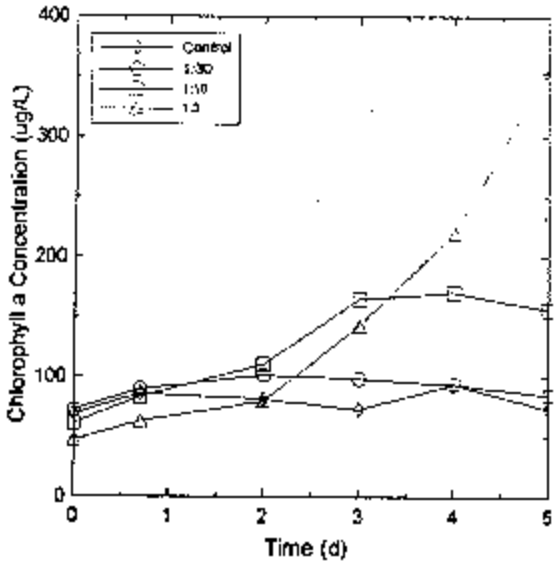

Fig. A1. Chlorophyll a concentrations vs. time following recycled water additions: Dec. 2000.

These results, in combination with the results presented in the main body of the report (*e.g.*, Fig. 3), indicate that the timing of recycled water inputs will not significantly influence algal response to increased nutrient additions.

Sediment Characterization and Alum Dose Determination

Sediment Characterization

The sediments of Lake Elsinore have been recently characterized (Anderson, 2000). In that study, 49 samples were collected from a regular sampling grid shown in Fig. 1. Samples were collected with a Ponar sampler. Locations of sampling sites and the lake margin were recorded with GPS. Depth was also recorded. Sediment samples were placed in 500 mL wide mouth glass jars with screw cap lip and stored on ice until transport back to lab. Sediment was then homogenized and subsampled for porewater analysis and sediment characterization. Results from sediment analyses are presented in Table 1.

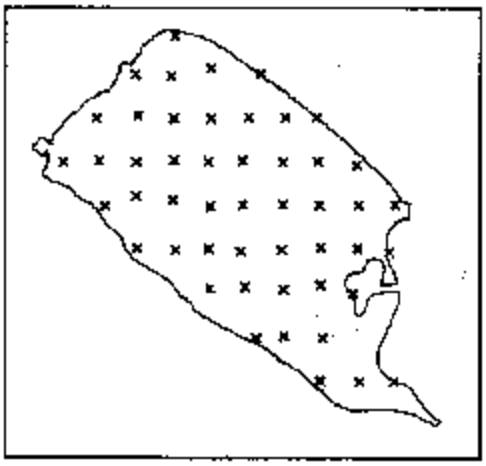

Fig. 1. Sediment sampling sites.

Table 1. Summary of sediment characterization data.

Property	Units	Mean	Std Dev	Median	Min	Max
Sediment						
Sand	%	27.6	33.1	10.8	0.0	95.5
Silt	%	38.7	18.0	43.0	2.2	75.5
Clay	%	33.7	20.2	38.7	2.3	59.6
Total C	%	4.04	2.31	5.4	0.1	6.8
Organic C	%	3.19	1.94	4.3	0.1	5.7
Inorganic C	%	0.85	0.46	0.9	0.0	1.5
CaCO3	%	7.08	3.83	7.7	0.0	12.5
Total N	%	0.36	0.20	0.5	0.0	0.6
Total S	%	0.78	0.50	1.1	0.0	1.3
Total P	mg/kg	760	249	851	44	1113
Inorganic P	mg/kg	524	183	556	37	853
Organic P	mg/kg	236	143	295	3	462

The sediments were generally fine-textured, with significant organic C, $CaCO_3$, and P contents (Table 1). The spatial distribution of total P within the basin is shown in Fig. 2.

