

REMOVAL OF DISSOLVED PHOSPHORUS USING CALCIUM AMENDMENT

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Summary

Previous preliminary research documented the capacity for removal of phosphorus from recycled water with Ca^{2+} amendment via *in situ* CaCO_3 precipitation in Lake Elsinore (Anderson, 2002). In that study, about 90% of the soluble-reactive phosphorus (SRP) in recycled water was removed from solution when recycled water was amended with agricultural gypsum to 200 mg/L Ca^{2+} and then mixed at a ratio of 30% recycled water into lake water.

The purpose of this study was to more carefully quantify SRP removal from solution using Ca amendment. Two different treatment scenarios were assessed: (i) amendment of recycled water with Ca, followed by flow into Lake Elsinore, and (ii) treatment of lake water following discharge of potentially high SRP waters from Canyon Lake. In both studies, SRP removal was quantified as a function of Ca dose, added as $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, and ratio of recycled water (or Canyon Lake water) to Lake Elsinore water. In addition, the kinetics of SRP removal was also quantified when $\text{Ca}(\text{OH})_2$ was used rather than $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. Results from field sampling conducted from January – June 2003 at the lake were also compared against Ca^{2+} , Na^+ , alkalinity, and SRP levels predicted using a mass-balance model.

Approach

Recycled Water Tests

Approximately 10 L of recycled water was obtained from the recycled water delivery channel upstream of the lake in mid-February 2003. An equal volume of Lake Elsinore water was also collected. The waters were returned to the lab and used to prepare a series of 7 different solutions of varying recycled water compositions. The relative volume of recycled water to lake water was varied from 0, 10, 30, 50, 70, 90 and 100 % in a series of 1-L plastic beakers. The waters were allowed to equilibrate overnight. Four different Ca^{2+} doses (0, 50, 100 and 200 mg/L Ca^{2+}) were then added to the series of waters using agricultural gypsum. Thus, a total of 28 different solutions were prepared (7

different recycled water ratios x 4 different Ca^{2+} doses). Samples from each of the solutions were taken after 0 (*i.e.*, before Ca^{2+} addition), 1, 5, 24 and 77 h, filtered through a 0.45μ polycarbonate filter, and analyzed for pH, alkalinity, SRP and Ca^{2+} .

Ca(OH)₂ Tests

Separate tests were conducted in which Lake Elsinore water was spiked to ~1 mg/L $\text{PO}_4\text{-P}$ with Na_2HPO_4 and then treated with 100 and 200 mg/L Ca^{2+} as Ca(OH)_2 . Preliminary experiments using Ca(OH)_2 indicated much more rapid CaCO_3 precipitation as compared with $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. As a result, samples were collected at much shorter time intervals (0, 1, 3, 6, 20, and 60 min), filtered and analyzed as described above.

Canyon Lake Water Tests

About 10 L each of Canyon Lake water and Lake Elsinore was collected in August 2003 and brought to the lab for tests as described above in the recycled water tests.

Results

Recycled Water Tests

The measured chemical composition of the different waters (0-100% recycled water) following overnight equilibration and prior to Ca^{2+} addition varied quite substantially (Table 1). The pH of the Lake Elsinore water was 8.80, while the pH of the recycled water in the delivery channel prior to entry into the lake was 8.20. The pH of the blended waters decreased with increasing % recycled water. Electrical conductance (EC) also varied, from 3.78 to 1.27 mS/cm for the lake water and recycled water, respectively (Table 1). The measured EC of the blended waters followed very closely the predicted EC assuming conservative behavior using the 2-member (lake and recycled water) mixing model, with an average deviation from ideal mixing <0.3% (Fig. 1). Thus, chemical changes associated with mixing the 2 waters were not substantial enough to alter the EC of the blended waters. Alkalinity ranged from 12.06 meq/L for the lake water to 3.96 meq/L for the recycled water (Table 1), with alkalinities of the blended waters also following ideal mixing behavior (Fig. 1, average deviation <0.1%). Calcium concentrations increased with increasing % recycled water, from 20.6 for the lake water to 64.8 mg/L for the recycled water (Table 1). As with EC and alkalinity, Ca^{2+} followed ideal mixing (Fig. 1). Concentrations of SRP also varied across the water mixtures, from 0.015 – 0.617 mg/L (Table 1).

Table 1. Measured chemical properties of the recycled water-Lake Elsinore test solutions prior to Ca ²⁺ addition (as gypsum).							
Property	% RW						
	0	10	30	50	70	90	100
pH	8.80	8.83	8.78	8.70	8.57	8.40	8.20
EC (mS/cm)	3.78	3.53	3.04	2.54	2.03	1.53	1.27
Alkalinity (meq/L)	12.06	11.12	9.61	8.08	6.34	4.79	3.96
Ca ²⁺ (mg/L)	20.6	24.6	33.2	42.3	51.2	59.8	64.8
SRP (mg/L)	0.015	0.006	0.092	0.243	0.386	0.536	0.617

Interestingly, non-conservative mixing behavior was found for SRP (Fig. 1). Since the other chemical parameters followed very closely the 1:1 line, there is no evidence for CaCO₃ precipitation resulting from mixing of lake water and recycled water; as a result, coprecipitation of SRP with CaCO₃(s) seems unlikely. Rather, it appears that rapid biological uptake of SRP by algae and bacteria are responsible for the observed loss of SRP from solutions at high lake water compositions (low % recycled water). The solutions were covered to exclude light except when sampling so as to minimize algal growth, so luxury consumption of SRP by non-growing algae or heterotrophic bacteria may have occurred in the test solutions.

