

LIMNOLOGICAL SURVEY OF CHRISTOPHER COLUMBUS AND ARCHER
LAKES WITH RECOMMENDATIONS FOR WATER QUALITY
IMPROVEMENTS AND MANAGEMENT



Prepared for the City of Tucson, Parks and Recreation Department

David Walker, PhD
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Site Description and Background

Christopher Columbus (CC) Lake is a small, relatively shallow, urban impoundment in Tucson, Arizona with a surface area of approximately 5 hectares and an average depth of roughly 1 meter (Fig. 1). Archer is a smaller lake immediately to the west of CC. There is a hydrologic connection between the two lakes and incoming water is first pumped into Archer eventually exiting via a small, man-made stream into CC Lake (Fig. 1). The main water source to the CC/Archer complex is from a groundwater well approximately 325 meters to the northwest of CC Lake (Fig. 2). Water is then pumped from this well into Archer near the vicinity of site ARC-1 (Fig. 1).

The outfall from the Roger Road Wastewater Treatment Plant (WWTP) lies approximately 150 m to the east of CC Lake and empties directly into the Santa Cruz River (Fig. 1). The Roger Road WWTP, built in 1951, treats both residential and industrial sewage from a population of approximately 419,000 residents of Tucson. It also receives waste from five major hospitals and has a maximum capacity to treat 148 million liters of effluent per day. WWTP operations utilize primary (screening/settling) and secondary treatment processes (trickling biofilter, nitrification-denitrification), followed by chlorination/bromination, before discharging effluent into the Santa Cruz River where much of the effluent infiltrates into the streambed (Galylean, 1996) with incidental recharge into the local aquifer. Since the eastern bank of the Santa Cruz River in the area adjacent to the wellhead and CC Lake is lined with soilcrete, this likely means most infiltration is either directly through the bottom of the streambed or into the alluvium to the west of the active channel, toward the direction of the wellhead and CC Lake.

Were it not for treated effluent discharges from WWTPs, the Santa Cruz River would be dry the vast majority of the year. Annual number of days with zero flow in the Santa Cruz River upstream of the outfall between water years 1999 and 2006 ranged between 300 and 330. The area downstream of the outfall has perennial flow.

Christopher Columbus Park, and CC Lake in particular, is a very popular recreational facility for Tucson residents. CC Lake is part of the Arizona Game and Fish Department's Urban Fisheries Program. Due to heavy angling pressure, most lakes in the urban fisheries program are operated on a put-and-take basis. Fish species commonly stocked (or known to exist) within the lake are bluegill, channel catfish, carp, crappie, hybrid sunfish, largemouth bass, and redear sunfish. Grass carp (white amur) of the triploid variety (sterile) were known to have existed in the lake at one time. Given the close proximity to the Santa Cruz River, obtaining a new license for their stocking seems unlikely. Rainbow trout are stocked during the winter months. Given that the average water temperature in the region is far higher than what any salmonid species could tolerate, it is highly unlikely any of these survive during the warm summer months. Boating on the lake is possible (canoes under 17 feet and boats under 14 feet; gas motors are prohibited). Swimming and wading are not allowed; however, persons have been observed swimming in the lake incidentally while sail-boarding and others have been observed wading in the vicinity of both boat ramps. Archer Lake is not stocked and no fishing signs are posted. Primary use at this small lake is for model boat use.

Fish kills of various magnitudes have been reported in both CC and Archer Lakes (the latter while not officially stocked, does contain various species of fish through either public stocking or fish swimming from CC to Archer). The exact causes of these fish kills is unknown. Dissolved oxygen depletion is a primary cause of fish kills in aquatic systems but these levels were not taken during previous fish kills. Both lakes have a history of cyanobacterial "blooms" (large mono-specific numbers) and large numbers of *Coelosphaerium* sp. have been identified by the author in the past.

Figure 1. Spatial Relationship of CC and Archer Lakes to the Santa Cruz River and the Roger Rd. WWTP.



Figure 2. Spatial Relationship of the Wellhead, the Santa Cruz River, and CC Lake.



Methods

Four sites were established; 3 within CC and one within Archer (Fig. 1). Due to the shallow-ness of Archer, launching a boat was impossible and wading deemed unsafe so samples were taken from shore close to where water is introduced into the system. GPS locations were:

ARC-1: 32°16'58.28"N, 111° 2'1.68"W

CC1: 32°16'58.08"N, 111° 1'52.89"W

CC2: 32°17'3.25"N, 111° 1'54.16"W

CC3: 32°17'7.90"N, 111° 1'57.44"W

To account for temporal variability, we sampled every other month from May 2007 through June 2008. Specific sampling dates were:

05/24/07

08/02/07

10/09/07

12/20/07

02/07/08

04/22/08

06/18/08

Water samples were collected from a small jon boat. Due to the very shallow nature of the lake, we did not collect samples at depth. Samples were collected from just beneath the surface in a horizontal Beta-style sampling bottle and transferred to appropriate containers for preservation. All samples collected were kept on ice for transport to the analytical laboratory (Columbia Analytical). The analytes sampled are given below.

Table 1. Analyte List

| Analyte | Reason | Lab |
|------------------------------------|--|---------------------|
| Ammonia-N | algal nutrient | Columbia Analytical |
| Nitrate+nitrite-N | algal nutrients | Columbia Analytical |
| Total Kjeldahl nitrogen | algal nutrient | Columbia Analytical |
| Total Phosphorous | algal nutrient | Columbia Analytical |
| Total and dissolved organic carbon | algal nutrients/measures of primary production | Columbia Analytical |
| Iron | measure of reduction/nutrient availability | Columbia Analytical |

| | | |
|---------------------------------|--------------------------------|---------------------|
| Manganese | measure of oxidation/reduction | Columbia Analytical |
| Arsenic | toxicant | Columbia Analytical |
| Selenium | toxicant | Columbia Analytical |
| Mercury | toxicant | Columbia Analytical |
| Dissolved oxygen | physico-chemical | UA |
| pH | physico-chemical | UA |
| Specific conductivity | physico-chemical | UA |
| Oxidation-reduction potential | physico-chemical | UA |
| Algal counts and identification | biological | UA |
| Chlorophyll <i>a</i> | biological | UA |

We used an Ekman dredge to collect sediment samples from site CC1 and CC3 on 5/24 and 8/02/07. Sediment was analyzed for levels of total organic carbon, total Kjeldahl nitrogen, total nitrogen, nitrate+nitrite-N, total phosphorous, beryllium, cadmium, calcium, chromium, copper, iron, manganese, sodium, and zinc.

Physico-chemical profiles were obtained using a Hydrolab Surveyor and Datasonde 4a. Measures of water temperature, pH, dissolved oxygen, oxidation-reduction potential (ORP), specific conductivity, were taken every 0.5 m starting from the top to the bottom of the lake at each site.

