PRELIMINARY LIMNOLOGICAL SURVEY OF CROCKER LAKE RESERVOIR, HILLSBOROUGH, CALIFORNIA WITH RECOMMENDATIONS FOR FUTURE LAKE PLANNING & MANAGEMENT

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1.0 SUMMARY

Crocker Lake in 2006 is a 1.4-acre reservoir with a larger upstream wetland situated in steep 60-acre canyon in Hillsborough, California. The circa-1905 dam once anchored the 700-acre Crocker Estate, and both dam and surrounding structures have historical importance. The site also contains relatively undisturbed wildlife habitat in the middle of a suburban area. A preliminary winter limnological survey indicated that the reservoir was still a beautiful asset but that its end is near (~10-15 years) due to one of the highest sediment accumulation rates in the nation (1.4 inches/y). Dredging the lake and reforming the erosion control basin upstream will restore the lake and extend its life for another 100 years. Other lake management techniques may be needed depending on a summer study. Costs of dredging (~$70,000-$420,000) depend on the degree of restoration (recommended plan ~$220,000). Fortunately, the lay of the land in the canyon and its past history will allow for a pleasing combination of erosion control dams/wetlands which could be encompassed within the cost of disposal of the dredge spoils. Other lake management options are less costly (>$10,000 to $100,000) but may not be needed; depending on the results from a summer survey (cost ~$10,000).

2.0 RECOMMENDATIONS

2.1. Narrative recommendations. Crocker Lake is reasonably healthy as far as a mid-winter survey can show. The immediate problem is the reservoir's extinction in the near future (~10-15 years) due to inflowing sediment and in-lake submerged and emergent weed growth. Eutrophication, excessive weed growth, fish kills and other problems cannot be assessed without a summer survey.

2.2 Action items

Action items for immediate attention for the lake

1. Initiate controls on sediment entering the reservoir. Begin plans to control erosion in the watershed using check dams &/or retention basins &/or wetlands filtration basins. Since the water supply of the Burlingame Country Club is involved, they should be brought into the negotiations since it is in their medium-term interests to support dredging. (Their water store will cease in 10-20 years when the reservoir silts in completely.)
2. Choose a dredging option(s) and initiate funding search. Federal-State grants require some kind of public access to the lake.
3. Prepare for a summer limnological survey (especially oxygen & nutrients).
4. Determine who controls the water level in the dry season.

Action items for consideration in the near future

- Determine if aeration/oxygenation is needed based on summer 2006 survey.
- Plan the kind of biomanipulation needed in future based on summer 2006 survey.
- Prepare a preliminary lake management plan to frame future actions.
- Remove water color-darkening eucalyptus and non-specimen pine trees

Action items for the more distant future

- Implement biomanipulation and other management techniques as appropriate from earlier actions.

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4.0 INTRODUCTION

Crocker Lake is a small reservoir constructed about 100 years ago as part of the 700-acre Crocker Estate (Figs 1-2). It is situated in a very steep and eroding canyon. The reservoir was primarily constructed to provide water to the estate, now the Burlingame Country Club but also served as a scenic focus for the owners and a fishing, swimming and sailing lake for their children as late as the 1940s (Beatty, 2002). The lake was stocked with black bass. The Country Club still owns the water rights to the water but it is not clear to what extent they can legally draw the water level down or even drain the reservoir and dry out the surrounding wetlands. Beatty states that the local residents did not comment on any level drops but since a pipe extends well below the water surface the Country Club certainly has the potential to lower the water level. The status of the water level is critical in the scenic and biological functioning in the reservoir and should be clarified.

The present-day park, shrunk to 60 acres, was deeded to the City of Hillsborough in 1977 and is to be used for "scenic land, watershed or ground water recharge land, and wildlife habitat." Numerous homes abut the property and have constructed paths, steps and gates to enter the area but there is no official public access. The primary reason for lack of public access is fire hazard from low-growing exotic brush. A group of citizens have proposed that it should become more available. This preliminary limnological survey is part of the knowledge needed to make public access of the park feasible.

5.0 PRELIMINARY SURVEY OF THE RESERVOIR

5.1 Methods

The parameters of the reservoir were estimated in two ways: from the recent color map and by a depth survey using a small boat on 25 January 2006. In addition most of the 60-acre site was walked to observe the upper swamp region and inflowing streams. The heavy rains in November and December 2006 had a large erosive effect that was obvious at this time.

5.2 Current Reservoir Area

Using a color aerial-photographic map on a 1"=160' scale for the entire park (Fig. 1), I estimated the current open water surface area at ~1.4 acres. In previous accounts the lake area was given as 5 acres (Beatty 2002) but further examination of the contour lines indicated that this was probably an error. Details of the physical limnology are shown in Table 1. From the 1"=160' scale map I estimated the open water from dam face to the inflowing creek was 500 feet. Maximum width was 160 feet just upstream of the dam and ~85 feet two-thirds of the way up-reservoir to the upstream end. An average of the two (123 feet) gives a mean width of the square thus formed. Thus the reservoir area is 500 feet x 123 feet = 61,500 sq. ft. or 1.4 acres (1 acre = 43,560 sq ft).