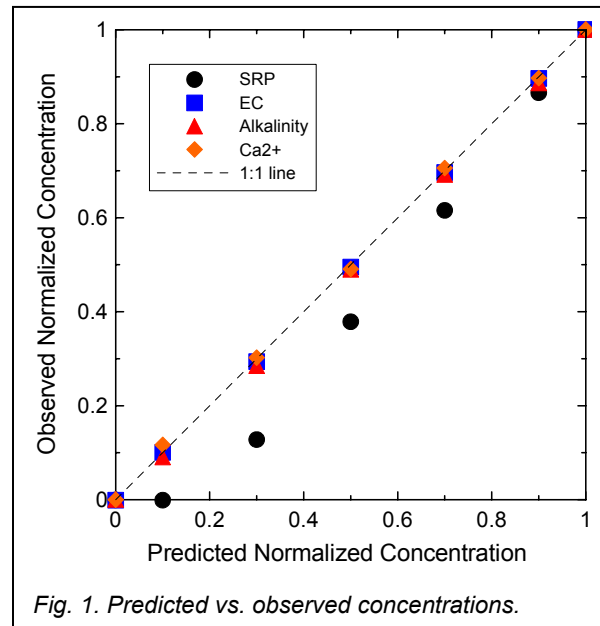
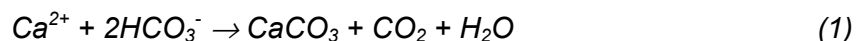
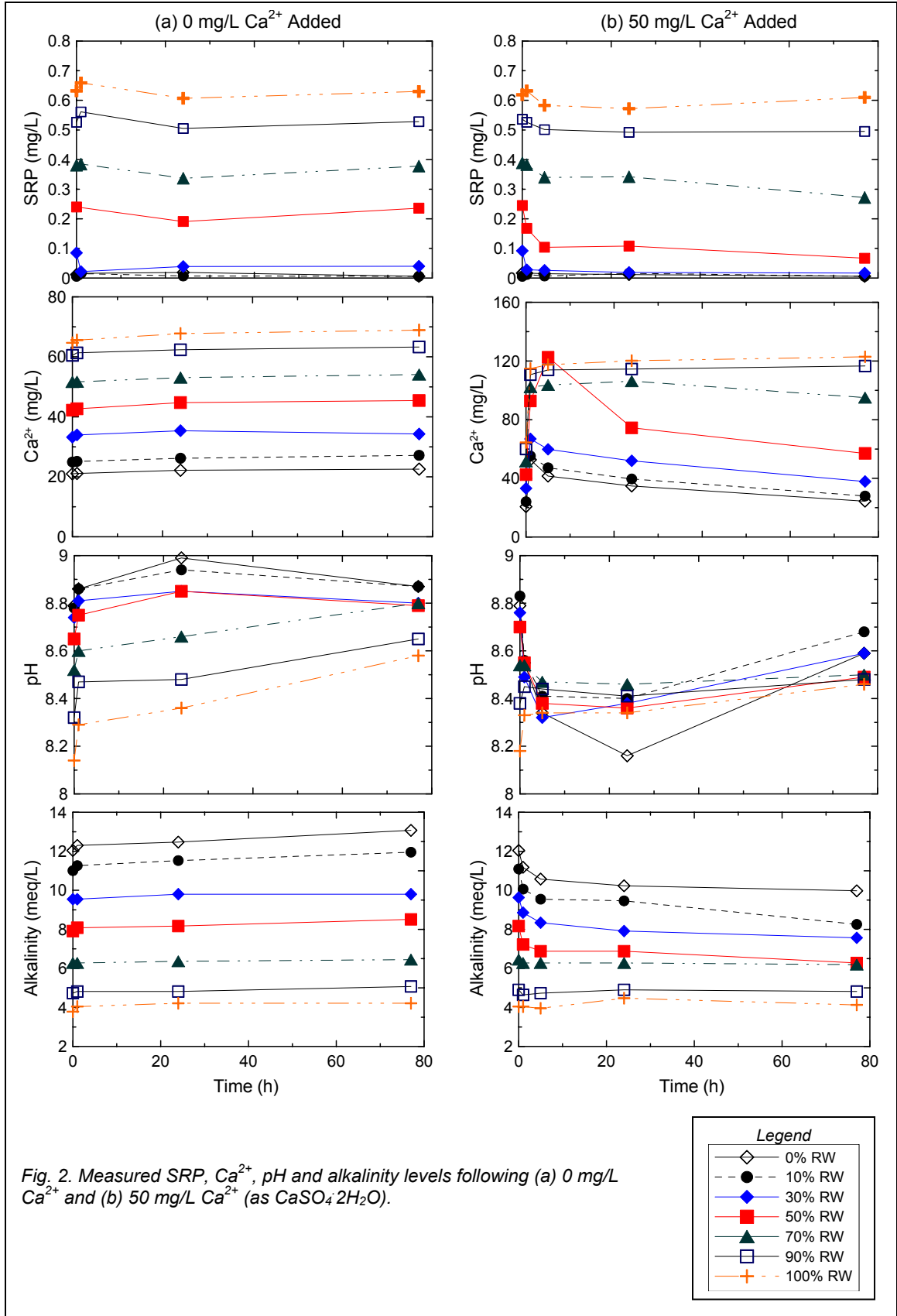


Fig. 1. Predicted vs. observed concentrations.

The waters were then spiked with 0, 50, 100 and 200 mg/L Ca²⁺ as CaSO₄·2H₂O and sampled over the next 3 days to evaluate SRP removal rates and other chemical changes over the next 3 days (Figs. 2-3). Solutions to which no Ca²⁺ was added generally showed no substantial changes in SRP, Ca²⁺ or alkalinity for any of the mixtures, although pH did tend to increase somewhat over time (Fig. 2a). The beakers remained open to the atmosphere since outgassing of CO₂ formed from the reaction:



has been previously recognized as an important factor affecting the pH in solutions undergoing CaCO₃ precipitation (Anderson, 2002).



More substantial changes in all chemical parameters occurred following 50 mg/L Ca^{2+} addition to the various solutions (Fig. 2b). The relative concentrations of SRP decreased most significantly for those solutions with 30-50% recycled water, while only modest decrease was noted for the 70% solution (Fig. 2b, SRP). Very little decrease over time was noted at the highest recycled water levels (and highest SRP concentrations).

Dissolved Ca^{2+} concentrations all increased from their pre-addition levels in Table 1 (shown at $t=0$ in the figures) to about 60-120 mg/L after 1-5 h (Fig. 2b, Ca^{2+}). Dissolved Ca^{2+} levels subsequently declined over the next ~72 h in samples with 70% or less recycled water, while no measured decrease was found in the 90 and 100 % recycled water solutions (Fig. 2b, Ca^{2+}). The extent of Ca^{2+} decline was most significant for the 50% mixture.

The pH of the solutions with 0-70% recycled water all exhibited a decline in pH over the first 24 h following gypsum addition, with the extent of decline closely related to the amount of lake water in the solutions (i.e., the 0% recycled water solution decreased from a pH value of about 8.8 to 8.4, while the 70% RW blend declined from about 8.55 to 8.5) (Fig. 2b, pH). The pH of the 100% RW exhibited an increase (Fig. 2b, pH) comparable to the control (Fig. 2a, pH). The pH values increased for the lowest % RW (most lake water) between 24 and 77 h.

Alkalinity levels decreased approximately 2 meq/L for the 0 – 50 % RW solutions, while very slight reductions were noted for those samples with higher % RW (Fig. 2b, alkalinity). About two-thirds of the reductions took place within the first 5 h. No significant changes in alkalinity were found for the highest %RW treatments when spiked with 50 mg/L Ca^{2+} as gypsum.