Chlorophyll *a* concentrations were performed using a Turner Designs TD-700 benchtop fluorometer following EPA-approved methodology. Algae counts and identifications were performed using an Olympus BH2 phase contrast light microscope and either a Sedgwick-Rafter cell or Neubauer Improved Hemacytometer used for enumeration using standard methodology.

To calculate nutrient loading to the lake(s), we sampled from the wellhead on 10/9/07.

We also sampled measures of water clarity and/or transmittance by using a Hach turbidimeter and a standard, black and white, secchi disk in the field. Sampling occurred between the hours of 1000 and 1400 local time.

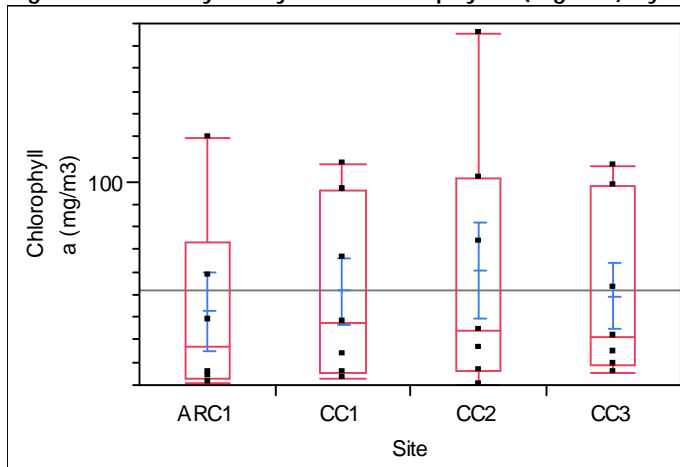
Results

Depths for all sites within CC were similar. CC is a very shallow lake with an average depth of 0.6 m and a maximum depth of between 1.2 and 1.5 m.

Algae

Chlorophyll *a* values (a measure of standing biomass of algae) varied greatly depending upon the season but, overall, were very high with an average annual concentration of 51.44 mg/m³ (Fig. 3).

Figure 3. Oneway Analysis of Chlorophyll *a* (mg/m³) By Site



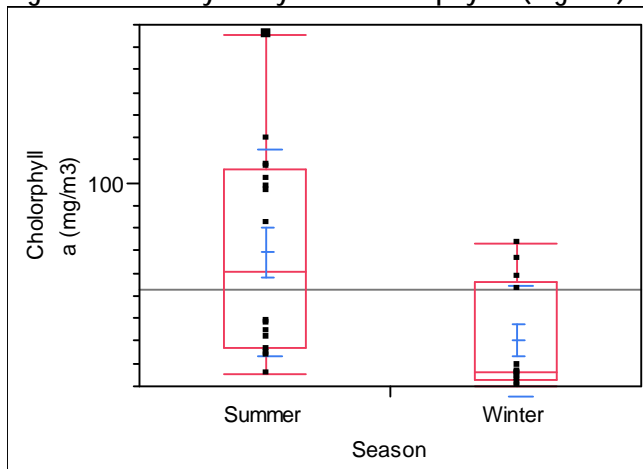
Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Site | 3 | 1131.382 | 377.13 | 0.1882 | 0.9033 |
| Error | 23 | 46077.480 | 2003.37 | | |
| C. Total | 26 | 47208.861 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|-------|--------|---------|-----------|-----------|-----------|
| ARC1 | 6 | 42.6067 | 18.273 | 4.807 | 80.407 |
| CC1 | 7 | 51.3814 | 16.917 | 16.385 | 86.378 |
| CC2 | 7 | 60.9829 | 16.917 | 25.987 | 95.979 |
| CC3 | 7 | 49.5229 | 16.917 | 14.527 | 84.519 |

The lack of regional seasonal differences usually results in a simplification of periods for algae growth; a non-growing season (i.e. winter) and a growing season (i.e. summer). For all sites combined, the mean summer (May – October) chlorophyll *a* levels were, as expected, greater than those during winter (November – April) (Fig. 4). Surprisingly, mean chlorophyll *a* levels in the CC/Archer complex during winter were still higher than most other urban lakes in the area during the summer. Mean concentrations of chlorophyll *a* during the summer at the CC lake/Archer complex were over twice the levels allowed by Arizona Department of Environmental Quality's (AzDEQ), Narrative Nutrient Criteria for Arizona Lakes and Reservoirs (NNC) and the winter chlorophyll *a* levels are at the upper limit (30 mg/m³) of those annual averages allowable by the same rule. Needless to say, algal biomass in CC and Archer Lakes is continually very high.

Figure 4. Oneway Analysis of Chlorophyll a (mg/m³) By Season

Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Season | 1 | 10445.097 | 10445.1 | 7.2058 | 0.0125 |
| Error | 26 | 37688.119 | 1449.5 | | |
| C. Total | 27 | 48133.216 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|--------|--------|---------|-----------|-----------|-----------|
| Summer | 16 | 69.2713 | 9.518 | 49.706 | 88.836 |
| Winter | 12 | 30.2425 | 10.991 | 7.651 | 52.834 |

Breaking down the specific types of algae in CC and Archer lakes reveals that both are dominated by species of cyanobacteria (Fig. 5). Taxonomically, cyanobacteria are more closely related to true bacteria than algae; however, ecologically they behave more similarly to phytoplanktonic algae. For the purposes of this report, cyanobacteria will be regarded as algae.

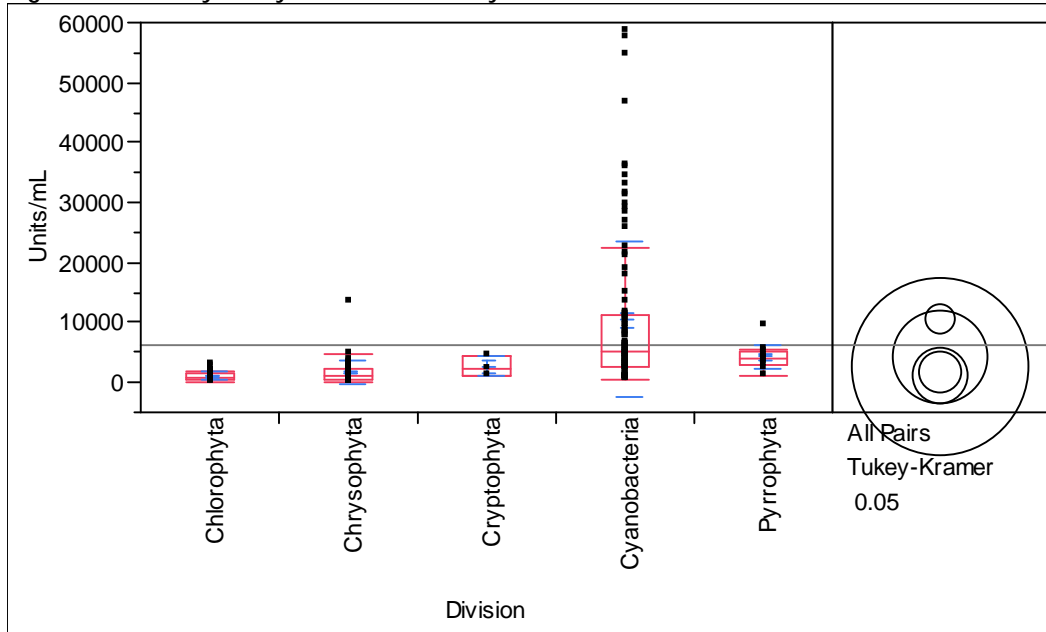
Microcystis sp. was the dominant type of algae, and cyanobacteria, found within CC and Archer Lakes (Fig. 6). Other notable types of cyanobacteria observed were species of *Arthrospira*, *Merismopedia*, *Oscillatoria*, *Cylindrospermopsis*, *Gomphosphaeria*, and *Anabaena*. All of these species are capable of producing a great variety of neuro- and/or hepato-toxins and, under ill-defined environmental conditions, have been known to cause illness and/or death in aquatic and terrestrial wildlife species and humans following either direct or incidental ingestion. It is impossible, however, to determine if any species is producing toxin(s) without actually sampling for the individual toxins; a task outside the scope of this project. The presence of so many species capable of toxin production is cause for concern.