Fig 1. Map of Crocker Lake Reservoir

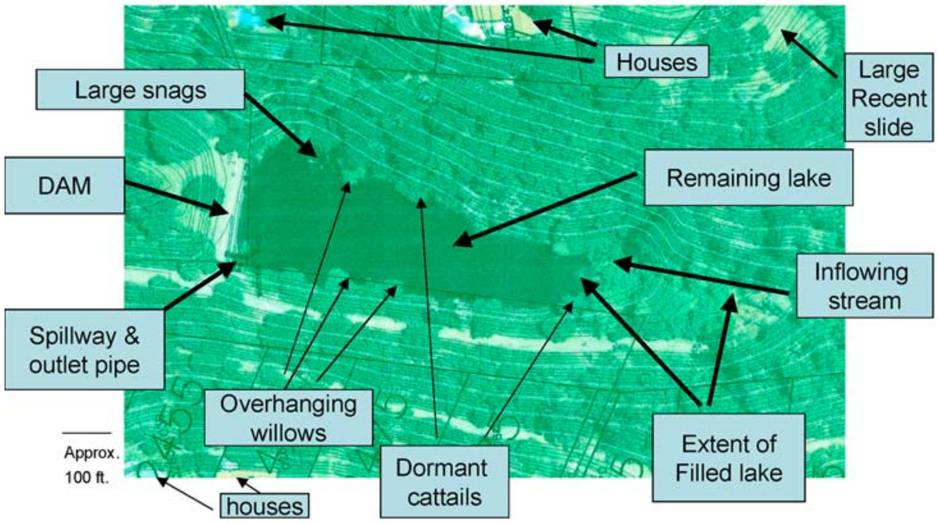
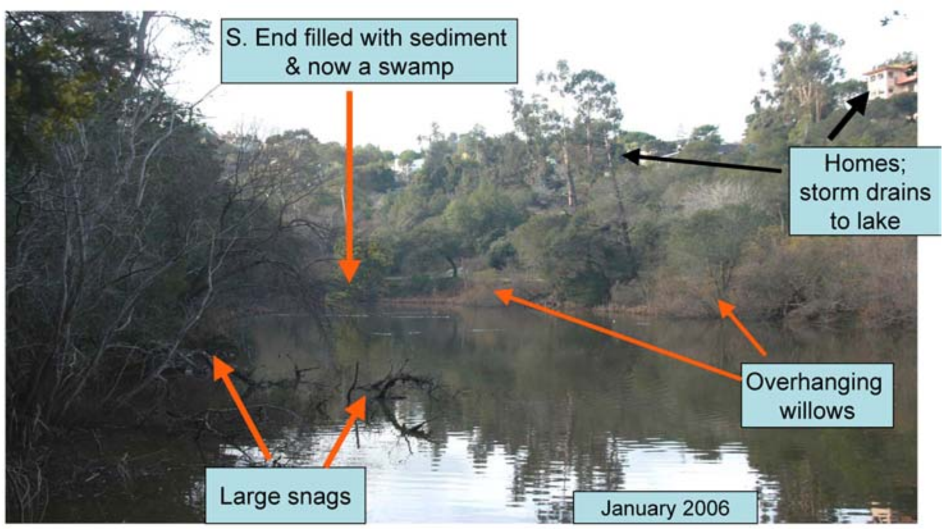


Fig 2. Crocker Lake Reservoir: General view to south from dam showing snags & willows



5.3 CURRENT RESERVOIR DEPTH AND BATHYMETRY

Depth was measured at 19 sites using a weighted line calibrated with a tape measure. It was quite calm but measuring from a very small inflatable boat gives some drift and other errors so accuracy is +/- one foot. The lake elevation was 285 ft ams with the water just flowing out of the bottom of the single large pipe that constitutes the only outflow other than the emergency spillway. Distance from shore was estimated in this small water body. The lake basin shape underwater was flat-bottomed, steep-sided pan shape as is common for small canyon reservoirs with erosive watersheds. The large flattish section covered about one-third of the lake (280 x 75 ft.) and was >15 feet deep (Fig. 2). The deepest spot was about 20 feet and this depth contour extends about 150 x 30 feet. The drop off from the water's edge was very steep as in the canyon above. In many spots around the edges the water was 5 feet deep as little as 5-10 feet out into the reservoir.

Table 1. Estimated physical limnology of Crocker Lake reservoir, Hillsborough California. The area of smaller lakes and reservoirs are traditionally given in the metric system as hectares (1 ha = 10,000 m^2 of a square of 100 m sides).

Parameter	**US units**	**Metric units**
Normal pool (surface elevation 285 ft amsl)		
Area, A	1.4 acres	0.53 ha
Depth max z_{max}	20 feet	6.0 m
Depth mean z (estimated from bathymetric survey on 25 Jan 2006)	12.3 feet	3.7 m
Volume, V	17.2 acre-feet	21,000 m^3
Maximum width	160 ft	48 m
Maximum length	500 ft	152 m
Maximum fetch, dam to inflow	500 ft	152 m
Hydraulic residence time, years	Not known	
Drainage area	163 acres	66 ha
Ratio, reservoir area: drainage area	1:116	1:116
Eutrophication prediction base on ratio	Very eutrophic	
Original pool (~ 1905?)		
Area, A	1.7 acres	0.69 ha
Depth max z_{max} (estimate)	50 feet	15 m
Depth mean z (estimated from slope from dam to creek downstream	25 feet	7.5 m
Volume V	43 acre-feet	53,000 m^3
Sediment accumulation		
Sediment accumulation 1905? -2006	~12 feet (mean) (~30 ft max)	3.6 m (mean) (~9 m max.)

5.4 EXISTING WATER QUALITY

Water quality is a general term that encompasses chemical, water clarity and general health. No measurements were made of most conventional chemistry or clues to the lake health such as dissolved oxygen, since these are best made in summer and are not needed at this preliminary stage. However, some observations were made that make a start on this section of the reservoir's examination.

Water Clarity and algae. Viewed from the water' edge, the water color was brown but on further examination held very little suspended sediment. A 1-liter sample was collected and held immobile overnight, and only a trace of sediment had sunk to the bottom. The sediment was examined at up to x70 power and was dominated by the ubiquitous, small organic particles found in most lake waters. No traces of brown tides of dinoflagellates (large motile brownish algae) which can occur in California at this time were seen. Serious nuisance algae such as blue-green algae (cyanobacteria) scums occur in summer and fall not in winter. These algae are common in lakes with excessive nutrients and the resultant purple white and green blue-green scums are not pleasant to see. For Crocker Lake the main threat is probably that these algae can be highly toxic to animals that drink the water. Death to dogs and possibly deer can occur within 30 minutes.

Effect of exotic trees. The brown color is probably thus due less to sediments than to dissolved color (humic substances) derived from the leaching of dead leaves in the drainage basin soils. Further examination in summer would be useful to determine more details of water clarity. Excessive dissolved color is not conducive to a healthy lake since it absorbs sunlight that would otherwise support algae, zooplankton, fish and birds. Fallen eucalyptus leaves and to lesser extent pine needles is the main source of dissolved humic color. To the extent possible, such trees should be eliminated in the drainage unless they are indigenous to the canyon or specimen trees with historical connections to the Crocker family. This clearance may go hand-in-hand with the needed reductions in fire risk since these foreign species are more flammable than the native species.

Zooplankton. The liter sample of surface water contained about 20 small zooplankton mostly *Daphnia* - the ubiquitous "water flea". Not a flea at all but related to crabs and shrimps, the tiny animal grazes on phytoplankton (microscopic floating algae) and is the prime food for young fish that will be hatching soon. Large zooplankton are also a winter food for ducks.

Shoreline vegetation. The shoreline was fully vegetated. Emergent vegetation, mostly cattails in clumps were scattered around the entire shoreline. In winter 2006 all cattails were either dormant in winter condition or dead. Since there is no record of herbicide use they are probably dormant. Cattails (*Typha*) are not the best shoreline vegetation as they tend to spread to all shallow (<2 ft) depths. However, they are natural in the region. The absence of bulrush (*Scirpus*), a better food plant for ducks, was surprising and suggests that the water level of the lake fluctuates over 3 feet in summer, at least in some years.