The observed temporal changes in Ca^{2+} , pH and alkalinity for the lowest % RW mixtures (highest lake water proportions, and highest pH and alkalinities) are consistent with trends previously noted (Anderson, 2002). Measurement of SRP concentrations on these samples suggests essentially linear partitioning or coprecipitation of SRP into CaCO_3 .

Results from higher Ca^{2+} treatment levels (100 and 200 mg/L) show broadly similar trends over time as described for the 50 mg/L dose, although more dramatic decreases in SRP, Ca^{2+} and alkalinities were found (Figs. 3). For example, at the 70% RW composition, SRP levels declined from an initial level of about 0.390 in the control to 0.272, 0.013 and 0.018 at the 50, 100 and 200 mg/L added Ca^{2+} levels, respectively.

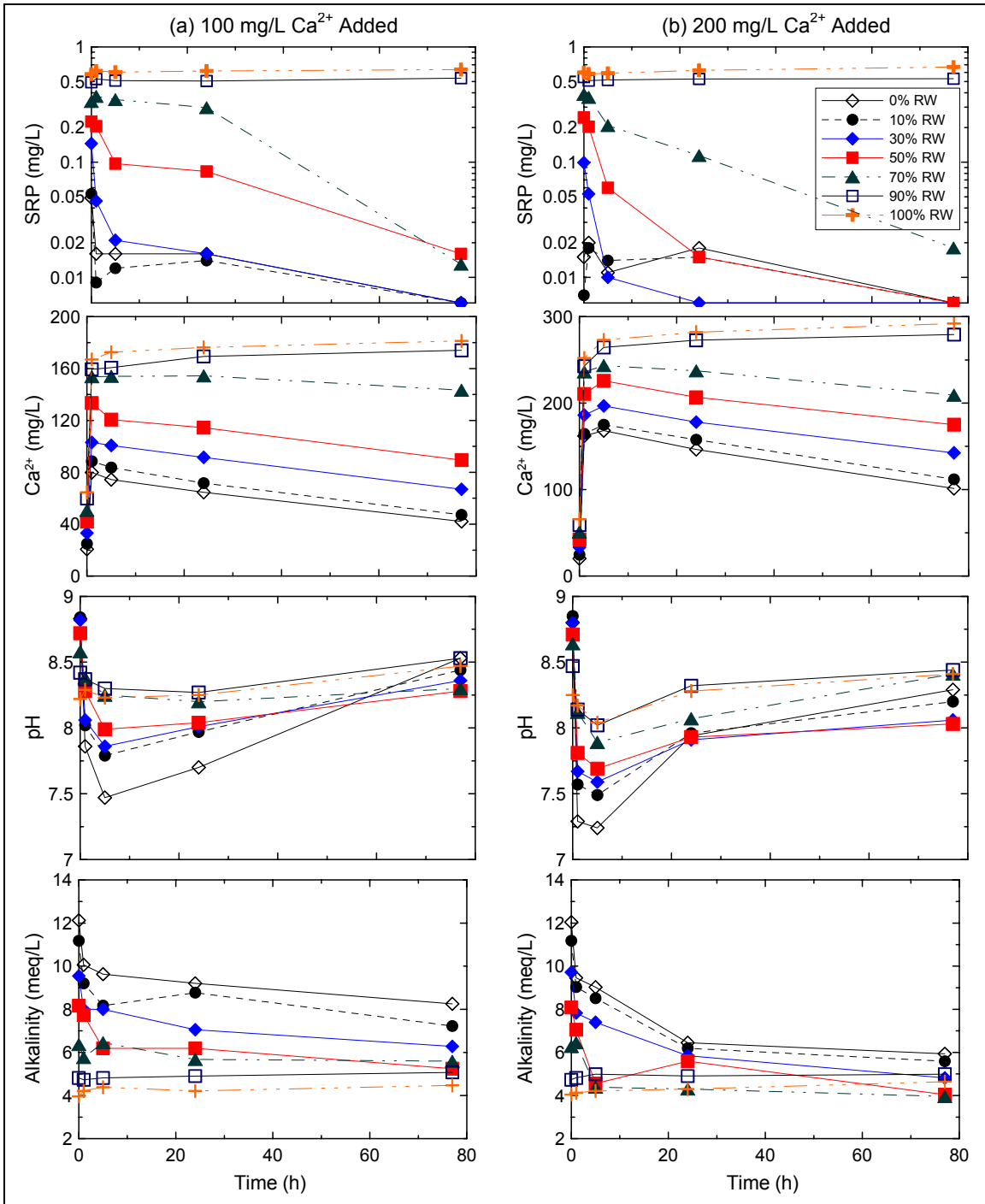
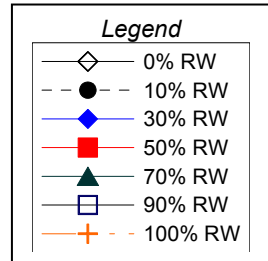
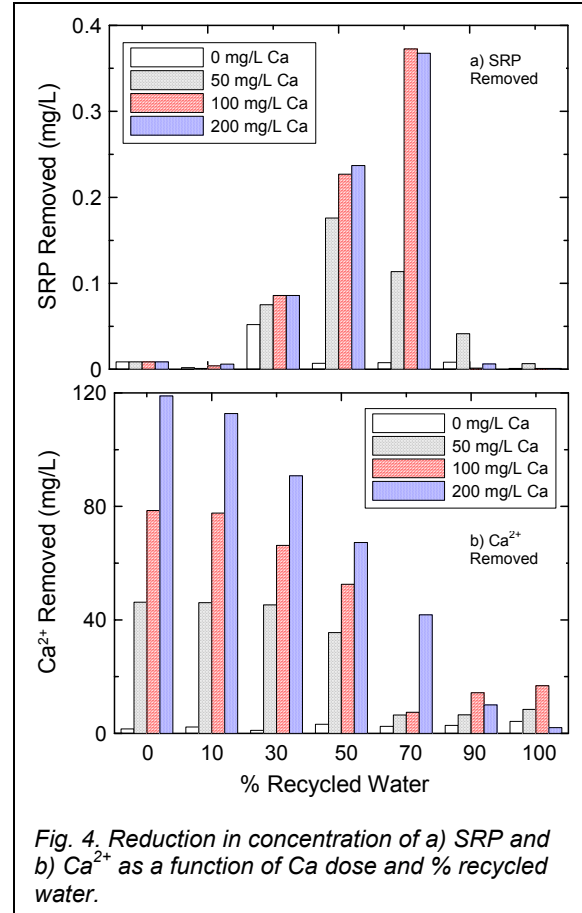


Fig. 3. Measured SRP, Ca²⁺, pH and alkalinity levels following (a) 100 mg/L Ca²⁺ and (b) 200 mg/L Ca²⁺ (as CaSO₄·2H₂O).