Large amounts of cyanobacteria are often associated with eutrophic (nutrient-enriched) conditions; however, they are also part of normal lake flora during summer. Problems arise only when they dominate the phytoplankton assemblage, as is the case in CC and Archer. Cyanobacteria are noxious to most types of zooplankton and are usually not grazed by them so they are able to out-compete other forms of algae. Generally, cyanobacteria have faster generational times than other forms of algae so that blooms can occur rapidly.

Cyanobacteria dominated the phytoplankton assemblage of CC and Archer lakes even during the cooler, shorter winter months. This is one reason why algal biodiversity was relatively low in both lakes. Currently, conditions within CC and Archer greatly favor the growth of large amounts of cyanobacteria throughout the year.

The numbers of cyanobacteria found were often far larger than the 20,000 cells/mL allowed under AZZDEQ's NNC. Additionally, the same NNC does not allow cyanobacteria to be in such an amount as to constitute > 50% of the total phytoplankton assemblage. Percentage of cyanobacteria in CC and Archer lakes were almost always well above this level.

Figure 5. Oneway Analysis of Units/mL By Division



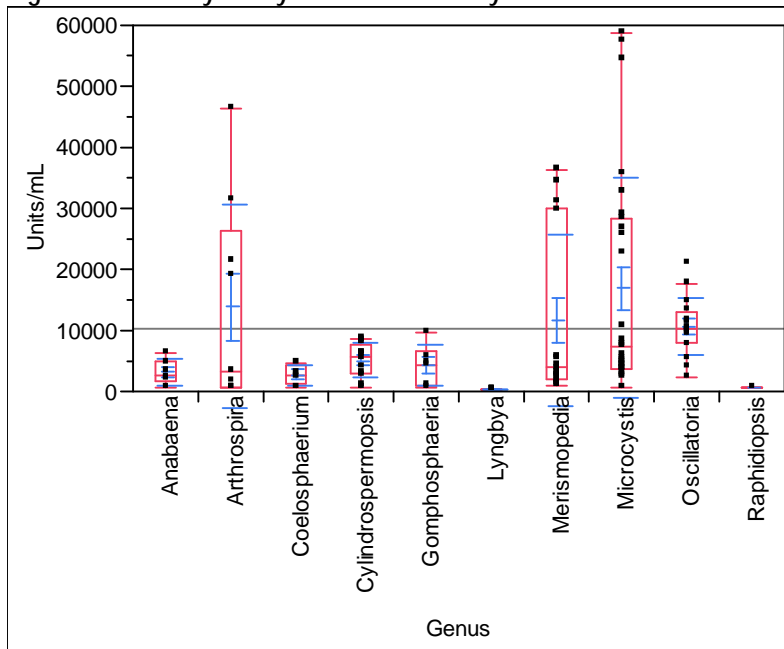
Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|-----|----------------|-------------|---------|----------|
| Division | 4 | 3797742295 | 949435574 | 10.8101 | <.0001 |
| Error | 192 | 1.6863e+10 | 87828851 | | |
| C. Total | 196 | 2.0661e+10 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|---------------|--------|---------|-----------|-----------|-----------|
| Chlorophyta | 30 | 1020.0 | 1711.0 | -2355 | 4395 |
| Chrysophyta | 54 | 1620.4 | 1275.3 | -895 | 4136 |
| Cryptophyta | 3 | 2600.0 | 5410.8 | -8072 | 13272 |
| Cyanobacteria | 99 | 10440.4 | 941.9 | 8583 | 12298 |
| Pyrrophyta | 11 | 4236.4 | 2825.7 | -1337 | 9810 |

Figure 6. Oneway Analysis of Units/mL By Genus



Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Genus | 9 | 2868494697 | 318721633 | 2.0651 | 0.0411 |
| Error | 89 | 1.3736e+10 | 154339592 | | |
| C. Total | 98 | 1.6605e+10 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|--------------------|--------|---------|-----------|-----------|-----------|
| Anabaena | 6 | 3183.3 | 5072 | -6894 | 13261 |
| Arthrospira | 9 | 13922.2 | 4141 | 5694 | 22151 |
| Coelosphaerium | 4 | 2725.0 | 6212 | -9617 | 15067 |
| Cylindrospermopsis | 12 | 5116.7 | 3586 | -2009 | 12243 |
| Gomphosphaeria | 6 | 4316.7 | 5072 | -5761 | 14394 |
| Lyngbya | 4 | 375.0 | 6212 | -11967 | 12717 |
| Merismopedia | 14 | 11628.6 | 3320 | 5031 | 18226 |
| Microcystis | 27 | 16874.1 | 2391 | 12123 | 21625 |
| Oscillatoria | 16 | 10656.3 | 3106 | 4485 | 16827 |
| Raphidiopsis | 1 | 600.0 | 12423 | -24085 | 25285 |

Nutrients

Nutrients are an exceedingly important aspect of the structure and function of aquatic ecosystems. This is especially true in closed urban lakes where little or no dilution or flushing of nutrients occurs and these are constantly recycled within the lake. Due to the importance of nutrients in aquatic ecosystems, some requisite background of their chemistry, biological importance, and inter-convertability is warranted. Two of the most vital macronutrients in aquatic ecosystems are nitrogen and phosphorous.