Snags. The banks contained numerous willows, some of which had tipped into the water. Large tree snags and tree trunks were present, especially near the dam opposite the outlet Fig. 2). When sampling in the open water the sounding line became tangled in underwater snags in deep water. In general, snags and fallen trees are beneficial for lakes since they provide additional habitat for fish.

6.0 SEDIMENTS

6.1. EVIDENCE FOR SEVERE EROSION & SILTATION BASED ON JANUARY 2006 SURVEY

The survey of the watershed in January 2006 revealed that the heavy rains in late 2005 (almost 4 inches in one day in the East Bay) caused severe erosion in the watershed. Almost certainly this silt has reached the reservoir.

- The upper end of the reservoir is a flat swamp with willows and cattails at the downstream end (Fig. 3). Just upstream of the reservoir, the area that is bounded by a berm is also now flat and a swamp. This berm appears to have been constructed to catch sediment before it reaches the reservoir, but the area is now full and no longer working as a catch basin. Both sites have filled in due to sediment deposition since the natural canyon is steep and V-shaped.
- During our visit there were large areas of at least two sections of the small inflowing creeks that had freshly eroded. In one example on the main creek just upstream of the fallen "Japanese Bridge" the old track over had completely washed out (Fig. 4). Whole banks of sediment had slumped and been washed downstream. In a smaller upper creek the drainage pipe from the road was sticking out about 8 feet indicating its original supporting soil had washed out. The entire canyon is very steep, and the high rains, compounded by runoff from impervious roads and homes, can easily wash away the soft soil. Smaller erosion examples were common along the graded tracks, especially below storm drainage pipes from homes and streets that ring the canyon. A large example of mass wasting from some years before was evidenced by a large, recently cleared and graded area. The reservoir is the first site along the creeks where sediment can settle so any sediment now in the creek will end up in the lake.
- Based on the shape of the un-flooded canyon and the depth survey, the reservoir has severely silted in since the dam was constructed. The original V-shaped lake bed has become flat (Fig. 5). The source of the sediment is erosion since almost no inflowing sediments, except the very fine ones, flow out over the dam. Typically reservoirs fill in many feet during the first two years as the waves work their way up the new shoreline. However, filling after that time depends on the condition of the watershed.

The recent rate of sedimentation as shown by the January 2006 watershed survey is alarming. It may be much greater than the historical average and could result in the lake filling in within 10-15 years.

6.2 ORIGINAL DEPTH AND SIZE OF THE RESERVOIR

The original size of the 1.7 acre reservoir (Fig 6) was based on the shoreline in the 2006 survey (Fig. 1) and an earlier sketch map (Fig 7). Based on the depth of the canyon just downstream from the dam I estimated that the original maximum depth was probably at least twice as deep (~40 ft) as the current maximum depth and even may have been 70 feet. More accurate data could be provided by coring it but it would be costly. There may be an original plan and depth-volume-area curve (hypsographic curve) in the old

Fig. 3. Lost upper section of the Crocker Lake Reservoir due to severe sedimentation – now a willow swamp

Fig.4 Severe erosion in main creek upstream of the Crocker Lake Reservoir

Fig. 5. Bathymetric map of Crocker Lake with depth contours in feet

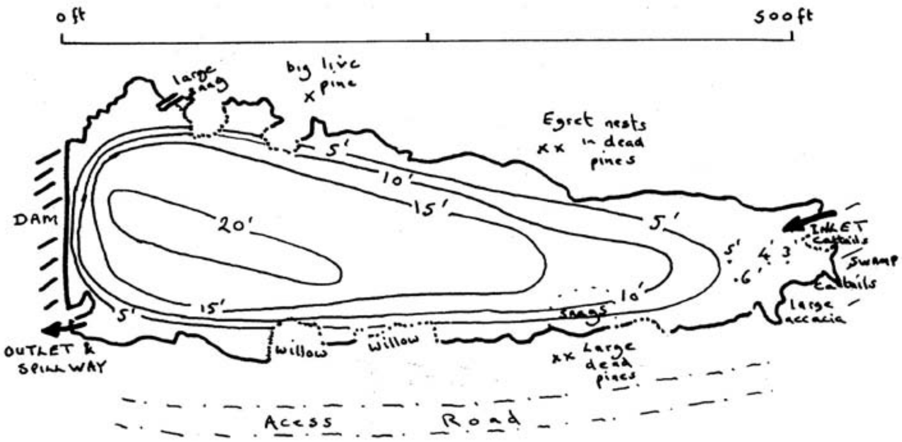
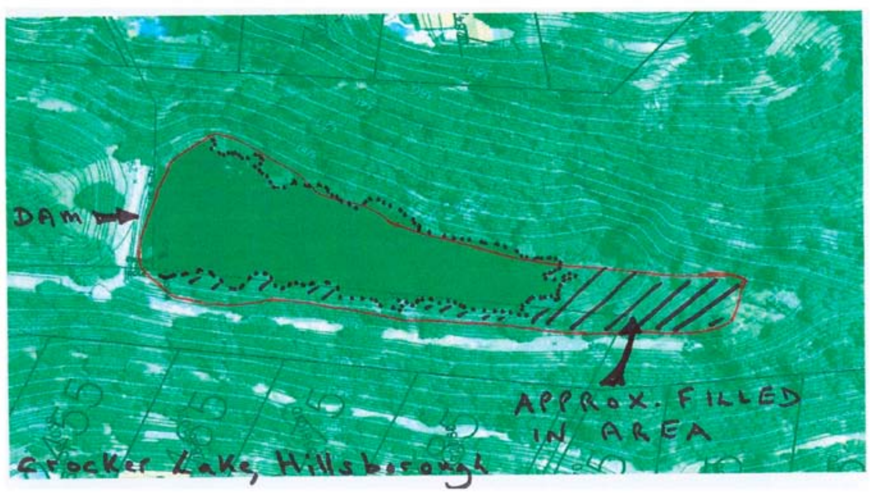


Fig. 6. Crocker Lake: Sediment filled area for dredging



files somewhere. The shallower sediments in the upper part of the reservoir or the swamp may be shallow enough to core for at least a few feet which could easily be carried out during the summer limnological survey.