The distribution of total P closely followed that of clay content (R^2 = 0.81), organic C (R^2=0.85) and total N (R^2=0.83). High total P levels were generally found in the deeper portions of the lake. As shown in Table 1, the total P in the sediments were principally associated with an inorganic fraction as defined by Aspila *et al.* (1976). In that work, inorganic P was defined as that extracted with 1 M HCl.

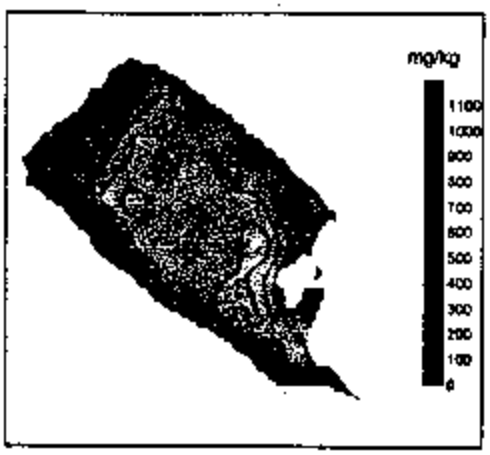

Fig.2. Total P distribution in sediment

Alum Dose Determination

The alum dose for Lake Elsinore sediments was determined using the method of Rydin and Welch (1999). Representative samples were collected from a site near the northwest shore located in about 4 m of water and from the central portion of the lake (~7 m depth). The samples collected near the center of the lake were finely textured organic muck, while the nearshore samples were sandy, coarse textured material. Dry-weight determinations on the fine organic sediment yielded a dry-weight content of 0.13 g dry-weight/g wet weight, while bulk density was measured at 1.13 g/cm^3. Dry-weight and bulk density of the coarse sediment was ~0.6 g dry-weight/g wet-weight and 1.87 g/cm^3, respectively. Triplicate samples were extracted with 1 M NH_4Cl (corresponding to loosely-sorbed P) and 0.11 M $Na_2S_2O_4$/$NaHCO_3$ (defined as mobile Iron-P) (Rydin and Welch, 1999). A significant amount of P was recovered from the fine organic sediment. Loosely sorbed P averaged 85±10 µg/g dry-weight, while Fe-P averaged 188±19 µg/g, for a total mobile inorganic P of the fine organic sediment of 273±32 µg/g. Negligible P was recovered from the coarse sediment (mobile inorganic P of 2.3±1.0 µg/g). This result is consistent with the total P distribution for the lake, which indicates very low total P near the margins of the lake (Fig. 2). Thus, only the fine organic sediments with high total P will be considered an important source of P to the water column. Following Rydin and Welch (1999) and assuming the top 4 cm is the active zone of P release, one calculates an areally-averaged mobile inorganic P content of 1.6 g P/m^2. Assuming an Al:P ratio of 100:1, one then calculates a dose of 160 g Al/m^2. Based upon the observed distribution of total P in Lake Elsinore (Fig. 2), it was estimated that about 60%, or ~2000 acres, of lake sediments are contributing P to the water column. Thus, a total alum dose

of 1280 metric tons (as Al) would be needed to inactivate the mobile inorganic P estimated for the sediments using a 100:1 Al:P ratio. A lower Al:P ratio of 30:1 has been used in some other studies; using such a ratio, the aluminum dose is reduced to 48 g Al/m^2 or a total Al dose to the lake of 384 metric tons.

References

Anderson, M.A. 2000. Internal loading and nutrient cycling in Lake Elsinore. 1st Quarterly Report to the Santa Ana Regional Water Quality Control Board. 10 pp.

Aspila, K.I., H. Agemian and A.S.Y. Chau. 1976. A semi-automated method for the determination of inorganic, organic and total phosphate in sediments. *Analyst* 101:187-197.

Rydin, E. and E.B. Welch. 1999. Dosing alum to Wisconsin lake sediments based on in vitro formation of aluminum bound phosphate. *J. Lake Reserv. Manage.* 15:324-331.