In aquatic systems, the forms of nitrogen of greatest interest are (in order of decreasing oxidation state):

- Nitrate (NO_3^-)
- Nitrite (NO_2^-)
- Ammonia (NH_3)
- Ammonium (NH_4^+)

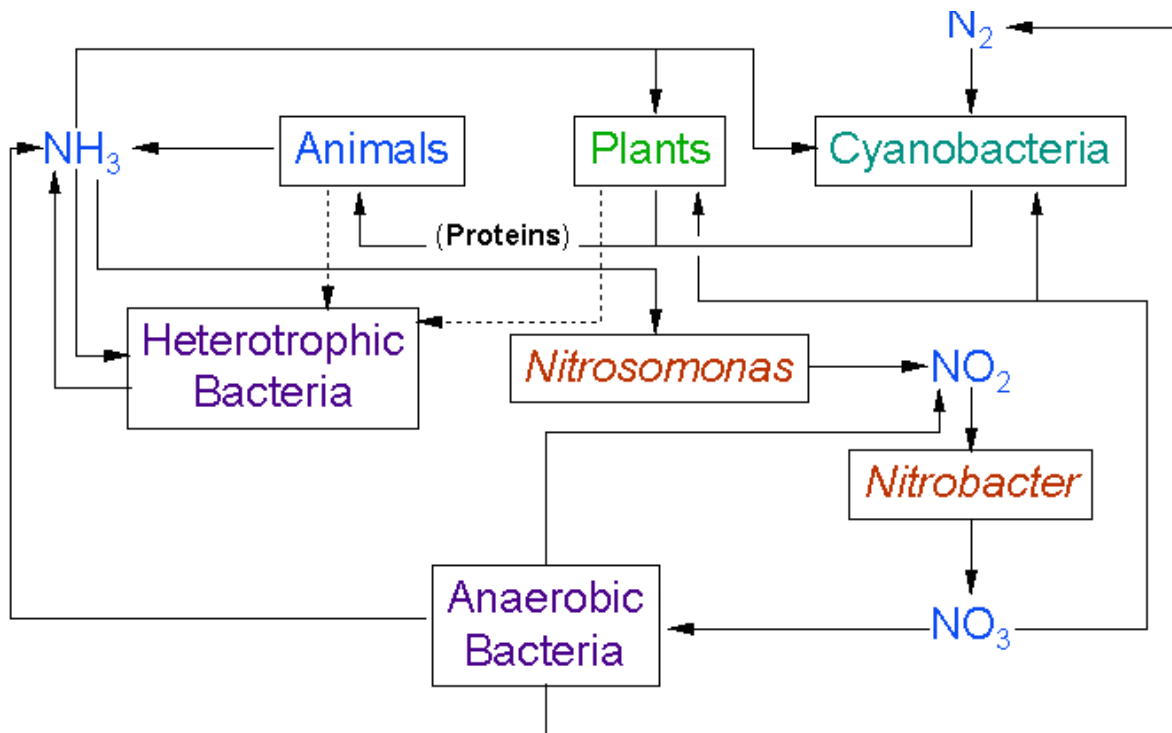
- Organic-N (amino groups)

Total oxidized nitrogen is the sum of $\text{NO}_3^- + \text{NO}_2^-$. Organic nitrogen is the organically bound fraction and includes such natural materials as proteins and peptides, nucleic acids and urea, and numerous synthetic organic materials. Analytically, organic nitrogen and ammonia can be determined together and referred to as "Kjeldahl nitrogen", a term that reflects the technique used in their determination. Total Kjeldahl nitrogen (TKN) is not synonymous with total nitrogen. If TKN and NH_3 are determined individually, "organic nitrogen" can be determined.

$$\text{TKN} + \text{NO}_3 + \text{NO}_2 = \text{Total Nitrogen.}$$

All forms of nitrogen (organic and inorganic) are interconvertible. The *nitrogen cycle* is an important component of overall biogeochemical cycling in aquatic systems.

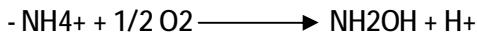
Figure 7. The Nitrogen Cycle in Aquatic Systems



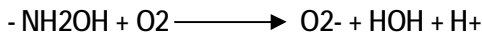
Ammonification is an important process in the nitrogen cycle and is, basically, the process of decomposition with production of ammonia or ammonium compounds especially by the action of bacteria on organic matter. Aquatic animals commonly excrete NH_3 as a waste product of metabolism. The excreted or mineralized NH_3/NH_4 is then available for direct uptake and utilization by other organisms or may be converted to more oxidized forms of nitrogen for incorporation into cells. In some nitrogen-poor lakes/reservoirs the excretory contribution (e.g., ammonification) from zooplankton can provide up to 90% of the nitrogen required by primary producers. Ammonification is the opposite of assimilation and protein synthesis. Both aerobic and anaerobic bacteria play vital roles in ammonification.

Nitrification Nitrification is the biological oxidation of NH_4 and NH_3 to NO_2 and then NO_3 . Nitrification is important because NH_4 and NH_3 are toxic to species of aquatic vertebrates. Nitrification is performed by

bacteria that gain energy from oxidizing reduced forms of nitrogen. The aerobic chemoautotrophs involved in nitrification are species of *Nitrosomonas* and *Nitrobacter*. Nitrification consumes, and simultaneously requires oxygen and is a 2-part process.



- The enzyme involved is ammonia monooxygenase.



- This process requires 66 kcal of energy/gram atom of ammonium oxidized.

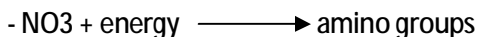
- Under anaerobic conditions;



Ammonium oxidation has important ecological significance in aquatic systems. The microbes that perform nitrification are relatively inefficient autotrophs that use the energy gained from oxidizing ammonia to fix carbon. Thus, these bacteria have a dual ecological role; they are involved in recycling nitrogen and in fixing carbon into organics. The microbes that perform nitrification are fragile. These organisms are acid-sensitive even though they produce acid. If a large source of nitrogen is dumped into the environment, these organisms can potentially kill themselves by metabolizing it to nitric acid. Since they are also strict aerobes, they can be killed if introduction of wastes leads to excessive growth of other species that deplete oxygen (i.e. eutrophication).

Denitrification is reduction of nitrate (NO_3^-) to nitrogen gas or to organic nitrogen compounds and can be a significant pathway for the loss of nitrogen from aquatic systems. There are 2 types of denitrification, assimilatory and dissimilatory.

Assimilatory nitrate reduction. Many organisms can only acquire nitrogen in the form of nitrate and must reduce nitrate to form the amino groups needed for metabolism.



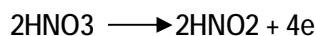
- The "energy" in the above equation is usually supplied by enzymatic activity (nitrogenase)

Dissimilatory nitrate reduction is performed by anaerobic bacteria that use nitrate as the terminal electron acceptor in the absence of oxygen. The overall equation is:



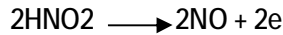
The individual steps of dissimilatory nitrate reduction are:

1) Reduction of nitrate to nitrite



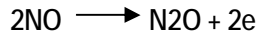
Enzyme: dissimilatory nitrate reductase

2) Reduction of nitrite to nitric oxide



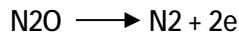
Enzyme: dissimilatory nitrite reductase

3) Reduction of nitric oxide to nitrous oxide



Enzyme: dissimilatory nitric oxide reductase

4) Reduction of nitrous oxide to dinitrogen



Enzyme: dissimilatory nitrous oxide reductase.

