Water Quality Management in Lake San Marcos:
Analysis of Available Data

FINAL REPORT

Submitted to:

City of San Marcos

San Marcos, CA 92069

Submitted by:

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Introduction

Lake San Marcos is a small privately owned reservoir located within the San Marcos Creek watershed in the Carlsbad hydrologic unit. The watershed includes urban, suburban and agricultural land uses, as well as wildlands. The lake suffers algal blooms and has been placed on the 303(d) list for nutrients, ammonia as N and phosphorus. The primary tributary to the lake, San Marcos Creek, is also listed for phosphorus, as well as DDE and sediment toxicity.

Objectives

A review was conducted to (i) analyze available water quality data and related information for Lake San Marcos, (ii) identify, to the extent possible, the factors and processes controlling lake water quality, (iii) identify any gaps in understanding of the limnology, ecology and water quality conditions in the lake, and (iv) to assess the feasibility of various techniques for improving water quality in Lake San Marcos.

Approach

Available data describing water quality conditions of San Marcos Creek and Lake San Marcos have been provided by the City of San Marcos, San Diego County, the San Diego Regional Water Quality Control Board, Vallecitos Water District, City of Escondido, San Marcos Unified School District, Lake San Marcos Community Association, and other private parties. The available documents and data have been compiled into 3 bound volumes totaling 3259 pages. This compendium has been reviewed, with key documents and datasets pertinent to the lake used to develop a summary of historical water quality as well as current conditions. The primary references used in this assessment are identified in Table 1.

Table 1. Primary references used in analysis.

Report	**Topic**	**Sampling Date**	**Compendium Pages**
Ball, 1974	Limnology, water quality	July - November, 1974	CMS 707-725; 2330-2338
Ball, 1979	Fishery	1978	CSM 707-725
Risk Science, 1991	Habitat, biology, water quality	October 1991	CSM 2561-2635 + Appendices
LSM Task Force, 2005	Bacteria, DO, DRP	June 2005	CSM 863-872
SDRWQCB, 2009	Water quality	May 2009	CSM 1023-1043
Anderson, 2009	Limnology, water quality	September 2009	Appendix to this report

Other documents and datasets were also used and have been identified and cited as needed. In many instances, these documents represent memos or short letters, often without clear authorship, and are simply cited by their page number in the compendium.

Results

Lake Basin Characteristics

The physical dimensions of a lake represent important baseline information needed to manage and restore lakes and reservoirs. For example, the area, depth and volume of a lake is needed to develop water and nutrient budgets, design aeration and oxygenation systems, and implement lake management strategies. Lake San Marcos came into being as a 40-acre lake following construction of a small dam on San Marcos Creek in 1946 (CSM000326). The current concrete arch dam was completed in 1962, the shoreline was recontoured, and the lake filled with Colorado River water from the San Diego Canal in 1963 (Ball, 1974). In response to a request from the County of San Diego concerning the elevation-area-volume relationships for the lake (CSM000669), a 1969 DWR memo provided area, capacity and depths taken from a 1952 application indicating a maximum depth of 38.5 ft, a lake surface area of 54 acres and a capacity of 480 acre-feet (CSM000671). This yields an average depth of 8.9 ft (Table 2). Following raising of the dam and other activities, the area, capacity and depth were reported to have increased by 50% or more (e.g., area of 80 acres and capacity of 1200 acre-feet) (LSM Fact Sheet).

Table 2. Basin characteristics reported for Lake San Marcos.

Characteristic	1952[a]	1963[b]	1974[c]	2006[b]
Area (acres)	54.0	80	57.9	NA
Capacity (acre-ft)	480	1200	658.5	NA
Mean Depth (ft)	8.9	15.0	11.4	NA
Maximum Depth (ft)	38.5	54	34	38

[a]DWR, 1969; [b]LSM Fact Sheet; [c]Ball, 1974

Ball conducted a bathymetric survey for the lake in 1974 and found values quite a bit lower than reported however (Table 2). In that survey, he reported the upper part of the lake, representing 78% of the lake surface area, was a constructed basin of rather flat uniform depth between 8-9 ft (CSM000711). The lower portion of the lake located within the natural steep-sided canyon was about 12 acres (22% of the lake area), with an average depth of 20 ft and a maximum depth of 34 ft (CSM000712). These values can be compared with more recent values measured by Norman Peet for the County of

San Diego Department of Public Works on Nov.19-20, 2005 (CSM000896-906). In that survey, lake depth was measured at 19 transects across the short axis of the lake (approximately E-W) with about 15 depth measurements per transect. The maximum depth reported was 27.9 ft at a transect in the southern part of the lake near the dam, while depths were typically 6-8 ft near the middle and upper-middle region of the lake. While the lake surface elevation was not specified in Ball's survey in 1974, assuming similar water levels, it appears that the upper part of the lake has filled in with about 2 ft of sediment in the intervening 31 years. This corresponds to an average sedimentation rate of about 0.8 inches/yr or 2 cm/yr. This sedimentation rate is intermediate between the sedimentation rate of 2.4 cm/yr reported by the USGS for Canyon Lake in southwestern Riverside County for the period 1927-1998 (USGS, 1998), and the average 20th century value of 1.35 cm/yr for Lake Elsinore (Byrne et al., 2004). A higher rate of sediment deposition near the dam is likely to have occurred due to the focusing of fine organic sediments into deeper water (Anderson et al., 2008), although the trend in maximum depth is unclear. A maximum depth of 34 ft reported by Ball (1974) is actually lower than that reported more recently by the LSM Task Force of 38 ft, although a survey transect about 100 ft from the dam conducted as part of the 2005 survey for the County revealed a maximum depth of 27.9 ft (CSM000899).

Infilling of lakes and reservoirs with sediment is a natural process, although accelerated sediment accumulation is commonly found in disturbed watersheds, especially those with significant agricultural activities. Lake San Marcos thus serves as a sediment trap, reducing sediment load to downstream reaches of the impounded San Marcos Creek. In addition to the loss of storage capacity and average depth of the lake, particulate forms of nutrients are also retained in the reservoir. This can lead to long-term biogeochemical recycling of nutrients from the sediments to the water column. Such nutrient recycling can persist for several years, or even a decade or longer in some cases.

<u>Nutrients</u>

Nutrient concentrations have been measured occasionally at the lake, with Ball (1974) offering the most comprehensive look at water quality. In that study, nutrient concentrations and other water quality parameters were measured monthly from July – November 1974. Concentrations reported in that study were averaged across all samples sites and dates for comparison with site-averaged single-day measurements made in 1991, 2005 and 2009 (Table 3).

Nutrient concentrations were very high in 1974, *e.g.*, with the average NO_3-N concentration over 14 mg/L and dissolved reactive phosphorus (DRP) of 1.6 mg/L (Ball, 1974). These very high concentrations of readily bioavailable forms of nutrients indicate that the availability of light, rather than nutrients, regulated phytoplankton abundance in the lake. By 1991, significantly lower nutrient levels were present in Lake San Marcos (Table 3). Dissolved nutrient concentrations were only about 5-10% of those found 17 years prior; total P was also substantially lower (0.37 mg/L, a reduction 85% from 1974) (Table 3). Moreover, relatively little of the total P was in a dissolved form, suggesting P may have been limiting algal growth.