The estimated the maximum length of the original reservoir (dam face to concrete spillway at the upper end of the level section) is 700 feet. The mean width of the reservoir is thus 103 feet (from three widths at equal spacing along the length of the reservoir of (160 + 85 + 65)/3 = 103 ft). The area of the square thus formed is 700 x 103 = 72,100 sq ft or 1.7 acres, not much larger than the current 1.4 acres.

6.3 HISTORICAL SEDIMENTATION RATE FOR CROCKER LAKE

From the 2006 bathymetric survey I estimated that an average of 12 feet of sediment have been deposited over about 100 years (Table 1). The resulting annual deposition rate is thus about 1.4 inches (~3.6 cm). The sedimentation rate for Crocker Lake is much higher than that in natural lakes but also higher than comparable water bodies in urban or rural areas (Table 2). Most natural lakes fill in very slowly (~0.005 inches (0.01 cm)/y when compressed by more sediment on top). Thus Crocker Lake Reservoir has filled in at 360 times the rate of a normal lake and about twice as fast as Mountain Lake in Golden Gate National Recreation area, which unwittingly received a load of sediment during the construction of Park Presidio Boulevard as well as the sediment from the military golf course. Only Cherry Creek Reservoir in Colorado has a similar sedimentation rate (1.4 inches/year) to Crocker Lake (Table 2). Cherry Creek Reservoir is large (850 acres) and has a huge watershed (245,500 acres) extending across farmed plains to the Rocky Mountains. The lake to watershed ratio of Cherry Creek Reservoir is 1:290 or 2.5 times that of Crocker Lake (Table 1) so has a greater sediment-generating potential.

Table 2. Sedimentation rates of lakes and reservoirs. Lakes fill in by two mechanisms; (i) inorganic silt deposition from inflowing streams and dust and (ii) deposition of organic matter such a dead phytoplankton and water weeds (in shallow waters). Crocker Lake Reservoir appears to be filled with inorganic sediment from the local creeks.

Name	**Sedimentation rate**	
	inches/y	**cm/y**
Natural lake	0.005	0.01
Deep Lake Washington, Seattle during sewage-pollution	0.16	0.4
Shallow lake in agricultural land, Strumpshore Broad, UK	0.2	0.5
Small urban Mountain Lake, San Francisco	0.8	1.9
Crocker Lake, Hillsborough, California	**1.4**	**3.6**
Large urban lake, Cherry Creek Reservoir, Denver, Colorado	1.4	3.6

Crocker Lake Reservoir is thus filling as fast as some of the worst examples in the nation. Actually there are worse examples such as a medium-sized reservoir in Texas and a few small natural lakes in the central agricultural region of the US. However, these reservoirs and small lakes are now extinct and the cause of their demise was obvious, at least in hindsight.

Most natural lakes were formed by the shrinking of glaciers 5,000 to 10,000 years ago as the last ice age ended, from wrinkling of the earth's crust or from volcanic activity (Horne & Goldman, 1994). Obviously, those formed in areas of high erosion have long vanished, becoming marshes or woodlands. In any event, the current erosion at Crocker Lake must be controlled for dredging to have a long-term effect.

7.0 CROCKER LAKE LIMNOLOGICAL PROBLEMS & POTENTIAL MANAGEMENT OPTIONS

7.1 WATERSHED AND IN-LAKE MANAGEMENT OPTIONS

Two general kinds of lake management are possible; in the watershed and in the lake. There are 5 general methods for watershed management to protect lakes and about 17 general methods of in-lake management. The best way to determine what management strategies should be used can be determined by first stating the problems known to occur at the lake and its watershed and then selecting a method(s) most suitable for curing the problem. Table 3 states the problems, and Tables 4 and 5 relate the problems to the possible methods of management of the watershed (Table 4) and in the lake (Table 5).

Table 3. Initial estimates of current problems in Crocker Lake and their probable causes. Fish kills and low dissolved oxygen require summer collections. It is assumed from discussion with the Crocker Lake Hillsborough citizen's group that the reservoir will be used for "non-contact" recreation (thus excluding swimming), that other uses will exclude sailing or boating on the lake, and that dogs and horses that can excrete near the lake will be excluded also. However, fishing may be allowed. A path may be constructed around the lake but up from the edges on the now non-developed side. BCC = Burlingame Country Club. (Adapted from Horne, 2002, 2005).

Problem to be addressed	Probable cause	Work needed soon
Lake facing extinction	Rapid filling in with sediments; loss of ~ 18% of surface area and > 50% of volume. Evidence of very high recent watershed erosion.	Reduce sediment inflow; dredge lake
Fish kills	Not know if they occur or if bottom water dissolved oxygen in depleted. Low DO is likely to occur	Late summer-fall DO/redox survey
Large water level fluctuations	May occur, water is extracted by a pipe from below the spillway level for irrigation at BCC	Install level gauge or stick. Record water level at monthly intervals for 2006
Malodors	Not known but due to likely anoxia (no oxygen) on lake bed. Can kill fish.	Odor sample (sniff test) from deep water in late summer
Algae	Not known. Could result from excessive nutrients from watershed & anoxic lake bed	Measurement of nutrients in early spring & summer
Polymixis	Shallow lake is stirred top-to-bottom by the wind	Take Secchi depth
Lakeshore vegetation	Cattails now present best replaced by seed-bearing bulrush for birds[1]	None

[1] Lower water level in summer will kill some shoreline marsh vegetation and favor rapid-growing cattails over bulrush.

The main immediate problem for Crocker Lake (Table 3) is that with the current high sedimentation rate, it is nearing the end of its life and will soon, possibly within a decade, become first a marsh and then woodland with a small creek flowing through it. Pleasant as that may be, it will no longer provide the rarest of aquatic habitats in the Bay Area, open freshwater surface. In addition, the Crocker family legacy will be lost if the lake turns into a forest. Other problems are less acute and some may be only trivial. The priority for these other potential problems can only be ascertained with a summer limnological survey.

Solutions to the problems at Crocker Lake fall into two classes: those in the watershed (such as erosion or sewage pollution) and those in the lake (such as dredging or weed control). Solutions for the watershed are shown in Table 4 and for the lake in Table 5.

Table 4. The 5 possible watershed methods to restore lakes and reservoirs. (Adapted from Horne, 2002, 2005).