Although denitrification requires anoxic conditions, it has been observed in aerated lake sediments and relatively thin biofilms on rocks in streams. Evidently, denitrification can occur in microzones of anoxia. Oxygen produced through photosynthesis by benthic algae may inhibit denitrification. Denitrification requires an organic carbon source and proceeds faster where more carbon is available in the water and sediments. Denitrification may contribute a significant portion of the oxidative metabolism in waterbodies where nitrate levels are high. Within any given waterbody, it is not a matter of all or nothing and denitrification usually occurs simultaneously with nitrification. Denitrification is done only by microorganisms, usually facultative anaerobes, and predominantly in two genera; *Pseudomonas* and *Bacillus*. Dissimilative denitrification is used in sewage treatment and bioremediation where denitrifying bacteria aid in converting organic nitrogen to nitrogen gas that escapes to the atmosphere.

As explained by the previous processes, all forms of nitrogen are interconvertible. While there are losses of nitrogen within any aquatic system there are simultaneous gains from the atmosphere, and from recycling within any given region. Problems with eutrophication arise when humans contribute to loading of nitrogen to a waterbody from either point or non-point sources of pollution.

Since the 1940's, driven by a massive increase in the use of fertilizer, the burning of fossil fuels, and an upsurge in land clearing and deforestation, the amount of nitrogen available for uptake in aquatic systems at any given time has more than doubled. Human activities now contribute more to the global supply of fixed nitrogen each year than natural processes. Anthropogenic nitrogen totals about 210 million metric tons per year, while natural processes contribute about 140 million metric tons. This influx of extra nitrogen has caused serious distortions of natural nutrient cycling in aquatic systems. Excess nitrogen can wreak havoc with aquatic ecosystem structure affecting the number and kind of species found.

Levels of nitrogenous species (ammonia [NH_4], nitrate + nitrite [$\text{NO}_3 + \text{NO}_2$], and TKN [total Kjeldahl nitrogen]), were significantly different between Archer and CC lakes although sites within the latter were not significantly different from each other (to simplify interpretation, data from all sites within CC lake are presented as a group mean) (Fig 8-11). Lower levels of oxidized species ($\text{NO}_3 + \text{NO}_2$) coupled with higher levels of reduced and/or organic forms of nitrogen in CC farther away from the source water (Figs 10 and 11) indicates that the majority of nitrogen enters the system in an oxidized state but that significant de-nitrification occurs along a linear gradient. This may be due to increased contact time with anaerobic sediment. The reduced forms of nitrogen are more bio-available for algae growth than

are the oxidized forms but due to inter-convertibility, all are capable of supporting algae growth. TKN has been proven to be the form of nitrogen most closely correlated in nitrogen-limited lakes and reservoirs in Arizona. Levels of all major forms of nitrogen species are, generally, much higher than in naturally-occurring surface waters of the state and higher than other urban lakes within the region. Concentrations of TKN are almost twice those allowed for urban lakes under AzDEQ's NNC.

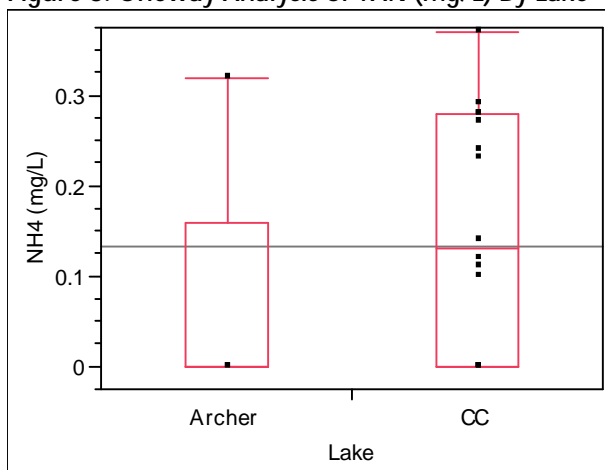
Levels of ammonia in both Archer and CC lakes were high (Fig. 8). This is of ecological concern because un-ionized ammonia (NH_3) is highly toxic to aquatic organisms so that any amount found in lakes, ponds, or streams is cause for alarm. Of all water quality parameters affecting fish, ammonia is the most important after dissolved oxygen.

Ammonia occurs in two forms in water, NH_3 and NH_4 which, when taken together, are referred to as total ammonia nitrogen or TAN whereas the un-ionized fraction as UIA. The toxicity of un-ionized ammonia (as compared to the less-toxic ionized form $[\text{NH}_4]$) is both temperature and pH dependent. Generally, toxicity is greater at decreased temperature but higher pH values. Lakes in the region certainly have increased temperature but also generally increased pH due to parent geologic material and the effect of photosynthesis by excessive amounts of algae.

Calculating the amount of UIA based on water temperature and pH (Emmerson et al. 1975), we found only one instance of its presence within the Archer site on 10/09/2007 at a level of 0.11. Sites within CC lake had hits of UIA during the August, October, and December sampling of 2007 and again during the February sampling of 2008 (Fig. 9). There was no significant difference in UIA levels between sites within CC and the highest levels occurred on 10/09/2007. The fact that CC has levels of UIA at times when Archer does not would indicate mechanism(s) within CC promoting denitrification. Since denitrification requires facultative anaerobes, and given the shallow nature of CC, anoxic lake sediments likely have a role in this process.

CC and, at least for brief periods Archer, have UIA and TAN levels that are known to be chronically toxic to fish species.