Table 3. Dissolved and total nutrient concentrations in Lake San Marcos – surface samples.

Nutrient	1974[a]	1991[b]	2005[c]	2009[d]	2009[e]
	Jul-Nov (n=5)	*Oct (n=2)*	*Jun (n=1)*	*May (n=3)*	*Sep (n=3)*
NH_4-N	1.07±0.34	0.13±0.03	-	0.16±0.04	0.16±0.13
NO_3-N	14.66±4.92	<0.1	-	0.07±0.03	0.16±0.04
Total N	-	-	-	2.72±0.79	3.14±0.12
DRP	1.64±0.49	0.085±0.035	0.34±na	0.044±0.023	0.064±033
Total P	2.56±0.93	0.37±0.08	-	0.23±0.03	0.16±0.01

[a]Ball, 1974; [b]Risk Sciences, 1991; [c]LSM Task Force; [d]RWQCB, 2009; [e]Anderson, 2009

Following the near-record runoff in early 2005 and resulting problems in the watershed, the measured DRP concentration in June 2005 had increased to 0.34 mg/L. Increases in DRP concentrations were also observed during this time period in other lakes in the region; e.g., DRP concentrations in Lake Elsinore increased markedly from values of 0.036 mg/L in June 2004 to 0.449 mg/L in June 2005 (Anderson and Lawson, 2005). Nutrient concentrations in May (RWQCB, 2009) and September (Anderson, 2009) of this year (2009) were comparable to concentrations reported in 1991 (Risk Sciences, 1991). It seems likely that changes in land-use and improvements in agricultural practices and waste treatment and disposal were responsible for the dramatic reductions in nutrient concentrations between 1974 and 1991. Analysis of water quality data suggests, however, that limited subsequent improvements have been achieved over the past 18 years, with periodic episodes of large external nutrient loading from the watershed.

Nutrient concentrations are known to increase dramatically in bottom waters of eutrophic lakes that are thermally stratified. Measurements of concentrations above the sediments were made only in 1974 and 2009 (Table 4). Very high concentrations were present in bottom waters of the lake in 1974; high concentrations of dissolved nutrients result from the mineralization and release of N and P from the sediments and accumulation in the hypolimnion of the lake. Concentrations of NH_4-N and DRP in 2009 were about 40% lower than found in 1974 (Table 4), but remain very high and no doubt contribute to algal blooms following cooling and mixing of the water column in the fall. Internal loading of nutrients from bottom sediments can account for >95% of the overall annual nutrient loading to the water column in shallow lakes during periods of drought (Anderson, 2001).

Table 4. Dissolved and total nutrient concentrations in Lake San Marcos – bottom samples.

Nutrient	1974[a]	1991[b]	2005[c]	2009[d]	2009[e]
	Jul-Nov (n=3)	*Oct*	*Jun*	*May*	*Sep (n=1)*
NH_4-N	18.62±3.14	-	-	-	10.27
NO_3-N	18.10±5.96	-	-	-	0.37
Total N	-	-	-	-	8.73
DRP	5.76±2.46	-	-	-	3.63
Total P	6.56±2.05	-	-	-	3.45

[a]Ball, 1974; [b]Risk Sciences, 1991; [c]LSM Task Force; [d]RWQCB, 2009; [e]Anderson, 2009

<u>Other Water Quality Measurements</u>

In addition to nutrient concentrations, a number of other measurements are often made to provide information about water quality in lakes. A simple measurement of water clarity is routinely made using a Secchi disk, a small disk with alternating quadrants of white and black. The Secchi depth (Z_{sd}) represents the depth at which the disk is no longer visible and is directly related to the turbidity in the water column due to both phytoplankton and suspended solids. The average Z_{sd} values have been very low since 1974 (Table 5). Values less than 2.0 m are generally considered to be excessively productive (eutrophic) and values <0.5 m are considered hypereutrophic (Carlson, 1977; Carlson and Simpson, 1996). Low transparencies also limit aquatic plant growth. Secchi depths were observed to increase since 1974, however, with transparencies 50% higher in 1991 (0.76 m) and 100% (2x) higher in 2009 (0.95 m) (Table 5). For comparison, Z_{sd} values for Canyon averaged about 1.0 m in 2006-07 (Anderson, 2007).

Chlorophyll concentrations were only measured on two occasions (October 1991 and May 2009) (Table 5). The reported concentration of 11.8 μg/L for 1991 is considered somewhat suspect given the low Z_{sd} value. A regression of Z_{sd} values and chlorophyll a concentrations yielded an equation by Rast and Lee (1978) of the form:

$$Z_{sd} = 6.35 * Chl\ a^{-0.473} \qquad (1)$$

A chlorophyll concentration of 11.8 μg/L would thus be expected to yield a Z_{sd} value of 1.98 m (compared to the value of 0.76 m reported) (Table 5). This Z_{sd} value is in fact predicted to yield a chlorophyll a concentration of 90 μg/L.

Table 5. Other water quality measurements in Lake San Marcos – near surface.

Property	**1974**[a]	**1991**[b]	**2005**[c]	**2009**[d]	**2009**[e]
	Jul-Nov	*Oct (n=2)*	*Jun (n=1)*	*May (n=3)*	*Sep (n=3)*
Z_{sd} (m)	0.48±na	0.76±0.15	-	-	0.95±0.15
Chl a (μg/L	-	11.8±3.3	-	152±67	-
pH	9.15±0.18	9.15±0.05	-	8.83±0.09	8.06±0.08
DO (mg/L)	-	3.8±1.5	8.4±na	17.4±3.2	5.0±2.6

[a]Ball, 1974; [b]Risk Sciences, 1991; [c]LSM Task Force; [d]RWQCB, 2009; [e]Anderson, 2009

The pH values found in Lake San Marcos are typical of productive lakes here in the arid western U.S., with daytime values exceeding somewhat the theoretical pH near 8.2 for waters in a calcareous watershed in equilibrium with atmospheric CO_2. Photosynthesis depletes dissolved CO_2, shifting the following equilibria to the left:

$$CO_2 + H_2O \leftrightarrows H_2CO_3 \leftrightarrows H^+ + HCO_3^- \qquad (2)$$

To compensate for the utilization of CO_2 by phytoplankton during photosynthesis, carbonic acid (H_2CO_3) undergoes dehydration; protons (H^+) react with bicarbonate (HCO_3^-) to replace lost H_2CO_3, thus lowering the H^+ concentration and raising the pH. The slightly lower pH found this past fall is thought to result from a partial mixing of deep water into the surface, bringing lower pH water with excess CO_2 to the surface as well.