Thus, at the higher Ca^{2+} additions, effectively all of the SRP had been scrubbed out of the water. Higher levels of added Ca^{2+} also consumed more of the alkalinity and resulted in lower pH values (Fig. 3). The amount of SRP and Ca^{2+} removed for the different treatments after 77 h is shown more clearly in Fig. 4. As one can see, the amount of SRP removal increased with increasing % recycled water, up to 70 % RW, and then fell sharply at the highest % RW levels (Fig. 4a). The amount of SRP removal also increased with increasing Ca^{2+} dose. In comparison, the amount of Ca^{2+} removed exhibited a somewhat different trend, wherein the amount of Ca^{2+} removed decreased with increasing % RW (Fig. 4b). Not unexpectedly, the amount of Ca^{2+} removed also increased with increased Ca^{2+} dose. Alkalinity exhibited similar trends (data not shown).



The amount of SRP and Ca^{2+} removed across these various treatments is related to the degree of supersaturation the water has with respect to $\text{CaCO}_3(\text{s})$. A convenient measure of this degree of supersaturation, and hence the potential for CaCO_3 formation and SRP coprecipitation, was estimated using the relationship:

$$SI = \log \left(\frac{\gamma_{\text{Ca}} [\text{Ca}^{2+}] K_{a2} \gamma_{\text{HCO}_3^-} [\text{HCO}_3^-] / 10^{-\text{pH}}}{K_{sp}} \right) \quad (2)$$

where SI is the saturation index, γ is the activity coefficient, K_{a2} is the acidity constant for the bicarbonate species, $[\]$ represent the dissolved ion concentration, and K_{sp} is the solubility product. To simplify these calculations, average activity coefficients representative of the typical solution conditions were used, as well as the assumption that all of the measured alkalinity could be assigned to the bicarbonate species. Ion

pairing and other solution complexation reactions were also ignored. The SI was found to vary from about 0.6 to 2.4 for the different treatments; the highest amount of Ca^{2+} removal (Fig. 3b) was found at the lowest % RW and highest SI values (Fig. 5). SRP removal was greatest near 70% RW and the highest initial SI value (Fig. 5a).

Ideally, a full kinetic description of the data in Figs. 2 and 3 would be developed to account for CaCO_3 precipitation and SRP coprecipitation reactions in these solutions. Such a model could then be coupled to a transport-dispersion model, although this effort lies outside of the scope of this project.

Nevertheless, the findings of this phase of the study reaffirm the rather slow approach to equilibrium following addition of Ca^{2+} as gypsum, requiring hours to days to approach apparent equilibrium (e.g., Fig. 3). Moreover, removal of SRP was found to follow CaCO_3 precipitation kinetics, with SRP concentration declines coinciding with losses of alkalinity and Ca^{2+} (Figs. 2-3). Normalized to the amount of Ca^{2+} in solution, a typical SRP removal rate was approximately $2.8 \pm 1.2 \mu\text{g SRP/mg Ca}^{2+}/\text{h}$.

$\text{Ca}(\text{OH})_2$ Tests

Separate experiments conducted using $\text{Ca}(\text{OH})_2$ rather than agricultural gypsum reveal much more rapid and more efficient SRP removal (Fig. 6). For example, 200 mg/L Ca^{2+} added as $\text{Ca}(\text{OH})_2$ removed all measurable SRP from a 1.1 mg/L solution within 20 min (Fig. 6), as compared with 24-77 h when added as $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (Fig. 3). Greater than 90% of the SRP was removed within the first 3 min at the 200 mg/L dose (Fig. 6). Somewhat less SRP was removed at the 100 mg/L dose. The calculated initial SI values for the 200 mg/L dose using $\text{Ca}(\text{OH})_2$ was 3.38, indicating a 30x increase in degree of supersaturation (since SI is log scale) as compared with the 200 mg/L gypsum dose.

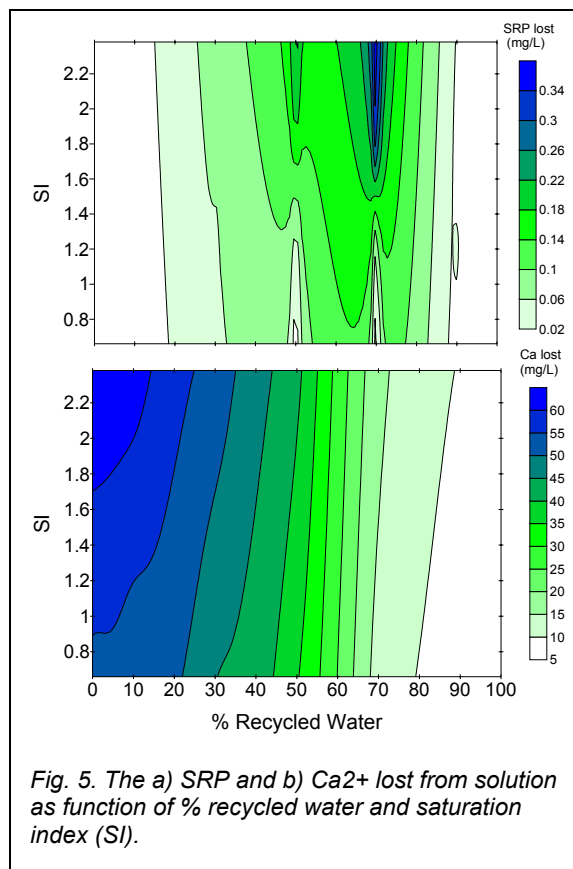


Fig. 5. The a) SRP and b) Ca^{2+} lost from solution as function of % recycled water and saturation index (SI).

Normalized to the amount of Ca^{2+} in solution, an average SRP removal rate using $\text{Ca}(\text{OH})_2$ was approximately $288 \pm 96 \mu\text{g SRP/mg Ca}^{2+}/\text{h}$. Thus, SRP removal was approximately 100x faster using $\text{Ca}(\text{OH})_2$ when compared with gypsum. The average amount of SRP retained per g CaCO_3 formed from $\text{Ca}(\text{OH})_2$ also appeared to be slightly higher than CaCO_3 formed from gypsum

(4.8 ± 1.0 vs. 2.4 ± 0.8 mg P/g CaCO_3 , respectively). Nevertheless, the amount of SRP retained by CaCO_3 formed *in situ* is still an order of magnitude or more lower than the amount potentially retained by $\text{Al}(\text{OH})_3$.