Figure 8. Oneway Analysis of TAN (mg/L) By Lake



Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Lake | 1 | 0.02958400 | 0.029584 | 1.6527 | 0.2114 |
| Error | 23 | 0.41172000 | 0.017901 | | |
| C. Total | 24 | 0.44130400 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|--------|--------|----------|-----------|-----------|-----------|
| Archer | 5 | 0.064000 | 0.05983 | -0.0598 | 0.18778 |
| CC | 20 | 0.150000 | 0.02992 | 0.0881 | 0.21189 |

Figure 9. Concentrations of UIA (mg/L) by Date

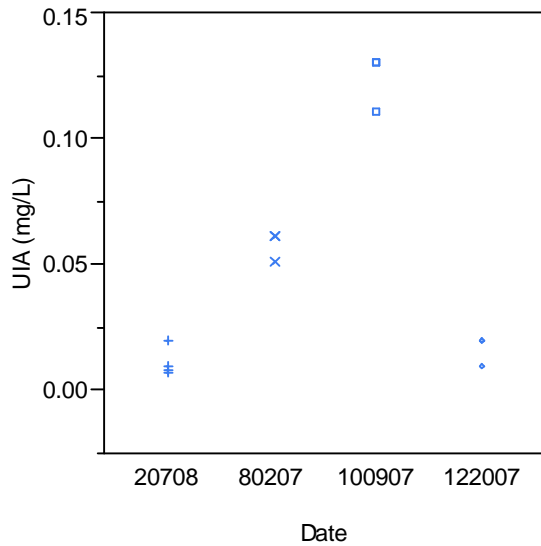
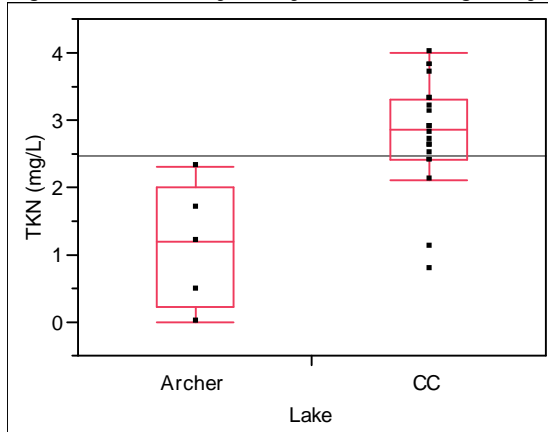


Figure 10. Oneway Analysis of TKN (mg/L) By Lake

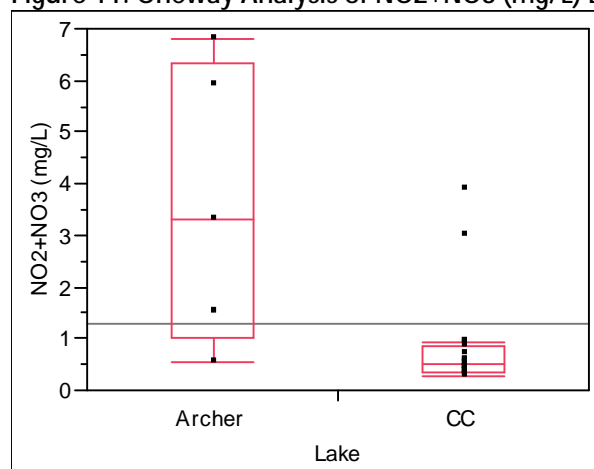


Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Lake | 1 | 11.115556 | 11.1156 | 15.5843 | 0.0006 |
| Error | 23 | 16.404860 | 0.7133 | | |
| C. Total | 24 | 27.520416 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|--------|--------|---------|-----------|-----------|-----------|
| Archer | 5 | 1.13200 | 0.37769 | 0.3507 | 1.9133 |
| CC | 20 | 2.79900 | 0.18885 | 2.4083 | 3.1897 |

Figure 11. Oneway Analysis of NO₂+NO₃ (mg/L) By Lake

Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Lake | 1 | 32.772523 | 32.7725 | 18.4138 | 0.0002 |
| Error | 26 | 46.274374 | 1.7798 | | |
| C. Total | 27 | 79.046896 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|--------|--------|---------|-----------|-----------|-----------|
| Archer | 5 | 3.61000 | 0.59662 | 2.3836 | 4.8364 |
| CC | 23 | 0.78522 | 0.27818 | 0.2134 | 1.3570 |

Phosphorous, like nitrogen, is essential to all life. Phosphorous functions in the storage and transfer of a cell's energy and in genetic systems. Cells use adenosine triphosphate (ATP) as an energy carrier which drives a number of biological processes including photosynthesis, muscle contraction, and the synthesis of proteins. Phosphate groups are also found in nucleotides (and therefore, nucleic acids). Phosphorous is (usually) more scarce environmentally than other principle atoms of living organisms including carbon, hydrogen, oxygen, nitrogen, and sulfur.

Phosphorous occurs naturally in rocks and other mineral deposits. During weathering, the rocks gradually release the phosphorus as phosphate ions which are soluble in water and the mineralized phosphate compounds breakdown. Phosphorous exists primarily as phosphates in two forms: orthophosphate, and organically bound phosphate. These forms of phosphate occur in living and decaying plant and animal remains, as free ions, chemically bonded, or mineralized and chemically bonded in sediments. Analytically, phosphorous in water is usually categorized as being either dissolved or particulate depending on whether or not it can pass through a 0.45 μm filter. The "dissolved" fraction can have a substantial colloidal component. Within the dissolved fraction, inorganic P (DIP) occurs as orthophosphate (PO₄). Dissolved inorganic phosphorous is sometimes referred to as "soluble reactive phosphorous" (SRP). "Total phosphorous" (TP) is determined on a non-filtered sample by heat and acid digestion which converts the sample to SRP for measurement.

In unpolluted rivers, SRP averages about 0.01 mg/L on a worldwide basis and total phosphorous averages about 0.025 mg/L (Meybeck 1982). Agricultural activities may increase SRP levels to 0.05 – 0.1 mg/L and municipal effluents may increase SRP concentrations to 1.0 mg/L or much higher. Particulate phosphorous includes P incorporated into mineral structures, adsorbed onto clays, and incorporated into organic matter.

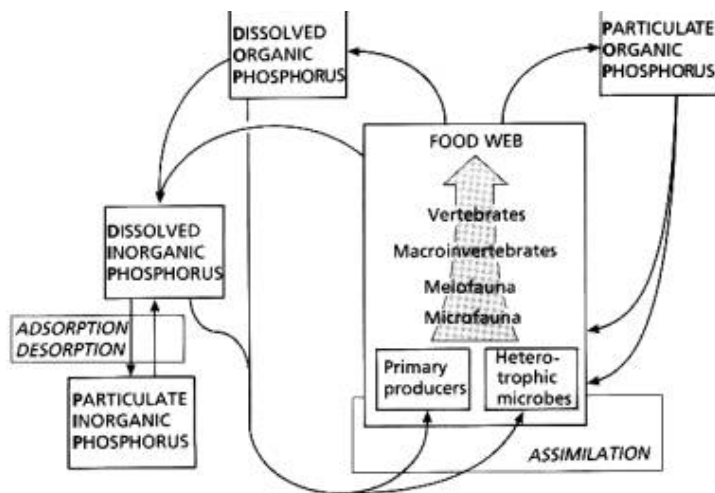
Worldwide averages of particulate phosphorous concentrations are about 0.5 mg/L. This level can be much higher depending upon land use and erodibility of the watershed.

Phosphorous is often the limiting macronutrient in regards to primary production in aquatic systems. Because of this, and its relative scarcity, it is quickly removed from its dissolved state and incorporated into living biomass. Bacteria and algae are both responsible for turnover rates as fast as 1 – 8 minutes (Rigler 1973). Turnover rates usually follow the order of (in order of decreasing turnover times):

Bacteria → algae → zooplankton → vertebrates.