The final and often critical water quality parameter for lakes is dissolved oxygen (DO). Adequate DO is necessary to support fish and other organisms in aquatic ecosystems. A value of 5 mg/L or higher is considered suitable for a productive fishery, although fish kills often result only when DO concentrations drop below 1-2 mg/L. Water in equilibrium with atmospheric O_2 has a DO concentration of about 8-10 mg/L (depending upon temperature), so values less than this indicates undersaturation resulting from net consumption of DO, while values greater than that indicates supersaturation (net production). The reported DO levels varied from values of 3.8 –

17.4 mg/L (Table 5); values below 8-10 mg/L found in October 1991 and late September 2009 indicate that anoxic bottom waters were partially mixed into the surface waters . Strong sulfide odors were present in bottom waters and very low DO levels were also present near the dam in the morning during the recent sampling on September 30, 2009 (Appendix). Rapid mixing of sulfidic bottom waters in the surface waters has resulted in numerous fish kills this past summer and fall (*e.g.*, Lake Elsinore and Canyon Lake), and extreme odors (*e.g.*, Upper Oso Reservoir).

Dissolved oxygen thus varies vertically within the water column of most stratified lakes in a manner that is related to the distribution of heat. That is, lakes thermally stratify with warm less-dense water floating on top of cooler, denser water (Fig. 1). Heat is added at the lake surface due to absorption of shortwave and longwave radiation, with wind energy only able to mix the heat a finite distance into the water column (the epilimnion). Beneath this layer is an often pronounced thermal gradient (metalimnion) and layer of cool, dense water (hypolimnion) (Fig. 1a). Buoyant forces keeping heat from being mixed down through the entire water column also prevent DO from being mixed downward; bacterial decomposition and respiration reactions rapidly consume available DO, resulting in anoxic or anaerobic conditions in the hypolimnion (Fig. 1b). It is in this zone that H_2S, NH_4-N and DRP accumulate (Table 4).

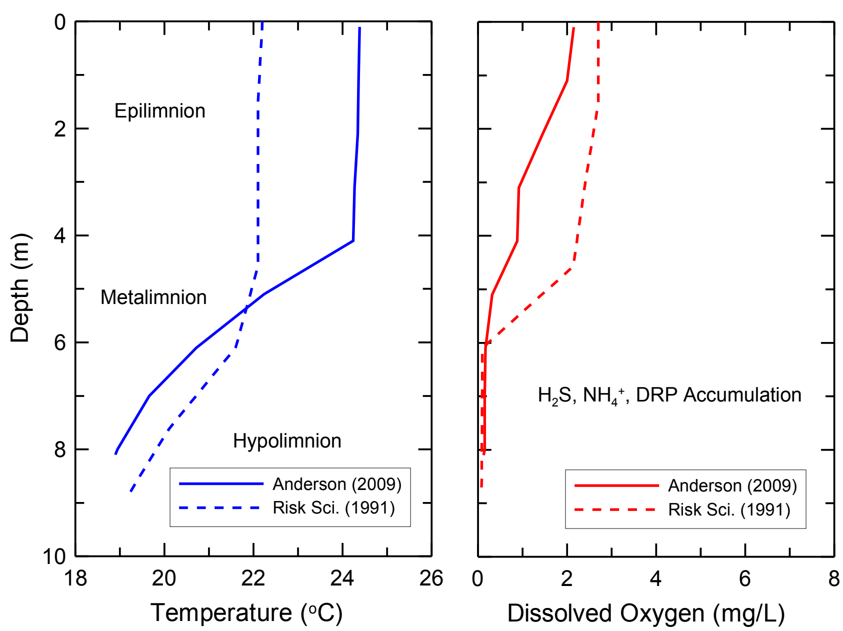

Fig. 1. Vertical profiles of a) temperature and b) dissolved oxygen in Lake San Marcos.

Broadly similar temperature and DO profiles were present on both September 30, 2009 (Appendix) and October 17, 1991 (Risk Sciences, 1991) (Fig. 1). Slightly greater cooling into the fall lowered the epilimnetic temperature of the water column measured by Risk Sciences relative to that present in late September.

These temperature and DO profiles are part of the regular seasonal trends in most lakes here in Southern California (*e.g.*, Fig. 2), where cool isothermal conditions are present in the winter, the surface water warms in the spring forming an epilimnion that reaches maximum temperatures in late summer (August) before cooling in the fall (Fig. 2). DO concentrations are initially high throughout the water column, although levels decline rapidly in the hypolimnion once the lake stratifies in the spring (Fig. 2).

An anoxic hypolimnion is thus present through much of the spring, summer and into the fall, with significant DO recurring only in the winter when the lake is well-mixed (Fig. 2). The mixing event in late fall brings this anoxic bottom water, also enriched in NH_4-N, DRP and H_2S, up into the surface resulting in potential fish kills and subsequent algal blooms.

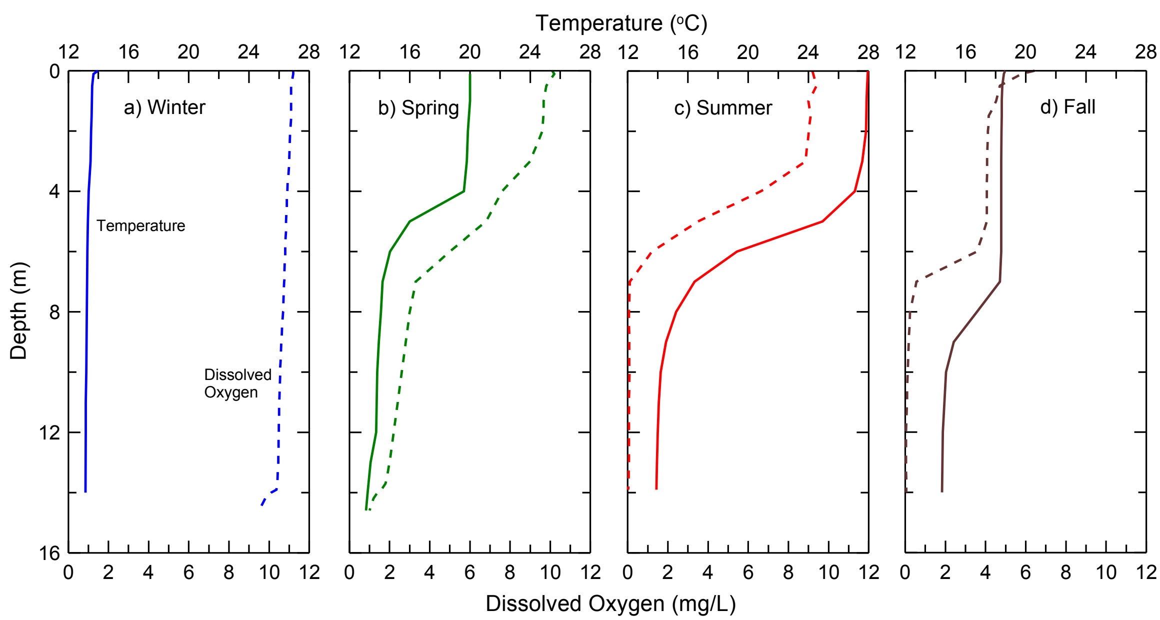

Fig. 2. Seasonal temperature and DO profiles in small lakes in Southern California (Canyon Lake, CA).