The implications of these findings are fairly clear when one considers that dispersion near the channel outfall is estimated to mix the waters over a time scale of minutes, rather than hours or days. That is, precipitation of CaCO_3 is too slow when Ca^{2+} is added as gypsum for efficient removal of SRP in the recycled water stream. The higher pH conditions fostered by the use of $\text{Ca}(\text{OH})_2$ in lieu of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ increases the degree of supersaturation of CaCO_3 , thereby increasing the rate of CaCO_3 precipitation and SRP removal.

The use of $\text{Ca}(\text{OH})_2$ does not reduce the excess alkalinity in the lake, unfortunately, but it also does not increase the sulfate concentration of the water; this does have some benefit, since it would not increase the amount of sulfate reduction that may take place in the lake sediments. For comparison, adding 100 mg/L Ca^{2+} as gypsum will approximately double the sulfate level in the lake.

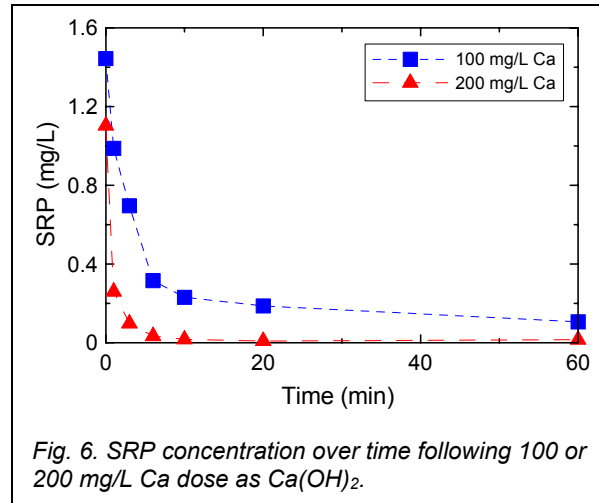


Fig. 6. SRP concentration over time following 100 or 200 mg/L Ca dose as $\text{Ca}(\text{OH})_2$.

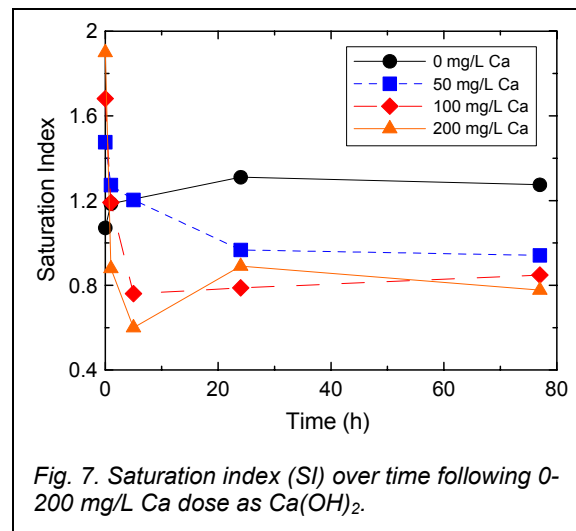


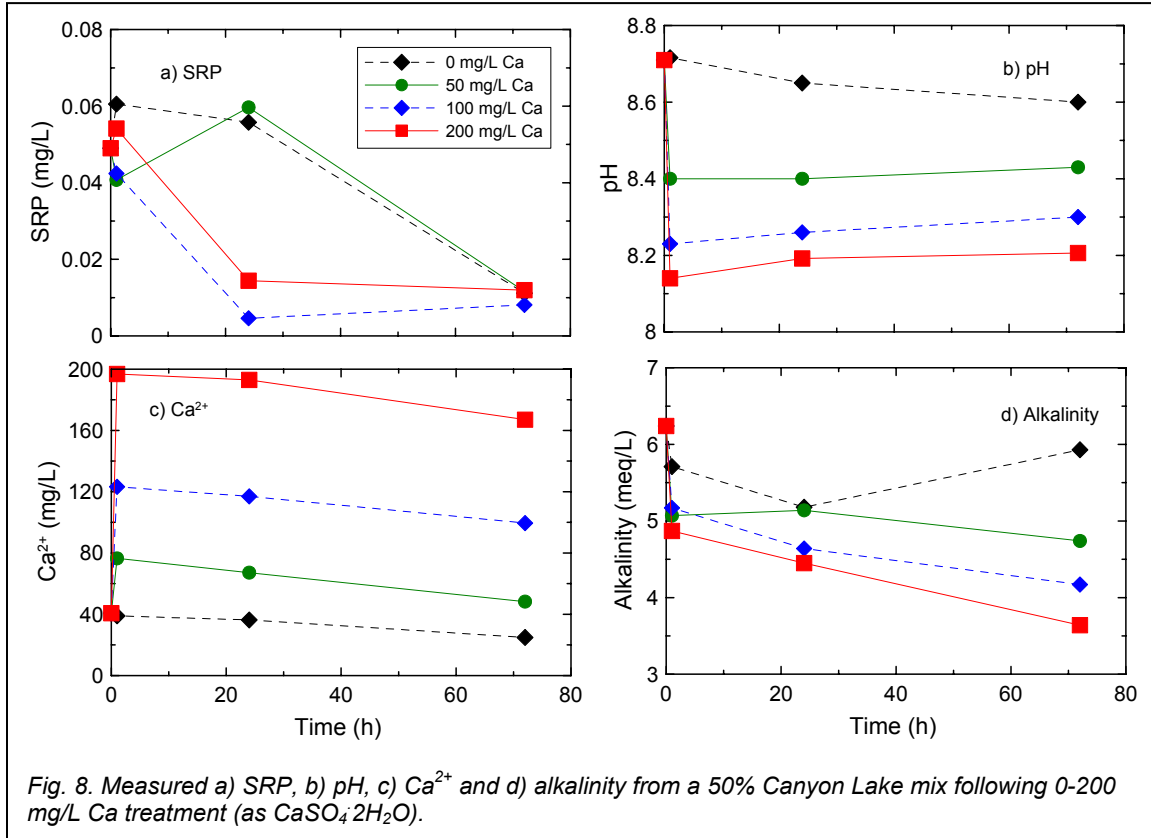
Fig. 7. Saturation index (SI) over time following 0-200 mg/L Ca dose as $\text{Ca}(\text{OH})_2$.