Method	Applicability for Crocker Lake	Use/Action
Treat domestic sewage (& other point-source waste waters, including industry)	Local residents sewer pipes are in unstable ground and may leak to the lake	Need check[1]
Treat non-point sewage (usually replace septic tanks with sewers)	Should not be applicable but there may be grandfather clauses	Need check[2]
Decrease landscape/agricultural fertilizer input	Probably citizen education could reduce this item	Need nutrient data in lake & creeks[3]
Detention basins to block entry of storm runoff & sediment out particles	<u>Highly applicable</u>; sediment and in park erosion must be reduced	Begin work
Constructed wetlands to filter inflow ("biological filters")	<u>May be applicable:</u> can be modified from existing wetlands in park & outside	Consider with detention basins

[1] A sewer pipe was being replaced at the Skyway-Macadamia entrance to the park in 25 January 2006. Sewage on at least that side of the park is led from the ring of homes on the hill crest, down the steep slopes to the main sanitary sewer that runs underneath the main upper access road in the park. It is inevitable that the laterals to the homes and the main sewer pipes will age, slide downhill and crack with earth movement, and be infiltrated by tree roots. This will release nutrients, bacteria and toxicants to the watershed. At least quinquennial remote camera inspections of laterals and the main sewer are needed.
[2] Older homes may have old septic tanks which leak by design. These should be sewered (check with department records).
[3] Measurement of major nutrients (nitrate, ammonia, total phosphorus) are needed a few times in one year in the lake and inflowing creeks.

Conventional Civil-Environmental Engineering provides some solutions to the problems of Crocker Lake shown in Table 3, but Ecological Engineering can be used in addition to or even to replace conventional methods. At Crocker Lake some sewers and storm drains are obviously causing erosion and may leak. However, citizen observations regarding pipes can be supplemented by direct examination of the sewers and lateral pipes using remote cameras. In some East Bay districts an examination of the sewer lateral within a 5-year period is required prior to the sale of any home.

Table 5. Review of the applicability of the in-lake methods for Crocker Lake. (Adapted from Horne, 2002, 2005).

Method	Applicability for Crocker Lake Reservoir	Use/action?
Dredging	Current sediments extensive and make lake too small and shallow, need to remove >20 feet to give summer stratification	Yes
Water level drawdown & water level fluctuation	Seasonal and inter-year variations unknown	Need data[1]
Destratification & lake mixing	Not applicable with make situation worse by stirring up sediments and nutrients	No
Macrophyte (water weed) harvesting	No weeds at present or than small cattail wetlands on edges.	No
Wetland algae filters (off-line wetlands)	Not applicable unless blue-green algae are found as a nuisance in summer-fall	Need data[2]
Algae (phytoplankton) harvesting	Not applicable (see above)	No
Selective withdrawal of hypolimnion water	May already be occurring in summer via pipe to BCC.	Find pipe depth
Dilution/flushing	No spare or clean water available in large amounts	No
Sediment sealing (fabric liners, barriers)	Not applicable unless nuisance weeds are present in summer. Steep reservoir sides reduces potential problem	No
Herbicides (for algae or macrophytes)	Not applicable: wildlife habitat is a priority and would conflict with chemical control of weeds in the water.	No
Oxygenation or aeration	Main method for preventing fish kills, odors, internal nutrient loading. May be applicable if low DO in summer	Need data[3]
Shading (dyes)	Probably not applicable, lake naturally colored	Need data[4]
Sediment sealing (alum, phosloc)	Not applicable lake has too large a drainage for this method	No
Pathogens of algae or macrophytes	Not applicable, algae will become immune	No
Grazers on algae or macrophytes	May be needed if nuisance algae bloom in summer-fall. Grazing *Daphnia* present in winter 2006	Need data[2]
Nutrient harvesting from fish or other biota	Not applicable; N and P removal expected to be small relative to inflows.	No
Biomanipulation	Should be main sustainable method to remove nuisance algae and tie up nutrients.	Yes

[1] Need monthly record of lake surface elevations and water use at BCC (from pumping energy/cost data) for a year. [2] Need summer-fall survey to see if nuisance algae are present. [3] Need summer-fall survey to see if DO is low in summer in deep water and if malodors are present in deep water. [4] Need Secchi disc measurements in summer to determine water transparency.

7.2 SUMMARY OF SELECTED RESTORATION METHODS

For Crocker Lake, three chosen methods or method combinations from Tables 3-4 can be summarized as follows:

A. Needed methods

- Dredging
- Biomanipulation

B. Methods that may be needed after some additional data is collected

- Oxygenation/aeration

The two methods that seem to be needed at once will be discussed in detail and cost estimated (see below). Oxygenation/aeration will be outlined and costs also approximated.

8.0 DESCRIPTION OF SELECTED METHODS 1. DREDGING

8.1 DREDGING - OVERVIEW

One popular option for old reservoirs and small lakes that have become filled in with sediments is dredging. It is a one-time solution with no serious long-term drawbacks. Crocker Lake contains considerable sediment and could benefit from dredging. Dredging is one of the 17 most widely used lake management tools and can be very effective in small water bodies where upstream erosion has been controlled (Table 4). It is less effective or effective for a shorter time if upstream-eroded sediment continues to reach the lake in excessive amounts.

The three main benefits from dredging Crocker Lake are these:

- Restoration of the original lake appearance and function, including increasing the surface area to restore lost open water habitat.
- Restoration of the original two-layer water ecosystem (warm surface, cool depths).
- Restoration of the original reservoir submarine contours.

Dredging can assist with any or all of these three options. The cost increases as the amount of sediment removed is increased.

The restoration of the original appearance is certainly important for Crocker Lake as the reconstruction of the old "Japanese" bridge that fell into the creek about 15 years ago. There are many small steep canyons in California but few preserve the beauty and way of life of a century ago. Both the lake and bridge are part of a whole that is one goal of the Crocker Lake Park concept.

8.2 Details of possible dredging to estimate scale of cost

8.2.1 Option #1. Restoration of original water surface area

The current surface area is ~1.4 acres and the estimated area in 1905 is 1.7 acres, so the water surface has shrunk by 0.3 acres, or 18%. The open lake water has been replaced with a mixture of shallow mud and terrestrial vegetation with some swamp including willows and a marsh including cattails (*Typha* sp.).

Option #1 would require the dredging of about 0.5 acres since the upstream area of the reservoir has become quite shallow (<5 feet). Water needs to be dredged to at least 6 feet to prevent overgrowth by cattails and willows so ~10 feet would seem a good prospect since it would allow some time for the sediment still entering the lake to remain below 6 feet. In January 2006 the lake was full at the time of the bathymetric survey. It is not know how far down the Burlingame Country Club pulls the water levels down in summer. This depth would need to be added to the dredging depth if the dry period were longer than a few months.