Fishery

Fish kills have in fact occurred occasionally at the lake; fish kills were recorded in 1968, 1974, 1976 and 2006, although other smaller episodes may have also occurred. Information concerning the fishery is restricted to two studies: Ball (1979) and Risk

Sciences (1991). A seine survey by Ball (1979) found most of the fish biomass to be in small bluegills, followed by bass and catfish (Table 6). This mass distribution is rather unusual since the fewer number of large fish tend to dominate the total fish biomass in a lake. Ball (1979) noted the presence of too many small bluegills and apparent over-fishing of bass. He made several recommendations to improve the fishery in Lake San Marcos, including the stocking of threadfin shad as forage for bass; construction of habitat in upper part of the lake through addition of rocks, aquatic vegetation such as water lilies; and installation of an aeration system.

Table 6. Summary of available fishery survey results.

Species	Ball (1979) (% by Mass)	Risk Sciences (1991) (% by Abundance)
Bluegill	46.9 %	-
Black bass	22.6 %	4.3 %
Catfish	19.3 %	-
Green Sunfish	6.1 %	-
Bullhead	0.1 %	1.4 %
Threadfin Shad	-	94.2 %

Risk Sciences (1991) conducted an overnight gill net survey about 12 yrs later and reported a different fishery in the lake. While the use of a very different sampling technique makes it difficult to compare these results with those from Ball (1979), the survey clearly shows the emergence of threadfin shad as a dominant fish in the lake. It is not clear if the shad were stocked based on Ball's recommendation or if they simply arrived in flows from the Colorado River aqueduct. The threadfin shad appear to have remained a dominant species, *e.g.,* in 2006 a fish kill removed a large number of the population. While threadfin shad are a favorite prey species for many large piscivores, they are zooplanktivores, grazing down beneficial zooplankton populations in the lake. As a result, they can adversely affect the zooplankton community and impair water quality.

<u>Zooplankton and Benthic Invertebrates</u>

The report by Risk Sciences (1991) provides the only assessment of invertebrates in Lake San Marcos. Zooplankton were sampled with a plankton trap deployed during the day in the photic zone at 2 sites on the lake. Surprisingly, no zooplankton were reported present in either of the samples. The small sample volume (30 L) near the surface during the daytime may have resulted in a severe undersampling of individuals.

Risk Sciences (1991) concludes that predation by shad and poor food quality may be responsible for their apparent absence in the lake.

Benthic invertebrates were sampled at the same 2 sites with an Ekman dredge. The dredge was used to sample the uppermost 10 cm or so of soft bottom sediments, with organisms subsequently sieved out of the mud. Risk Sciences reported high abundance of chironomids at one of the sites, although few other types of benthic invertebrates were found (Risk Sciences, 1991). Chironomids (midge larvae) are common in nutrient-rich bottom sediments with low DO concentrations, and are thus often an indicator of poor water quality (EPA). These benthic invertebrates are presumably a part of the diet of bluegills and other fish species in the lake.

<u>Phytoplankton</u>

Abundant blue-green algae have been reported in Lake San Marcos in 1974 (Ball, 1974) and more recently in the summer of 2005 (CSM000866 & 877). Risk Sciences also evaluated the phytoplankton community in the lake in October 1991. A comparatively diverse community was present at that time, with diatoms and dinoflagellates comprising 22 and 32% of the total population, with a substantial number of cryptophytes and green algae also present (20 and 18%, respectively). As a group, blue-green algae comprised only 8% of the phytoplankton of the lake (Risk Sciences, 1991). Inspection of water samples from July 2009 found a diatom-dominated phytoplankton community (chiefly *Synedra spp*.), while a more diverse community was present in September 2009, one that included diatoms, green algae, dinoflagellates and small colonial blue-green algae (Appendix). Unlike other types of phytoplankton, diatoms and dinoflagellates both have a nutrient requirement for silicon (Si); the presence of large numbers of diatoms in mid-July is somewhat unusual, since diatoms are most abundant in the winter and early spring, when cooler temperatures are present and runoff delivers a fresh supply of Si to the lake. Si limitations (<0.5 mg/L) are often witnessed by late spring (*e.g.*, in Lake Elsinore, Big Bear Lake), at which time green algae and then blue-green algae tend to take over. The large numbers of diatoms in mid-July provides some indication of a steady-input of Si to the lake, presumably through groundwater flow.

Water Budget

Sources of water to Lake San Marcos include flows from San Marcos Creek, direct precipitation onto the lake surface during rain events, local runoff into the lake from storm drains and the local watershed, and spring and other ground water sources. Water is lost from the lake due to outflow and to evaporation. Mathematically this can be represented as:

$$\frac{dV}{dt} = Q_{SMC} + Q_{Runoff} - Q_{out} + PA_s - EA_s \pm G \quad (3)$$

where V is the volume of the lake, t is time, Q_{SMC} is the surface inflow from San Marcos Creek, Q_{Runoff} represents other surface inflows, *e.g.*, storm drain flows, Q_{out} is the flow at the spillway, P is the precipitation rate, A_s is the lake surface area, E is the evaporation rate, and G is net groundwater flow. Groundwater flow is often calculated from the difference between observed lake volume and the other inputs and outputs.

During the summer, there is no direct precipitation on the lake and greatly reduced inflows from San Marcos Creek and local runoff. As a result of such conditions, most lakes in the region undergo pronounced reductions in lake surface level in the summer due to evaporation. In fact, evaporation removes about 0.8 m (2.6 ft) of water over the May-September time period based upon meteorological data at the Escondido CIMIS station (CIMIS, 2009). At a surface area of 58 acres, this corresponds to 150 acre-feet of water lost from the lake due to evaporation, occurring at an average rate of 3 acre-feet per day (or 1.5 cfs). Observations of the surface elevation within an estimated 6-8" of the dam crest in July and September 2009 suggests large inputs of water into the lake through the summer. The magnitude of these inputs can be estimated from equation 3 assuming approximate steady-state volume (i.e., dV/dt=0). Thus, to maintain approximate steady-state volume in the lake, inflows of about 1.5 cfs are required (eq 3). Recent measurements made by San Diego County indicate that inflows due to San Marcos Creek is about 0.3 cfs, while the sum of the major storm drains adds another 0.12 cfs inflow to the lake (CSM000152). Against an average evaporative flux of 1.5 cfs, and correcting for the change in storage (about 0.1 cfs), this leaves an unspecified additional input of up to 1 cfs to the lake that we can reasonably hypothesize is principally due to groundwater flow (Table 7).

This groundwater would be high in dissolved Si, and thus may account for the previously noted persistence of diatoms in the lake through much of the year. Interestingly, Ball (1974) also noted high lake levels and estimated that >200 af of water enters the lake annually from springs and irrigation drainage. Groundwater flows are thus helping to maintain lake level, unlike most other lakes in the region.

Table 7. Dry-weather water balance (July 2009).