Canyon Lake Water Tests

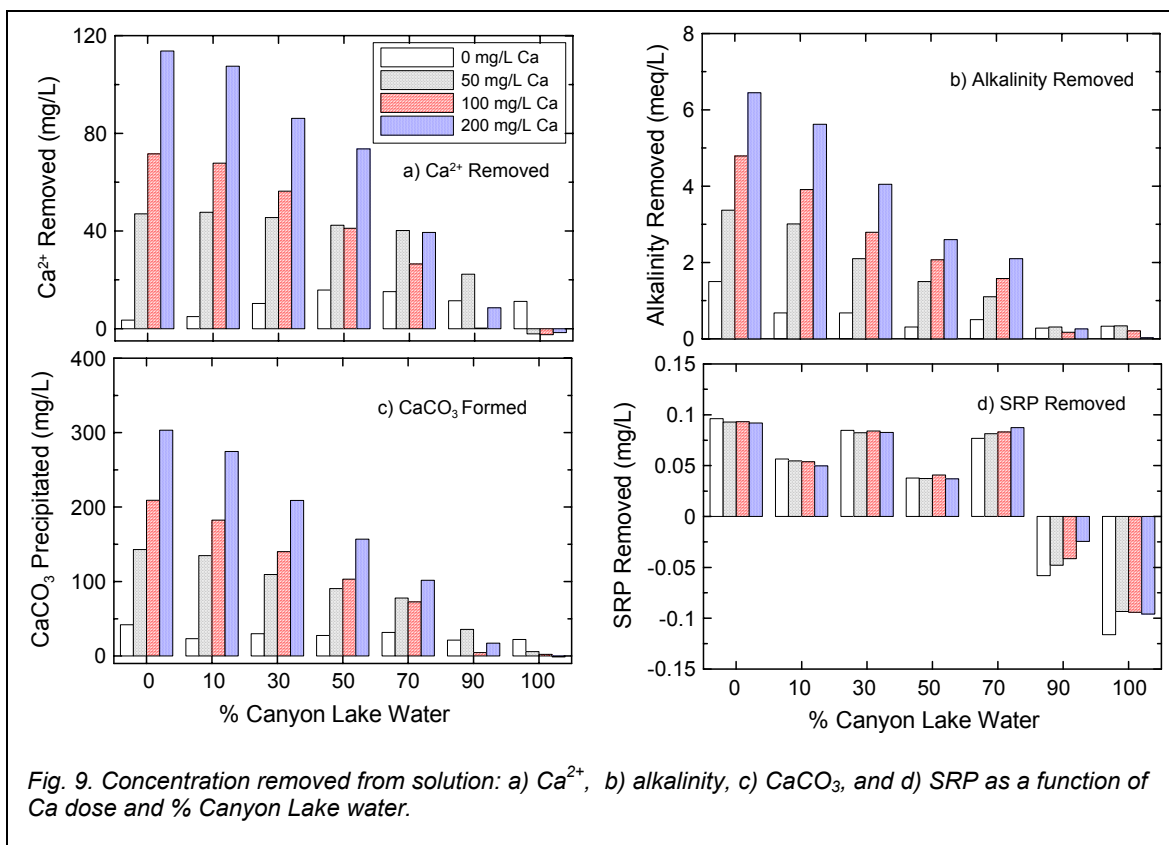
Tests comparable to those described above for the recycled water were also conducted using Canyon Lake water. The chemical properties of the Canyon Lake-Lake Elsinore mixtures prior to Ca^{2+} addition (Table 2) were broadly similar to the recycled water test solutions (Table 1) with the exception of SRP, where much lower levels were found. The pH, EC, and alkalinity all declined monotonically with increasing percent Canyon Lake water, while dissolved Ca^{2+} concentrations increased, reflecting the relative differences in the chemical composition of the 2 lakes. The SRP levels were similar, thus no clear dilution effects were noted (Table 2). Moreover, conservative mixing behavior appeared to be in place for all dissolved constituents, although variability in measured SRP and, to a lesser extent, alkalinity and Ca^{2+} , leaves open the possibility for weak non-conservative behavior for these constituents after overnight equilibration.

Property	% Canyon Lake Water						
	0	10	30	50	70	90	100
PH	8.84	8.78	8.82	8.71	8.69	8.52	8.38
EC (mS/cm)	3.44	3.19	2.77	2.11	1.63	1.09	0.80
Alkalinity (meq/L)	11.4	10.1	7.9	6.2	5.2	3.7	3.1
Ca^{2+} (mg/L)	19.0	24.0	31.8	40.7	53.9	65.9	68.0
SRP (mg/L)	0.107	0.071	0.095	0.052	0.099	0.068	0.073

SRP, Ca^{2+} and alkalinity levels all declined, while pH increased, over time following an initial increase in Ca^{2+} and drop in pH after Ca addition (e.g., Fig. 8). Similar behavior was found in the recycled water tests (Figs. 2 and 3), except that loss of dissolved constituents was also witnessed for the Canyon Lake-Lake Elsinore samples without Ca amendment (Fig. 8). SRP levels declined in all 4 treatments (0 – 200 mg/L Ca doses) from about 0.05 to 0.01 mg/L (Fig. 8a). In contrast, no loss of SRP, Ca^{2+} or alkalinity was seen in the recycled water tests (Figs. 2 and 3). This implies that some natural loss of Ca^{2+} , alkalinity and SRP occurs via precipitation of CaCO_3 when these waters mix. Similar temporal trends were observed for the other solution ratios (data not shown).



The amounts of Ca^{2+} , alkalinity and SRP lost from solution and CaCO_3 formed after 3 days for the different Ca doses and Canyon Lake-Lake Elsinore ratios are shown in Fig. 9. Not unexpectedly, the greatest Ca^{2+} and alkalinity losses occurred for those solutions with the highest Ca dose (200 mg/L) and the lowest amount of Canyon Lake water (highest amount of Lake Elsinore water, 100 %) (Fig. 9a,b). At any given % Canyon Lake water, the amount of Ca^{2+} and alkalinity lost increased with increasing Ca dose. The amount of CaCO_3 formed can be separately estimated from both Ca^{2+} lost (Fig. 9a) and from the alkalinity removed (Fig. 9b); generally good agreement was found for the 50-200 mg/L doses within the 0-70% Canyon Lake water mixtures (often within a few % of each other), although poorer agreement was found in the 0 mg/L Ca dose tests and at the highest (90 and 100%) Canyon Lake water mixtures. Nevertheless, while the average estimated mass of CaCO_3 precipitated (Fig. 9c) necessarily followed quite closely the Ca^{2+} and alkalinity loss results (Fig. 9a,b), SRP removal was not well-correlated with CaCO_3 formation (Fig. 9d). In fact, at the highest % Canyon Lake, SRP was actually released to solution (i.e., negative removal was found) (Fig. 9d).