Assuming an area of 2,400 square yards (~half an acre) to a depth of 3 yards (9 feet) the amount to be removed would be 7,200 cubic yards (2,400 x 3). Typical costs for dredging and local disposal of the sediments (assuming they were clean) start at $\$10/y^3$. Thus the cost for option #1 begins at ~$72,000 (Table 6). The lake volume would increase by the amount of sediment removed, giving about a 26% increase in volume over the current situation. This additional capacity could support the lake and/or the Burlingame Country Club in times of drought.

Table 6. Cost estimates for dredging of Crocker Lake. BCC = Burlingame Country Club, that uses the water for irrigation downstream.

Dredging option	Benefit summary	Volume increase	Volume removed & estimated cost
#1. Restoration of original lake surface	Restores beauty of the entire lake surface Provides some additional water for BCC	4.5 af (26%)	7,200 y^3 $72,000
#2. Restoration of original 2-level ecosystem, preventing lake extinction	Restores lake ecology Prevents lake extinction Provides much water for BCC	9 af (52%)	15,000 y^3 $150,000
#1 and #2 combined[1]	**Restores surface area & most of ecology**	**13.5 af (78%)**	**22,000 y^3 $220,000**
#3. Restoration of original submarine contours	Restores original lake shape underwater	12.3 af (72%)	20,000 y^3 $200,000 (added to #1 and 2)

[1]Recommended option

8.2.2. Option #2. Restoration of the original two-layer water ecosystem (warm surface, cool depths) and prevention of lake extinction within a decade

When lakes and reservoirs are very shallow (>5 m small lakes; <10 m deeper lakes) the wind and convection forces frequently mix the water top-to-bottom (= polymictic, or many-mixing, lake). Thus the water and bottom sediment temperatures follow those of the air quite closely although with about a 6-week lag due to the high specific heat of water. In polymictic lakes only warm-water organisms such as bass and bluegill can survive comfortably through the summer. Also polymictic lakes are usually more eutrophic (more productive, more algae and fish) than stratified lakes, since the mixing of the whole water column moves nutrients directly from the sediments to the sunlit upper water.

In deeper lakes and reservoirs, the wind is not strong enough to mix the water all the way to the bottom and two layers form: the surface-water epilimnion layer is less dense than the lower, cold hypolimnion and thus floats on top from spring to autumn. This leaves a deep layer of cool water for trout and other cold-water organisms and increases the diversity of the system. The separation of the two layers also reduces eutrophication, since algae in the upper sunny water cannot access nutrients near the sediments. For restoration of a two-layer ecosystem, at least a depth of 35 feet would be needed, or about 15 feet more than the current layout. The thermocline (boundary between warm and cool layers) would then form at about 10-15 feet in spring and drop to the bottom by the fall.

Deeper dredging should be carried out along with the Option #1 but could be done separately with a smaller lake. Costs will be assumed for work in addition to the Option #1. The current area of the reservoirs is ~6,300 square yards (~1.4 acres) but the edges slope steeply down so that the area to be excavated drops with depth. A full analysis of the volume of sediment requires a more sophisticated calculation but it can be assumed that the mean depth-averaged area to be dredged is about half of the surface or about 3,000 square yards (0.6 acres). If the sediment were removed to a depth of 5 yards (15 feet), the amount to be removed would be 15,000 cubic yards (3,000 x 5).

Typical costs for dredging and local disposal of the sediments (assuming they were clean) start at $\$10/y^3$. Thus the cost for option #2 begins at ~$150,000 (Table 2). The lake volume would increase by the amount of sediment removed (9 acre-feet), increasing the capacity over the current situation by about 50%. The additional water could support the lake and/or the Burlingame Country Club in times of drought.

8.2.3. Option #3. Restoration of the original reservoir submarine contours

This option would be the full lake restoration and would provide maximum protection as well as restoring the original ecosystem. The reservoir would be excavated to the original depth as determined by mapping with sonar and some checking with sediment cores. The estimate of maximum depth at this point is not easy given the dearth of data but it has been assumed (Table 1) based on the depth of the creek immediately downstream of the dam. The estimated original volume is 43 af (Table 1) and Options #1

+ #2 (4.5 + 9 = 13.5 af) add to the current estimated volume of 17.2 af to give a volume of 30.7 af. Thus the final sediment removal option volume is 43-30.7 = 12.3 af or about 20,000 y^3. Note that this estimate is more approximate than for Options #1 & #2.

8.3. RAISING THE WATER LEVEL COMPARED WITH DREDGING

There are two ways of raising the water level: (i) keeping the existing dam and raising the water level in the existing dam, or (ii) raising the dam and the water level behind it. Either option would flood the shallow marshes at the upper end or increase the water volume retained so they would have some similar effects to dredging. There would be an advantage to raising the water level, in that the surface area of the reservoir would increase, but the sides are so steep that this effect would be small.

Raising the water level by raising the overflow height would be inexpensive compared with dredging. Adding to the dam would be expensive (~$1 million or more?). It is unlikely that the dam safety authority would look favorably on increasing the pressure on a 100-year-old earth-filled dam that is showing signs of erosion from the winter rains in 2006. A more expert opinion could be sought on this matter. A new dam would have permitting concerns for downstream flows to San Francisco Bay but these would probably not be overwhelming, considering the use of the water downstream at present by BCC.

8.4 WHY THE RESERVOIR MUST BE DREDGED SOONER THAN LATER

The annual sediment deposition rate for Crocker Lake is very high at about 1.4 inches/y (0.11 feet/y or 3.5 cm/y). Since over a third of the present lake is over 15 feet deep it would take over 100 years to fill it in completely. So why should there be an urgent need for dredging now? There are two reasons:

1. **Lakes fill in faster near the end of their life**. The final phase of extinction for all lakes is non-linear. Until now the lake has been filled in by inorganic sediment from the surrounding land. As the water shallows to about 10-15 feet, submerged plants begin to grow and fill the lake in with organic sediments generated from the peat of decayed plants. Crocker Lake has reached this critical stage and can be expected to change from a lake to a marsh with almost no open water within 10 years and become dry land in 20 years. Submerged plants can be restricted by chemical applications, but this is probably not an appropriate solution for Crocker Lake given its focus on wildlife and use of water downstream.
2. **New high rates of erosion**. The 2006 survey showed very serious new erosion of the upstream creeks. The average rate of 1.4 inches/y was probably greatly exceeded this winter. Since there is no sign that this accelerated rate of erosion is to be controlled, the lake may well fill with sediment in a few years.