Water	**Flow rate (cfs)**
Inflows (+)	
San Marcos Creek	0.3
Storm drains	0.12
Precipitation	0
Losses (-)	
Evaporation	1.5
Outflow	0
Change in Storage	0.1 cfs
Difference (Groundwater)	0.98 cfs

<u>Current Understanding of Lake San Marcos</u>

This review allows one to draw some general conclusions concerning the lake:

- The northern and middle part of lake is shallow with direct connection between nutrient-rich sediments and the surface layer of the water column

- Internal recycling of nutrients maintains high algal productivity and low water clarity throughout the year

- Algal turbidity limits the growth of aquatic macrophytes

- The southern part of lake is deeper and thermally-stratified through the summer-fall

- Rapid depletion of DO occurs in hypolimnion following stratification, making it unsuitable for fish, zooplankton and other aerobic organisms

- NH_4-N, DRP and H_2S accumulate to high concentrations in the hypolimnion

- Cooling temperatures in fall results in mixing of H_2S, NH_4-N and DRP into upper water column

- This depletes DO there, potentially triggering fish kills, while also fueling subsequent algal blooms

- The ecology in the lake is probably not presently suited for sustaining good water quality

- Groundwater flows help to maintain lake level through much of the year

Gaps in Understanding

While the available data is very important in defining the water quality conditions and processes affecting water quality in Lake San Marcos, some significant questions remain. Additional insights about the lake can help guide the restoration and efficient management of the lake. Five specific areas were identified (although additional data needs will likely be identified in the future):

i. *Better understanding of the current bathymetry and depth-area-volume relationships.* The recent survey conducted for the County of San Diego clearly indicates the accumulation of sediment and loss of depth through much of the lake. Notwithstanding, the estimated 300 soundings collected along the 19 horizontal transects are not sufficient to develop a detailed bathymetric map and depth-area-volume relationships for Lake San Marcos. These data are needed to conduct more accurate water budget, modeling and water management calculations for the lake.

ii. *Direct information about sediment distribution, thickness and properties.* Related to the need for higher resolution bathymetry is the need for information about the thickness, properties and distribution of sediment within the basin. In addition to depth to sediments, the thickness and distribution of bottom sediments provides essential information about the volume of sediment retained in the lake, and depositional processes operating here. This information is critical if sediment dredging is being considered anywhere in the lake now or in the future. Understanding the characteristics of the sediments (*e.g.*, hardness, texture, nutrient and contaminant concentrations) is also necessary when considering dredging or recontouring of the lake bottom. The distribution of different sediment types can also influence selection and design of in-lake treatment.

iii. *Rates of internal nutrient recycling.* In addition to understanding the distribution, thickness and types of sediments in the lake, it is also important to quantify the rate of internal nutrient recycling from each of the major sediment types, and the contribution of internal recycling to the lake's overall nutrient budget. Moreover, being able to focus on regions of high-nutrient sediments allows one to more carefully target treatment to those regions that are responsible for disproportionately large fraction of nutrients entering the water column.

iv. *Rates of external loading of nutrients.* The rate of external loading of nutrients from San Marcos Creek, and from groundwater, nuisance runoff and other inputs represents a critical gap in knowledge about the lake. Quantifying the flows, concentrations and external loading of nutrients are required for development of an overall nutrient budget for the lake, for its management, and for the efficient use of resources in managing water quality. Following the development of a nutrient budget, water quality modeling can be conducted to predict the extent of reductions in external and internal loading that would be necessary to achieve specific water quality objectives.

v. *Ecology and food web of the lake, including fishery and zooplankton communities.* Finally, significant questions remain about the ecology in Lake San Marcos. It will be essential to characterize the ecology, especially the zooplankton community, if one is to favorably modify it to improve water quality and develop a balanced sustainable food web and fishery.

Possible Remediation Strategies

Despite uncertainties about the lake, it is helpful to review some of the approaches used to improve water quality in impaired lakes. The focus here will be on in-lake techniques for the control of nutrients and algae, although it is implicit that BMPs and other actions within the watershed also need to be undertaken to limit external loading of nutrients to the lake. A number of different options exist for reducing algae (and nutrients) in lakes. Techniques include a range of mechanical, chemical and biological controls that differ in their mode of action, advantages and disadvantages (Table 8) (NALMS, 2001).

Out of these 17 different control strategies, 13 of them could conceivably play some role in the restoration of Lake San Marcos. Dilution and flushing were not considered practical given the limited water supply in the region, since flushing rates of 10-15% each day would probably be needed to substantively improve water clarity. Settling agents and pathogens were also discounted since settling agents treat only the symptom of the problem and would represent a significant recurring cost, while use of pathogens remains an experimental technique to this point. Selective nutrient addition was also discounted since it has not been demonstrated to be effective in lake studies and is more appropriate for nutrient-poor lakes where increased fish production is desired, rather than for algal control in eutrophic lakes (Table 8).

Table 8. Management options for control of algae in lakes (NALMS, 2001).			
Option	**Mode of Action**	**Advantages**	**Disadvantages**
Physical Controls			
1. Hypolimnetic aeration or oxygenation	Addition of air or O_2 maintains oxic water & sediments	Reduces internal loading of P; provides habitat for fish, zoo	May promote supersaturation of gases for fish
2. Circulation and destratification	Use of air or water to mix water column	Reduces surface algal scums, internal P loading; adds DO	May spread problems
3. Dilution and flushing	Addition of water can dilute or flush nutrients, algae	Reduces nutrient concentrations and their detention in lake	Diverts water from other uses; possible downstream effects
4. Drawdown	Lowering lake level allows oxidation of sediments	Reduce nutrients, increase capacity for flood control	Possible impacts to aquatic plants, downstream impacts
5. Dredging	Sediment is removed	Can reduce internal loading, increases water depth	Removes vegetation, benthic invertebrates; disposal issues
6. Light limitation	Creates light limitation	May achieve control of rooted plants as well	May induce thermal stratification, anoxia
7. Mechanical removal	Filters lake water	Algae and nutrients removed as needed	High backwash and sludge handling, labor, capital
8. Selective withdrawal/ release	Discharge of anoxic high nutrient bottom water	Removes bad water efficiently	Downstream problems if not treated
Chemical Controls			
9. Algaecides	Algaecides applied to target areas	Rapidly eliminates algae,	Toxic to non-target organisms, nutrient recycling
10. Phosphorus Inactivation	Application of alum or other salts that floc, bind P	Removal of algae and P; forms barrier limiting P release	Possible pH and toxic effects
11. Sediment Oxidation	Addition of chemicals to oxidize sediments	Slows internal recycling of nutrients, reduce SOD	May affect benthos
12. Settling agents	Addition of floc agent to settle algae	Removes algae and increase clarity	May affect benthos
13. Selective nutrient addition	Change nutrient ratio, alter algal community	Can promote non-nuisance forms of algae	Increase algal abundance, downstream effects
Biological Controls			
14. Enhanced grazing	Manipulation to achieve grazing control over algae	May increase water clarity, increase fish biomass naturally	May involve new species, difficult to control
15. Bottom-feeding fish removal	Remove fish that resuspend bottom sediments, nutrients	Reduces turbidity and nutrient inputs to water column	Targeted fish species difficult to control
16. Pathogens	Addition of inoculum to attack algal cells	Can be highly specific	Experimental, uncertain results
17. Competition and allelopathy	Plants can compete with algae for nutrients, light	Natural biological interactions, improve habitat	Plants can become nuisance

The remaining control strategies all offer some potential benefit to water quality, although costs vary widely (Table 9). For example, the simple strategy of selective withdrawal/release can be a relatively inexpensive way to remove nutrients from the lake if some makeup water is available, although downstream effects would need to be considered. Aeration is the most commonly used lake management technique, helping to mix DO throughout the water column, slow release of nutrients from the sediments, and keep nuisance algae fro accumulating to excessive levels near the lake surface. Dredging often represents the most expensive technique, but is the only one that deals with excess sediment accumulation and loss of depth and storage volume in lakes.