Lysis of algal cells and mineralization of organic matter appears to release SRP following incubation of Canyon Lake water in the dark, while any release occurring in test solutions with larger relative amounts of Lake Elsinore water apparently resulted in coprecipitation with CaCO₃ forming in these waters.

This SRP behavior deviates from that found using recycled water, where much stronger effects due to Ca dose and % compositions were noted (Fig. 4), although the initial SRP levels present in the Canyon Lake-Lake Elsinore test solutions did not reach the high (up to 0.6 mg/L) concentrations as found in the recycled water tests. Moreover, the Canyon Lake-Lake Elsinore experiments were conducted using water collected in the summer, rather than the spring as was done in the recycled water tests, so a different algal (and microbial) community was in place. Specifically, a mixed diatom-cyanophyte community was in place in the spring, while a blue-green algae (cyanophyte) community dominated by *Oscillatoria* was in place in the summer (data not shown). The luxury consumption apparently in place in the recycled water tests may have also been operating in the Canyon Lake-Lake Elsinore tests as well, with the lower initial SRP concentrations magnifying this effect.

If we ignore possible luxury consumption of SRP by heterotrophic bacteria and algae, one calculates the amount of SRP retained per g CaCO₃ decreased from about 2.3 mg P/g CaCO₃ in the absence of Ca addition, to 0.7, 0.6 and 0.4 mg P/g CaCO₃ for the 50, 100 and 200 mg/L Ca doses. These values compare with mean values of 2.4±0.8 mg P/g CaCO₃ found for in the recycled water tests when gypsum was added, and 4.8±1.0 mg P/g CaCO₃ when Ca(OH)₂ was used.

In addition to these laboratory studies, Ca²⁺ and other major cations, as well as alkalinity and SRP measurements were made on samples collected prior to and following the Canyon Lake spill(s) to gain some insight into the chemical changes and possible SRP removal occurring under actual field conditions.

The total daily inflow from the three major sources of water (EVMWD, EMWD and Canyon Lake) is shown in Fig. 10a. Two major spills from Canyon Lake rapidly added significant quantities of water to the lake (Fig. 10a), with Canyon Lake providing an estimated 10,377 af of water to Lake Elsinore (Anderson and Veiga-Nascimento, 2003). Smaller amounts of water were input from EMWD and EVMWD (an estimated 1,350 and 3459 af, respectively, for the July 2002 – June 2003 period) (Anderson and Veiga-Nascimento, 2003).

The chemical composition of each of these 3 source waters were combined with flow information (Fig. 10a), precipitation and evaporation data (CIMIS, 2003), initial lake volume and initial lake chemical composition to develop a model of the predicted chemical evolution of Lake Elsinore for the period January 1 – June 30, 2003. The Na⁺ concentration in the lake was predicted to decrease quite dramatically following the Canyon Lake release that began on February 25th, from about 680 mg/L down to 540 mg/L (Fig. 10b). Releases from EMWD shortly prior to and overlapping with this same time period yielded a less substantial although still perceptible predicted reduction in Na⁺. A second release from Canyon Lake occurred on March 15 – 18 that further reduced the predicted Na⁺ concentration in the lake from 540 to 480 mg/L. Following these inputs, as well as the steady, low discharge rate from EVMWD (11 af/d), dissolved Na⁺ was predicted to increase slowly as a result of evapoconcentration effects (Fig. 10b). Discrete samples collected from 3 m depth near the center of the lake yielded Na⁺ concentrations that followed quite closely the predicted concentration over time (Fig. 10b). Thus, for a generally conservative ion such as Na⁺, the model did a good job of reproducing observed levels in the lake.

Alkalinity was also found to be reasonably reproduced by the model (Fig. 10c), suggesting conservative behavior for this species as well. In contrast, however, observed Ca^{2+} concentrations were 10-15 mg/L lower than those predicted following the spring runoff events, indicating a net loss of Ca^{2+} from the water column (Fig. 10a). It is known that the high alkalinity of Lake Elsinore promotes precipitation of CaCO_3 , although loss of Ca^{2+} should correspond with a loss of alkalinity. This apparent contradiction (i.e., non-conservative behavior for Ca^{2+} but apparent conservative behavior for alkalinity) can be reconciled by considering 2 points. First of all, the high concentration of alkalinity in the lake relative to its Ca^{2+} concentration would tend to obscure modest changes in alkalinity resulting from loss of Ca^{2+} from solution. For example, a loss of 10 mg/L Ca^{2+} from solution by precipitation as CaCO_3 represents a 25% reduction in the dissolved Ca^{2+} concentration, but only a 5.9 % reduction in alkalinity (0.5 meq/L lost against a background concentration of 8.5 meq/L).

The large relative loss of Ca^{2+} from solution can be seen in Fig. 11, where the relative (observed/predicted) concentration of Ca^{2+} declines in March and again in June (when evaporation rates increase), while Na^+ and alkalinity deviate comparatively little from the conservative line (observed/predicted concentration of 1.0). Nevertheless, some deviation was noted; for example, the concentration ratio for alkalinity ranged from 0.94 – 1.06, so a 5.9% deviation between