When the lake silts up over the next 10-20 years to become first a marsh then a woodland, several consequences follow. First, it will eliminate the summer water store for the Burlingame Country Club irrigation supply. A small summer flow will be available but no storage from winter can occur. Second, and perhaps more importantly, the loss of the lake will make a mockery of "Crocker Lake" park. Third, the costs for dredging will increase rapidly as the organic sedimentation adds to the present inorganic sediment deposition. For these three reasons (water supply, historical rationale for the park, and dredging costs) it is recommended that one or more of the dredging options be carried out as soon as practicable.

8.5 Disposal of the dredge spoils: In-site options

Dredging itself costs about $5/cubic yard in most sites. Disposal is a variable cost depending on two factors; the distance to the disposal site and the quality of the sediment. For Crocker Lake most of the sediment appears to be eroded from the canyon so should be of good quality with no toxicants. However, drainage from the streets may have provided lead (from gasoline prior to the modern lead-free kind), copper (from brake linings of more expensive automobiles), zinc (from particles of automobile tires and zinc-plated gutters), PAHs (poly-cyclic aromatic hydrocarbons from used automobile crankcase oil that drips onto the road), and pesticides (from garden and roadside vegetation control, termite and other insect control). These can be tested for and, if present, the cost will increase since special sites are used for toxic disposal. However, if the sediment is just moved within the canyon, tests may not be needed.

The recommended course of action for dredging is to combine Options #1 and #2 giving a net sediment volume of about 22,000 cubic yards. This is quite a large volume; for scale, a full-sized pickup truck holds about 6.5 y^3 and large dump trucks up to 20 y^3. I have used a typical cost for haulage to a nearby site of $5/cubic yard for estimated costs. However, I do not know if there is a convenient local landfill site available. Costs can rapidly increase if the sediment has to be hauled to Livermore or disposed of in the open sea.

It is thus fortunate that there are three good possibilities for in-canyon disposal at Crocker Lake and at two of these sites fill may be needed for other reasons. Cost for local disposal is low. The sites within the park that would benefit from additional sediment are in order of priority:

- Raising the old berm above the lake to re-create a sedimentation basin
- Raising the turning area just below the berm to create a more level site
- Extending the area near the Macadamia-Skyway entrance to create better off-road parking

These sites should be considered for disposal of any dredge spoils.

9.0 EROSION CONTROL IN THE WATERSHED

9.1. Erosion processes in natural and urban streams

Natural erosion occurs from land wasting and streambank erosion. In dry areas such as California, erosion is high since there is sometimes not enough dense vegetation to prevent raindrops from shattering wet soil into small particles easily washed away in floods. Under natural conditions only about 5% of rain runs off directly into creeks. The remaining 95% of precipitation sinks into the soil and slowly seeps into creeks via the shallow groundwater table (vadose zone). In developed areas, impervious house roofs, parking lots, and streets send 100% of rain flows directly to the creeks increasing the natural flows many times. Compacted soils in driveways, paths and most garden soils also show increased runoff and decreased percolation ability. In Hillsborough probably about 25% of the total land area has increased runoff.

When the increased discharge of street and house runoff enters the creek, the natural erosive forces on the stream bank are enhanced. Downcutting and sidecutting occur until a new equilibrium is established between creek shape and high flows. The amounts of sediment eroded even from small creeks is surprisingly large. In the Crocker Lake drainage, we observed several recent landslides and bank erosions from the November 2005 heavy rains. In addition, dust and construction or garden soil makes its way to the streets and is added to the stream load.

Streambank erosion is natural and has been considerably enhanced in the Crocker Lake drainage. But whether natural or enhanced, the sediment is retained behind the dam. The problem is how to prevent new sediment reaching the lake, especially once it has been dredged to restore some of its original area and depth.

9.2 FUTURE PROBLEMS WITHOUT EROSION CONTROLS

If Crocker Lake is dredged it will continue to fill in at the rate of 0.3 feet per year and will thus need dredging again in the relatively near future. In terms of aesthetics it will soon lose a substantial area of open water in a few years, especially if there is another large rain like that of November 2005 or about 15 years before that eroded large chunks of the creek upstream. Therefore erosion control upstream of the lake would be advisable if it can be carried out economically. Fortunately, it seems that the lay of the land in the canyon and past history allow for a pleasing combination of check dams/wetlands with reduction in the cost of disposal of the dredge spoils.

9.3 EROSION CONTROL USING EXISTING LAND LAYOUT: RAISING THE EXISTING BERM

In new planned developments, the increased drainage flow from urban areas is contained (for small storms of 0.5 to 0.75 inches) or held in detention basins for a few hours (larger storms). Usually the detention basin is a year-round ugly depression in the ground, but in more advanced developments, wetlands have been incorporated. Nonetheless, these require space which is hard to find in existing developments, especially old ones such as Hillsborough. Thus something within the existing 60-acre park would be better for erosion control. Unfortunately, the very steep slopes of the canyon make check dam or retention basin sites difficult to find.

To overcome this problem, John Roberts has suggested using the level area just upstream of the lake. He has concluded that this area once served as a de facto sedimentation basin. It was created behind the otherwise mysterious large berm, which was originally the downstream wall of the detention basin and is drained by the still-functioning concrete spillway. The original basin is now completely filled with sediment and supports a natural wetland of high ecological value. John Roberts suggests that we could resurrect the old detention basin by increasing the level of the berm. In principle, the old basin could be excavated, but this would give two problems: what to do with all the sediment and the temporary disturbance of the wetland birds and animals.

Increasing the level of the existing berm by only a few feet would provide long-term sediment protection with only a minor disturbance of the wildlife. As the sediment accumulated in the area following storms, wetland and other plants would grow over it as they have done for the past century. An extension of the current spillway would be needed but this is only a small task.

Sediment for the construction of the berm would be costly but the sediments from the dredging of the lake provide an ideal source. In addition, using the sediments this way would substantially reduce the cost of dredging since the two sites are within a few hundred meters of each other.

10.0 BIOMANIPULATION

10.1 BIOMANIPULATION OVERVIEW

Biomanipulation is the management of the ecosystem to produce the desired effect in terms of water quality, biota and lake health. Biomanipulation should be the eventual goal of all lake management since it offers a sustainable solution to lake problems. However, if outside influences, sediment, nutrients, fish stocking, weed cutting, water extraction and others continue to upset the natural balance then some other management techniques (eg, dredging) are needed. Thus the goal of biomanipulation in some lakes and most artificial reservoirs is to reduce costly lake maintenance to a minimum. Ecological Engineering is defined as sustainable and its concepts are integral in biomanipulation.