Table 9. Relative costs of possible management options for Lake San Marcos.

Option	Suitability	Relative Cost
Physical Controls		
1. Hypolimnetic aeration or oxygenation	Y	$$$
2. Circulation and destratification	Y	$$$
3. Dilution and flushing	N	-
4. Drawdown	Y	$-$$
5. Dredging	Y	$$$$
6. Light limitation	Y	$$
7. Mechanical removal	Y	$$$
8. Selective withdrawal/release	Y	$
Chemical Controls		
9. Algaecides	Y	$$
10. Phosphorus Inactivation	Y	$$$
11. Sediment Oxidation	Y	$$$
12. Settling agents	N	-
13. Selective nutrient addition	N	-
Biological Controls		
14. Enhanced grazing	Y	$-$$
15. Bottom-feeding fish removal	Y	$$
16. Pathogens	N	-
17. Competition and allelopathy	Y	$-$$

[a] these relative costs represent very rough order-of-magnitude estimates: $ = $1K-$10K; $$ = $10K-100K; $$$ = $100K-$500K; $$$$ = >$500K.

Chemical controls, such as algaecide application, can be comparatively inexpensive, although recurring treatments are typically needed since this treats only the symptom of the problem. Algaecides are generally effective at low μg/L concentrations and keep nuisance algae from accumulating to excessive levels; other chemical treatments that may require multiple mg/L doses to be effective become very expensive owing to the large volume of water in the lake. Algaecides can also render the sediments toxic with excessive applications, creating other longer-term problems. Phosphorus inactivation with alum has been used with some success in lakes, although it is necessary to reduce external loading as much as possible to extend the effectiveness of such a treatment. The El Nino cycle in Southern California makes it difficult to use alum to achieve long-term nutrient and algal control. Sediment oxidation via the introduction of nitrate or other oxidants into the sediments is a way to oxidize the sediments and slow internal nutrient recycling, although this approach can potentially create problems for benthic organisms. (It may be that groundwater flow into the lake is helping to achieve this if NO_3^- is present.)

Biological controls potentially offer the least invasive and most natural ways to improve water quality in lakes and reservoirs (Table 8). Since zooplankton graze upon phytoplankton a part of the natural food web in lakes, actions to maximize zooplankton populations can result in improved water clarity especially at low-moderate nutrient levels. *Daphnia* and other large-bodied zooplankton are especially important in this regard. Removal of benthivorous (bottom-feeding) fish such as carp can also improve water quality by reducing the amount of sediment and nutrients resuspended during their foraging. Competition with phytoplankton for nutrients by aquatic plants and attached algae can also favorably shift biomass production away from phytoplankton and thus increase water clarity and overall water quality.

A Strategy for Lake San Marcos

As one can see, a number of different in-lake strategies can be employed to improve water quality in Lake San Marcos. Emphasis should be placed on those actions that can reduce nutrient concentrations in the water column (per the 303(d) listing), avoid fish kills and other problems such as odors, and improve water clarity. Excessive nutrients are the cause of the impairment, and thus properly deserve intense focus. While it will be critical to control external loading of nutrients to the lake, actions within the lake will also be necessary to meet water quality goals. In some cases, in-lake treatment can offer a more cost-effective strategy for reducing nutrient concentrations than actions in the watershed. Insufficient information exists about the nutrient budget for the lake, its ecology, sediment characteristics, and rates of internal nutrient recycling and oxygen demand to predict the extent of improvements that could be expected by implementing particular restoration actions. Nevertheless, it is useful to discuss, in general terms, possible strategies for the lake.

1. Selective withdrawal/release - It is estimated that about 100 acre-feet or 15% of the lake volume lies below the thermocline in summer. This volume of (hypolimnetic) water receives NH_4-N, DRP and H_2S liberated from the sediments in the deep water in the southern part of the lake that accumulate to high concentrations (Table 4). These chemicals remain out of the surface layer, however, and thus typically present problems only when mixed into the surface waters in the fall. This can create severe algal blooms and fish kills however. One way to reduce the amount of nutrients and H_2S accumulated in the hypolimnion would be to release water through the 6" pipe near the bottom of the dam when sufficient inflows exist. That is, excess water would be better released from the bottom of the lake than over the spillway. This would reduce the accumulation of nutrients and H_2S and deepen the generally well-aerated epilimnion. This action would potentially have no direct costs to implement, although very careful consideration would need to be given to the downstream impacts.

2. Aeration, hypolimnetic oxygenation, or destratification - All of these strategies aim to eliminate anoxia (low DO) in the bottom waters of the lake and reduce internal nutrient recycling, especially of phosphorus. Aeration involves mixing the water column using air injected in the bottom of the lake (Fig. 3a); the air bubbles rise to the surface, driving anoxic bottom water up to the surface while mixing aerated water downward. This destratifies the lake (*i.e.*, eliminates the thermal gradient in the water column (Fig. 2).

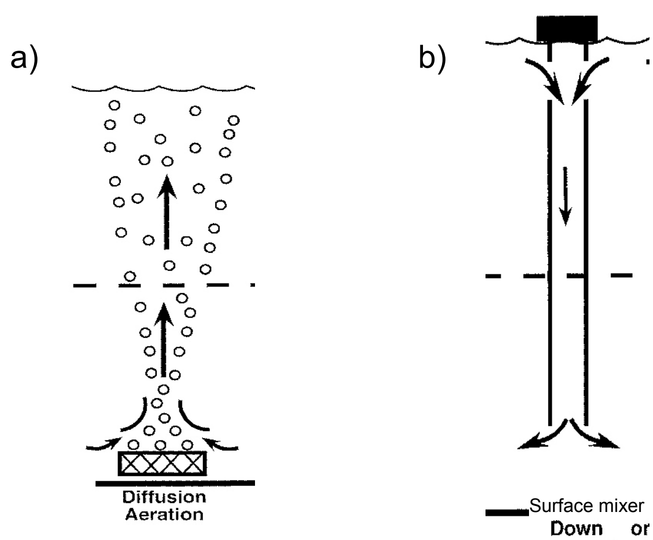

Fig. 3. Schematic of a) diffused aeration and b) surface mixer with draft tube (taken from NALMS, 2001).