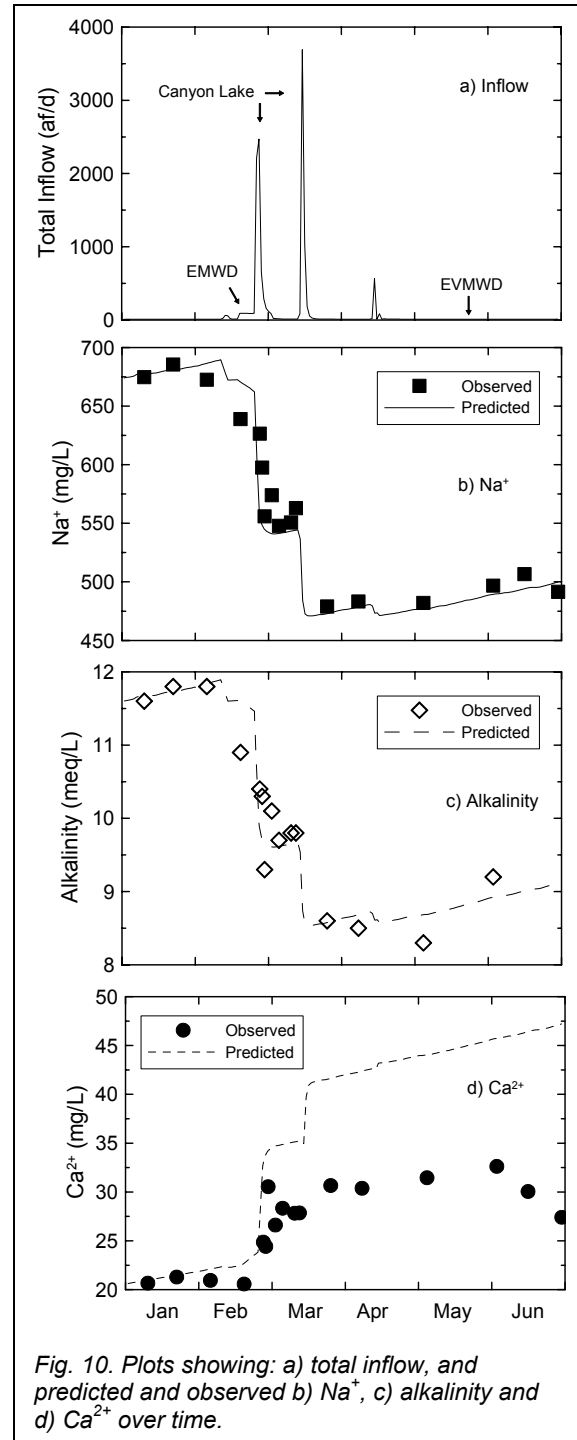


Fig. 10. Plots showing: a) total inflow, and predicted and observed b) Na^+ , c) alkalinity and d) Ca^{2+} over time.

measured and predicted concentration is within the observed range. Moreover, these model calculations consider only water column interactions, although alkalinity production and release from the sediments is a potentially important long-term source of alkalinity to the water column of Lake Elsinore. For example, it can be shown diffusive flux of alkalinity from sediments with a porewater alkalinity

of 20 meq/L, as commonly found from earlier peeper investigations at the lake (Anderson, 2001), should yield a flux rate of about 30 meq/m²/d. With an average depth of 3.5 m and assuming that 75% of the sediments are capable of providing this level of alkalinity production, this corresponds to a predicted increase in alkalinity of 1.2 meq/L over the 6-month period depicted in Fig. 10c. Thus apparent conservative behavior for alkalinity is not unexpected.

Predicted and observed SRP concentrations varied by a large margin, with predicted SRP concentrations increasing to 0.16 mg/L by June, while observed SRP levels were often below detection (Fig. 12a). (For such samples, it was assumed that the SRP concentration was one-half of the detection limit or 0.004 mg/L). Nevertheless, observed SRP concentrations did edge up in response to both the 1st and 2nd Canyon Lake discharges (occurring at inflection in predicted SRP line), although concentrations subsequently decreased (Fig. 12a). The differences between the observed and predicted SRP concentrations indicate that SRP is very effectively removed from the water column. Unlike Na⁺, Ca²⁺ and alkalinity,

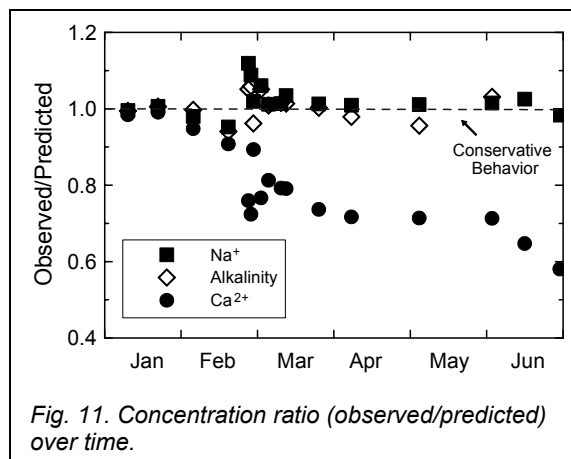


Fig. 11. Concentration ratio (observed/predicted) over time.

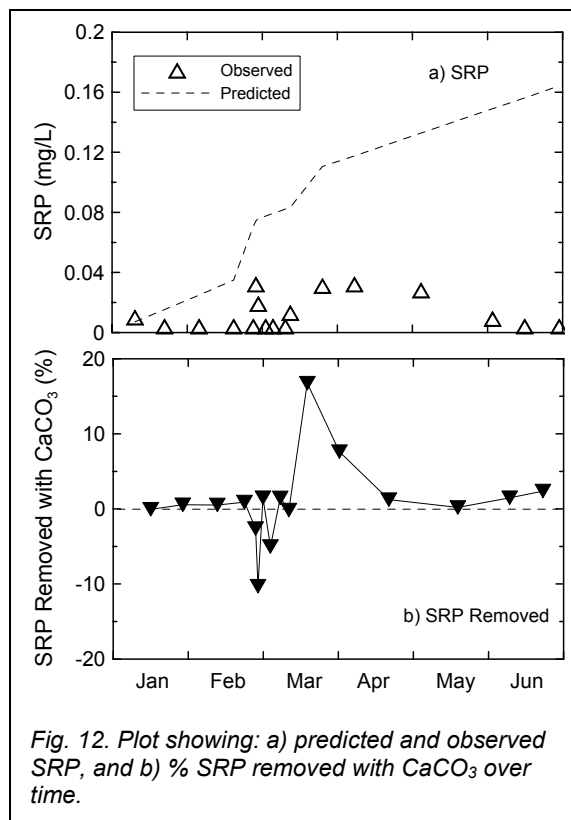


Fig. 12. Plot showing: a) predicted and observed SRP, and b) % SRP removed with CaCO₃ over time.

which are in a sense biologically inactive, SRP is rapidly taken up by algae in the lake. In fact, calculations suggest that only a percent or two of the SRP in the water column would be removed via coprecipitation with CaCO_3 under typical conditions, although about 16% of the SRP removed in mid-March was attributed to coprecipitation with CaCO_3 (Fig. 12b). Using the results from an earlier study evaluating Ca^{2+} addition for removal of SRP from Lake Elsinore water (Anderson, 2002), one estimates that a Ca-dose of 50-200 mg/L in March could have increased the SRP removal by CaCO_3 precipitation from 16% to perhaps as much as 82-94%.

Conclusions and Recommendations

In light of the above findings and other work on the matter, the relative merit of metal salt additions for treatment of the recycled water decreases in the order $\text{Al}^{3+} > \text{Ca}(\text{OH})_2 > \text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. Alum treatment of the recycled water stream followed by solids removal prior to discharge to the lake remains the preferred method, although addition of 100-200 mg/L Ca^{2+} as $\text{Ca}(\text{OH})_2$ to the recycled water stream prior to discharge to the lake will also help reduce SRP levels. Development of a model to help predict the extent of SRP removal may be undertaken to better predict the extent of reduction, although a short-term pilot test would identify more completely the optimal dose for maximizing SRP removal. Use of agricultural gypsum is not appropriate for the recycled water stream, although it could be used for treatment of the whole lake following large external loading events since mixing and dilution would not be an issue.

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