It's been estimated that (in freshwater lakes) zooplankton excrete about 20% of the phosphorous required by phytoplankton whereas bacteria can excrete up to 80%. Therefore, food web dynamics play a large role in either the sequestration or recycling of phosphorous in aquatic systems. The speed at which phosphorous is moved between biotic and abiotic compartments makes interpretation of different forms difficult. It's impossible to distinguish between zooplankton-P, bacterial-P, algae-P, and sometimes even inorganic-P. The best way to quantify phosphorous in a body of water is by analysis of total phosphorous.

Figure 12. The Phosphorous Cycle in Aquatic Systems (from Calow and Petts, 1992)

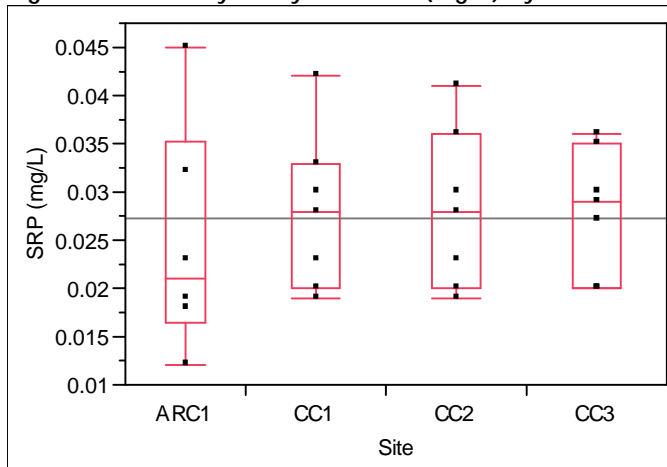


Concentrations of neither SRP nor Total P were significantly different between sites and concentrations of either were, in fact, surprisingly low given the large amount of algal biomass in the lakes (Figs 13 and 14). All concentrations were below the 0.1 mg/L standard as given in AzDEQs NNC. Apparently, however, there is enough phosphorous in the CC/Archer Lake complex to sustain an excess of algae growth.

Levels of total P were higher in the summer than winter (Fig 15). This is likely due to much of the phosphorous in the water being bound into algae and/or bacteria the concentrations of which are higher during the summer than winter. Also, during winter, when dissolved oxygen levels over the sediment is higher, phosphorous becomes bound with iron in the sediment taking it out of the water column and unavailable for biological uptake.

It appears that phosphorous is the nutrient "limiting" algal growth in both CC and Archer lakes. The concept of nutrient limitation is often erroneously used. Given the amount of algal biomass in CC and Archer lakes, there is really no nutrient limiting primary production, however, it is possible for biomass to be even greater if more phosphorous were introduced into the system.

Figure 13. Oneway Analysis of SRP (mg/L) By Site



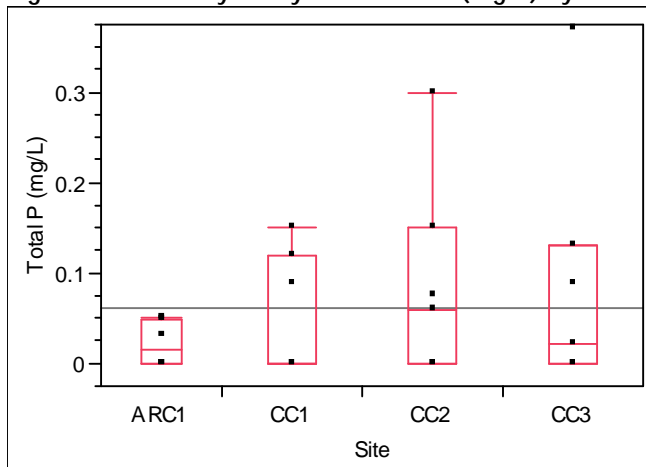
Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Site | 3 | 0.00004860 | 0.000016 | 0.2122 | 0.8869 |
| Error | 23 | 0.00175540 | 0.000076 | | |
| C. Total | 26 | 0.00180400 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|-------|--------|----------|-----------|-----------|-----------|
| ARC1 | 6 | 0.024833 | 0.00357 | 0.01746 | 0.03221 |
| CC1 | 7 | 0.027857 | 0.00330 | 0.02103 | 0.03469 |
| CC2 | 7 | 0.028143 | 0.00330 | 0.02131 | 0.03497 |
| CC3 | 7 | 0.028143 | 0.00330 | 0.02131 | 0.03497 |

Figure 14. Oneway Analysis of Total P (mg/L) By Site



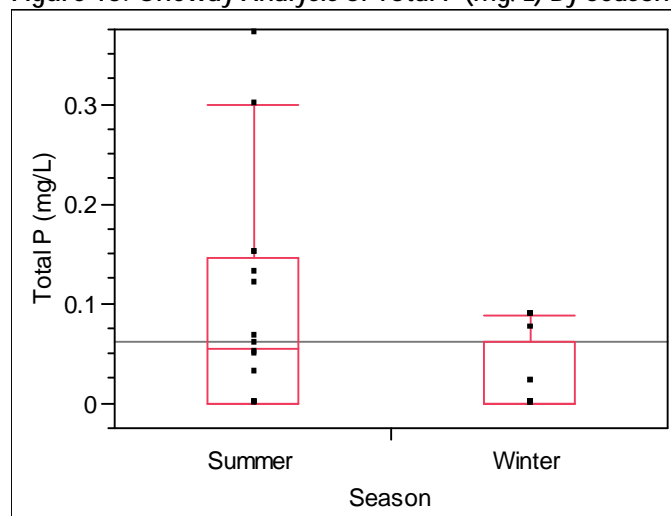
Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Site | 3 | 0.01836708 | 0.006122 | 0.6670 | 0.5809 |
| Error | 23 | 0.21113121 | 0.009180 | | |
| C. Total | 26 | 0.22949830 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|-------|--------|----------|-----------|-----------|-----------|
| ARC1 | 6 | 0.021500 | 0.03911 | -0.0594 | 0.10241 |
| CC1 | 7 | 0.051286 | 0.03621 | -0.0236 | 0.12620 |
| CC2 | 7 | 0.083714 | 0.03621 | 0.0088 | 0.15863 |
| CC3 | 7 | 0.087143 | 0.03621 | 0.0122 | 0.16205 |

Figure 15. Oneway Analysis of Total P (mg/L) By Season



Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Season | 1 | 0.03284430 | 0.032844 | 4.3423 | 0.0471 |
| Error | 26 | 0.19666067 | 0.007564 | | |
| C. Total | 27 | 0.22950496 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|--------|--------|----------|-----------|-----------|-----------|
| Summer | 16 | 0.092125 | 0.02174 | 0.0474 | 0.13682 |
| Winter | 12 | 0.022917 | 0.02511 | -0.0287 | 0.07452 |