10.2 DETAILS OF BIOMANIPULATION FOR CROCKER LAKE

Biomanipulation in lakes is the adjustment of natural lake forces such as zooplankton grazing and riparian plant sediment control to give a desired and sustainable high quality lake. There are three main components for most lakes including Crocker Lake:

- <u>Enhancement of large zooplankton that eat algae</u> that cloud the water. The resulting clear water is aesthetically pleasing. The zooplankton are protected first by ensuring that small fish that eat them are not over-abundant (normally this is done by stocking or not fishing out larger predatory fish that eat small fish). Large zooplankton can filter algae from the surface water of the entire lake in a week if allowed to become abundant. Second, by allowing some submerged or shoreline emergent vegetation (e.g. pondweeds or bulrush), a protected area for zooplankton to hide from small fish grazing in the daytime is created. Third, ensuring that there is adequate oxygen in the deepest, dark water of the lake provides an alternative refuge from small fish predation.

- Enhancement of some submerged and shoreline vegetation. Not only does this vegetation provide protection for large zooplankton but the plants stabilize the sediments to keep eroded mud from clouding the lake water. In addition, nitrate is removed in the root zone by bacteria that convert it to nitrogen gas. The main need for riparian vegetation is a water level that does not fluctuate too much (few feet/year). Negotiations with the Burlingame County Club may be needed to ensure more stable water levels in return for greater water volume following dredging.
- Removal of sediment grubbing fish (primarily introduced European Carp). Since carp were introduced to North America by a misguided German professor, they have been a nuisance. In lakes they grub up the bottom, recycling nutrients that grow algae, but also killing submerged plants and stirring mud into the water. If carp or similar large bottom-feeding fish are present, then their eventual removal is recommended. Catfish, which are also bottom fish, are not a problem since the larger individuals are predatory on other fish, not bottom insects or mud. If fishing is allowed in the lake, then notices need to be posted not to dispose of living "bait fish" in the lake. These small fish are usually imported from the east of the US and contain many nuisance fish including green sunfish and carp. Some anglers dump any remaining bait fish into the lake when fishing is completed.

10.3 Costs of biomanipulation

Biomanipulation is sustainable and thus is essentially free. However, some actions such as plantings and fish removal have some small costs. These cannot be estimated in detail this time but should be under $10,000 over the first five years.

11.0 LAKE MANAGEMENT METHODS THAT MAY BE NEEDED AFTER ADDITIONAL DATA IS COLLECTED

11.1 OXYGENATION/AERATION

Until a survey of dissolved oxygen at depth is make in Crocker Lake, it is not known if oxygen/aeration is needed. Aeration (addition of oxygen as compressed air bubbles) is the most common form of lake management. Aeration is inherently inefficient at oxygen addition since air is 80% nitrogen gas and only 20% oxygen gas. Thus oxygenation (addition of pure oxygen as bubbles or dissolved gas) is sometimes used to reduce the size and noise of the equipment. Mixing the lake with compressed air bubbles is more efficient and can oxygenate the lake if high-oxygen surface water is stirred down to the sediments.

These methods replace missing oxygen in eutrophic lakes where oxygen has been depleted in deep water and in sediments. Oxygen depletion in lakes is due to eutrophication and consequent decay of sunken algae on the lake bed. The main advantages of maintaining oxygen in lakes are that highly toxic hydrogen sulfide is not produced and that internal loading of phosphate and ammonia from the sediments is reduced. Oxygenation or aeration is also effective in reducing or eliminating fish kills. For stratified lakes, aeration or oxygenation of the hypolimnion (deep cool water) is preferred. Current methods applicable to a small reservoir such as Crocker Lake would probably use small air or oxygen pumps powered by solar or wind power and add air or oxygen in the deepest area.

11.2. COSTS OF AERATION OR OXYGENATION

As stated earlier, until a survey of dissolved oxygen at depth is made in Crocker Lake, it is not known if oxygen/aeration is needed. However, given the small size of the lake, estimated costs for an aeration or oxygenation installation would range from $25,000 to $100,000, depending on the severity and duration of the low-oxygen periods (again, if any exist).

12.0 COMPARISONS WITH PREVIOUS WORK AND RECOMMENDATIONS FOR CROCKER LAKE

Only two reports were found that refer to the Crocker Lake Reservoir in terms of its limnology (Aquatic Environments Inc (1999), and Beatty (2002)). There is a short half-page section in Beatty (2002) that refers to the lake with the following points (comments in italics are mine):

- The water level has remained fairly constant and is fed by a year-round stream [*there are springs in the Canyon*] but there are no records of the fluctuation in lake level with time.
- The amount of water drawn from below the spillway by the Burlingame Country Club for summer golf-course irrigation is unknown [*the pipe has recently been repaired but the intake depth is not known*].
- There is no record of dredging in the reservoir.
- “Algae” and cattails are removed periodically to satisfy State Dept. of Dam Safety requirements. [*It is assumed that floating debris or plants growing around the exit pipe are removed. “Algae” is probably a term encompassing pond weeds.*]
- The depth is assumed to be 12-15 feet. [*Soundings in January 2005, when the lake was full, found much water at this depth but maximum depths of around 20 feet.*]
- The lake has become shallower due to silt washed in with winter rains.
- There is no record of water quality or water chemistry.
- Chemicals or nutrients from streets and surrounding homes may be in the lake but these may be buffered by the upstream vegetation.
- The lake appears in good condition and the water is clear but a photograph in 1981 shows cloudy water. [*It is not clear how a photograph could illustrate water clarity.*]
- Frogs and waterfowl were present.
- There are no records of problems or repairs at the dam.

Most of the comments by Beatty seem reasonable in the light of this 2006 report, although it is not clear at what time(s) of year Beatty visited the reservoir.

The second report of Crocker Lake was the 1999 Aquatic Environments (AE; Alamo, CA) document. They visited Croaker [*sic*] Lake and made some detailed management recommendations for the Town of Hillsborough. No limnological data was taken but some details such as the "undesirable" presence of edge vegetation such as cattails and overhanging branches of trees. The scope of work for AE focused on monthly maintenance needed for the lake. A few of the aspects of the AE's recommendations (for example, possible aeration) are similar to one in this report.

However, the AE study differs from this report in that it was designed to give Crocker Lake tidy shoreline edges, no algae or floating weeds. Such a concept is appropriate for lakes and ponds in city centers, but it requires detailed monthly maintenance and application of weed-control chemical and dyes. Given the current idea that Crocker Lake and the surrounding 60 acres should be a mostly natural area with minimal human interference, the Aquatic Environments Inc. recommendations such as algaecide applications are no longer applicable. Other recommendations made by AE, such as weir maintenance, may be needed as the future design of the park becomes clearer.

13.0 REFERENCES

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Fig 7. Map of Crocker Lake Area