Clean Lakes Inc. has recently submitted a proposal for two alternate configurations for a diffused aeration system for the lake (CMS000978-984), a deep-water aeration system that addresses the anoxia and stratification in the southern deep part of the lake ($24,031), and a whole-lake system that would also include the shallower upper part of the lake ($74,350). The upper system would help prevent stagnation of the water column.

An alternative approach is to mix warm naturally well-aerated surface water downward using a surface impeller, delivering DO to the bottom waters, setting up circulation and serving to destratify the water column as well (Fig. 3b). The diffused aeration approach is more commonly used than surface mixers, although the surface mixers are theoretically more efficient, using less energy than diffused aeration systems that require operating a compressor(s). Surface mixers do require anchoring a relatively large floating platform on the lake, however.

The third approach involves injection of pure O_2 or O_2-saturated water into the hypolimnion of the lake. This can be done in several ways, including full-lift or partial lift aerators, a Speece cone, or other large devices that include a surface structure. The size and cost of these devices would not be practical for Lake San Marcos, although direct O_2 injection into the bottom waters in a way similar to the diffused aeration system (Fig. 3a) could potentially be implemented. Such a system involves pumping pure O_2 into gas permeable tubing, where it dissolves fully into the water. No bubbles form, so vertical mixing of the water column does not occur and therefore differs from the diffused aeration system. The O_2 can be either delivered or produced on site.

While each of these systems may achieve the goals of increasing DO, reducing nutrients, and improving clarity, capital costs, operating costs, reliability, and aesthetic and navigational impacts should also be considered. Given the small surface area of the lake, a fully submersed system would be preferable since it would not negatively impact the view across the lake or present navigational concerns. On those grounds, the diffused aeration system or hypolimnetic oxygenation systems would be preferable to surface mixers or full- or partial-lift aerators. Simplicity, reliability and low capital costs make a diffused aeration system, such as that proposed by Clean Lakes, Inc. (CSM000978-988) a reasonable engineering approach to improving water quality in the lake. It may be advisable to initially install the deep-water system to gain some experience with lake aeration and its impact on water quality. Operating costs should be low (per specs on CSM000982 it should be only about \$9/day assuming two 10.6 Amp/115 V compressors at an average electricity cost of \$0.15/kWh).

3. Biomanipulation.

a) Enhanced Grazing - Diffused aeration and (if practical) bottom withdrawal/ release represent engineering activities that are expected to reduce nutrient levels and improve DO concentrations and clarity, especially in the southern part of the lake. Efforts to optimize natural processes should also be considered. Although current information about the zooplankton and fish communities is not available, it is expected that enhanced grazing of phytoplankton by large bodied *Daphnia* and other zooplankton will improve clarity of the lake. To achieve this, a top-down approach is recommended whereby periodic stocking of the lake with piscivorous fish such as largemouth bass will control threadfin shad populations in the lake. This top-down approach can be seen assuming a simple linear food web for Lake San Marcos that consists of 4 types of organisms: phytoplankton, zooplankton, zooplanktivores (such as threadfin shad), and piscivores (*e.g.*, largemouth bass) (Fig. 4). Phytoplankton abundance is directly related to the availability of nutrients (*e.g.*, P) in the lake, so control of nutrients through watershed actions and through aeration via the so-called "bottom-up" approach is expected to reduce phytoplankton levels. At the same time, grazing by zooplankton (*i.e.*, "top-down" control) also lowers the phytoplankton levels in the lake. Minimizing nutrient inputs *and* maximizing zooplankton grazing thus yields the lowest standing crop of phytoplankton, and best clarity and overall water quality (Fig. 4).

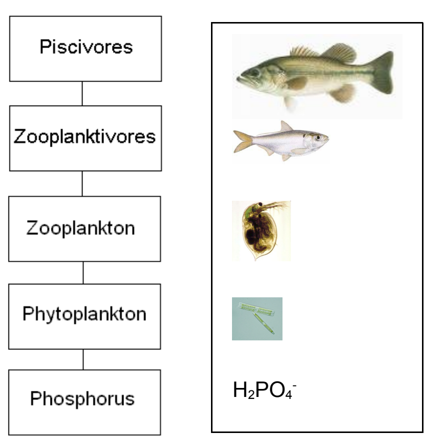

Fig. 4. Simplified linear food web showing relationship between availability of nutrients and different trophic levels in a lake.

However, zooplankton themselves are subject to predation by zooplanktivores, especially shad and other small fish. Thus, in lakes with high rates of predation, there are correspondingly low populations of zooplankton, resulting in little loss of phytoplankton due to grazing (a healthy *Daphnia* population can potentially filter the entire lake volume in 10 days). A correlation thus exists between zooplanktivore population and phytoplankton abundance, while an inverse relationship exists between zooplankton and their predators. It is advantageous then to minimize excessive zooplanktivore predation on zooplankton. This can be achieved through introduction of large sport fish capable of preying on, *e.g.*, shad. This strategy has been implemented at Lake Elsinore for several years. Along with removal of benthivorous carp and other actions, we have seen a favorable change in the fishery there (Anderson, 2008). (Carp, if shown to be present in high numbers in Lake San Marcos, should also be removed from the lake.) At the same time, aeration will help make the deep water in the lake more habitable for zooplankton.

b) Competition - Efforts should also be made to foster growth of non-nuisance aquatic plants such as water lilies, as found in the southern part of the lake. Aquatic plants remove nutrients from the sediments, thus reducing internal nutrient recycling. Aquatic plants also provide surfaces for attached algae that directly compete with phytoplankton for available nutrients in the water column. Aquatic plants further provide DO to the water column and protection for zooplankton and larval and juvenile fish. Moreover, water lilies and other emergent and floating-leaved aquatic plants provide habitat for birds and offer an attractive natural looking shoreline.

<u>Development and Implementation of Regular Monitoring Program</u>

It will be important to begin a regular monitoring program for the lake. Such a program is necessary to quantify the improvements in water quality achieved through in-lake and watershed management efforts. It will also provide needed information to guide adaptive management for the lake, quantify seasonal and longer-term trends in water quality, record inter-annual variability in water quality and response to drought and El Nino events, and develop a more complete understanding of the limnology of Lake San Marcos. At the absolute minimum, 2 simple but critical measurements should be made, specifically Secchi depth and lake level. If a staff gage is not presently installed at the lake, then one should be installed immediately. Secchi depth and lake level should be recorded weekly, and more frequently following rain events in the watershed. These measurements can be done from a dock, so it is not necessary to launch a boat. Secchi depth measurements should be made in an area that is open so as to avoid stagnant water where surface algal scums may accumulate. Several sites on the lake could be used to capture the spatial variability in transparency, but a single consistent sampling site, *e.g.*, off the far end of dock near the boat launch, would be adequate to capture short-term and longer-term trends in clarity of the water.

To quantify progress with respect to numeric nutrient targets or other water quality objectives for the lake, samples should also be collected and analyzed for total N and total P and dissolved nutrient concentrations (NH_4-N, NO_3-N and DRP). Chlorophyll concentrations and Secchi depth measurements at these sites could also be determined. These samples would be best collected from a boat on a quarterly basis. Three sites representing the northern, central and southern parts of the lake should be sampled. Samples collected directly into bottles below the surface of the lake would be adequate.

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Appendix

Lake San Marcos: September 30, 2009

Field and Laboratory Results

Water column measurements and water samples were taken at 3 locations on Lake San Marcos on September 30, 2009 (Fig. 1; Table A1). Sampling was conducted between about 9:00 – 11:30 a.m. I was assisted by Keith Plank and Fran Geneau. Special thanks to Keith Plank who graciously provided his boat and his time for this sampling.

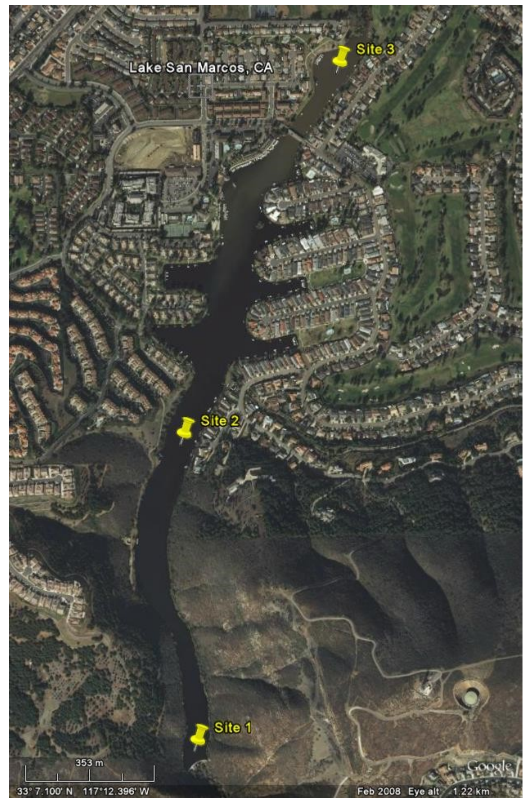

Fig. A1. Sampling sites.

Location of the sites were recorded using a Garmin eTrex GPS using the WGS84 datum. Water column temperature, dissolved oxygen (DO) and electrical conductance (EC) were recorded at 1 m depth intervals from the surface of the lake to the bottom sediments using a Hydrolab Quanta sonde. Maximum depth and conditions just above the sediments were also recorded. Transparency of the water was measured using a Secchi disk. Water samples were taken using a van Dorn sampler.

Table A1. Sampling sites on Lake San Marcos (9/30/09): latitude, longitude, depth and Secchi depth.

Site	Latitude	Longitude	Depth (m)	Z_{sd} (m)
1	33º 06.582’	117º 12.527	8.1	1.1
2	33º 07.035’	117º 12.549’	3.6	0.8
3	33º 07.584’	117º 12.262’	1.2	ND

Water samples were returned to the lab, promptly filtered through a 0.4 μm polycarbonate filter, and frozen until analysis of dissolved nutrients (NH_4-N, NO_3+NO_2-N and dissolved reactive P, DRP). Unfiltered water samples were digested using persulfate following Standard Methods (APHA, 1998). NO_3+NO_2-N, NH_4-N and DRP concentrations in the filtered and digested samples using colorimetric methods on a Spectronic 100 (Hach, 2009).

Depth at the 3 stations varied markedly, from a depth of 8.1 m at site 1 near the dam to 1.2 m near the inflow from San Marcos Creek (Table A1). Secchi depths were uniformly low in the lake, although the measured Z_{sd} value was slightly higher at site 1 (1.1 m) than at site 2 (0.8 m) (Table A1). A measurement was not made at site 3.

Results from the Hydrolab casts reveal a stratified water column was in place at this time, with about a 5.5ºC difference in temperature between the surface and above the sediments at site 1 (Table A2). More significantly, low DO concentrations were present even in the epilimnion there (DO about 2 mg/L near the surface, and <0.5 mg/L below 4 m depth) (Table A2). Strongly reducing conditions were evident based upon the H_2S odor from the bottom water sample. An anoxic hypolimnion is common in eutrophic lakes in the region, although such low DO concentrations in the surface are unusual. It seems that a partial mixing event may have occurred, and mixed some of the cooler anoxic hypolimnion in the upper part of the water column. Observations reported by fisherman of patches of water with colloidal white particles in suspension are consistent with such a mixing event that also brings up bicarbonate and promotes precipitation of $CaCO_3$.

Table A2. Results from water column profile measurements.

Site	Depth	Temperature (ºC)	DO (mg/L)	EC (mS/cm)
1	0	24.38	2.15	2.28
	1	24.36	2.00	2.28
	2	24.34	1.45	2.28
	3	24.27	0.92	2.28
	4	24.24	0.88	2.27
	5	22.24	0.32	2.14
	6	20.72	0.17	2.04
	7	19.66	0.15	2.01
	8	18.95	0.15	2.12
	8.1	18.9	0.13	2.12
2	0	25.03	5.51	2.28
	1	24.62	1.60	2.27
	2	24.51	0.80	2.27
	3	24.43	0.35	2.27
	3.6	24.13	0.25	2.21
3	0	25.54	7.32	2.16
	1	24.78	5.45	2.16
	1.2	24.78	4.41	1.83

Electrical conductance, a measure of the salinity or ionic concentration of the water, remained relatively stable near 2.2 mS/cm, although limited variability was present.

Water column conditions at the other 2 sites indicated no substantial vertical stratification of temperature present, owing to their shallow depth, although DO concentrations did vary (Table A2). The low DO concentrations above the sediments at site 2 may reflect high sediment oxygen demand. At the very shallow site 3, the surface layer was over 1ºC warmer than at site 1, reflecting heating (Site 1 was sampled first, at about 9:00 a.m., followed by site 2 at about 10:30 a.m., and finally site 3 shortly after 11:00 a.m.). Higher surface DO concentrations at sites 2 and 3 results from increased rates of photosynthesis and production of DO.

Inspection of the water sample from site 2 following centrifugation under a Nikon E600 compound microscope revealed a fairly diverse phytoplankton community. No effort was made to quantify cell abundance, although diatoms, green and blue-green algae, and some dinoflaggelates were observed, without a single group dominating the community.

Chemical analyses indicate nutrient concentrations well in excess of Basin Plan objectives for total N and total P, with comparatively little N and P in surface water samples in dissolved readily-available forms such as NO_3-N, NH_4-N or DRP (Table A3). Much higher concentrations of dissolved nutrients, especially NH_4-N and DRP, were present in the water sample collected from 7 m depth near the dam that resulted from mineralization and release from the bottom sediments (Table A3). Here, total N and total P concentrations were actually somewhat lower than the dissolved forms. This was attributed to the high sulfide concentrations present in this sample that reduced the efficiency of the persulfate digestion process.

Table A3. Results from nutrient analyses.

Site	Depth (m)	NO_3-N	NH_4-N	DRP	Total N	Total P
				(mg/L)		
1	3	0.19	0.30	0.04	3.26	0.16
	7	0.37	10.27	3.63	8.73	3.45
2	1.8	0.17	0.14	0.10	3.12	0.16
3	0.5	0.12	<0.10	0.05	3.03	0.16

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