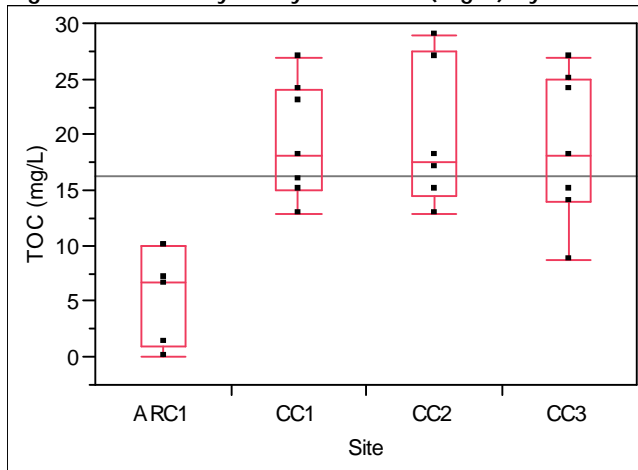
We measured both total and dissolved organic carbon from CC and Archer lakes. Although carbon is, technically, a nutrient for algal growth (and carbon dioxide essential for photosynthesis), its ubiquitous nature means that it is rarely, if ever, limiting. The amount of organic carbon in a lake offers insight into the amount of biomass (total organic carbon or TOC) versus the amount that has either died (dissolved organic carbon or DOC) or the influence of reclaimed water which is notoriously high in organic carbon.

Total alkalinity is the total concentration of bases, usually carbonate and bicarbonate, in water and is usually expressed as mg/L of calcium carbonate. Analytically, total alkalinity is expressed as the amount of sulfuric acid needed to bring a solution to a pH of 4.2. At this pH, the alkalinity in the solution is "used up" and any further addition of an acid results in drastic swings in pH levels. Total alkalinity, by definition, is the ability of a water body to neutralize acids. In other words, it is the "buffering capacity" of a water body.

Levels of both TOC and DOC were significantly different between CC and Archer lakes but none of the sites within CC Lake were significantly different from each other (Figs 16 and 17). The difference noted between CC and Archer might be due to the decreased residence time of water in Archer essentially flushing material into CC where organic carbons accumulate because there is no outlet from this system. Levels of organic carbon found within CC Lake are considered relatively high. There was only a slight

difference based upon season with organic carbon levels being slightly higher during the summer rather than winter.

Figure 16. Oneway Analysis of TOC (mg/L) By Site



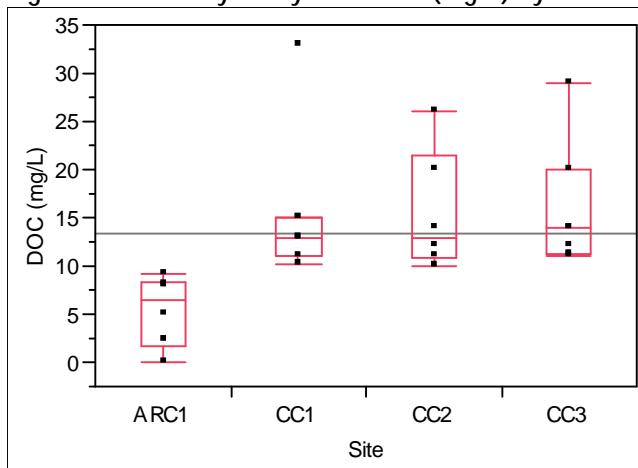
Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Site | 3 | 847.4998 | 282.500 | 8.2914 | 0.0007 |
| Error | 22 | 749.5704 | 34.071 | | |
| C. Total | 25 | 1597.0702 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|-------|--------|---------|-----------|-----------|-----------|
| ARC1 | 6 | 5.8000 | 2.3830 | 0.858 | 10.742 |
| CC1 | 7 | 19.4143 | 2.2062 | 14.839 | 23.990 |
| CC2 | 6 | 19.8167 | 2.3830 | 14.875 | 24.759 |
| CC3 | 7 | 18.8114 | 2.2062 | 14.236 | 23.387 |

Figure 17. Oneway Analysis of DOC (mg/L) By Site



Analysis of Variance

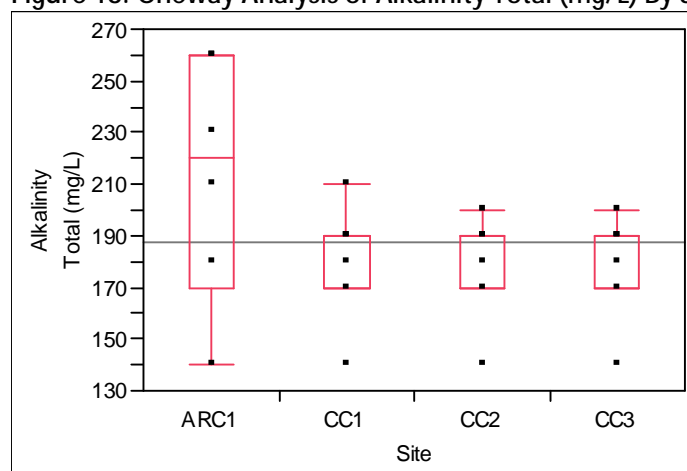
| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Site | 3 | 488.2230 | 162.741 | 4.0458 | 0.0197 |
| Error | 22 | 884.9405 | 40.225 | | |
| C. Total | 25 | 1373.1635 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|-------|--------|---------|-----------|-----------|-----------|
| ARC1 | 6 | 5.4500 | 2.5892 | 0.080 | 10.820 |
| CC1 | 7 | 15.7429 | 2.3972 | 10.771 | 20.714 |
| CC2 | 6 | 15.5167 | 2.5892 | 10.147 | 20.886 |
| CC3 | 7 | 15.9000 | 2.3972 | 10.929 | 20.871 |

Levels of total alkalinity, as is typical for most lakes in the region, were relatively high (Fig. 18). Levels were slightly higher in Archer than CC but there was no difference between sites within CC. With these levels of alkalinity, it appears that both lakes are well-buffered against sudden changes in pH, although, it is known that pH levels, like dissolved oxygen, decrease in lakes and streams at night due to respiration by algae (Diel patterns). We did not perform any night-time sampling at the lakes.

Figure 18. Oneway Analysis of Alkalinity Total (mg/L) By Site



Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Site | 3 | 5047.619 | 1682.54 | 2.0563 | 0.1340 |
| Error | 23 | 18819.048 | 818.22 | | |
| C. Total | 26 | 23866.667 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|-------|--------|---------|-----------|-----------|-----------|
| ARC1 | 6 | 213.333 | 11.678 | 189.18 | 237.49 |
| CC1 | 7 | 181.429 | 10.811 | 159.06 | 203.79 |
| CC2 | 7 | 180.000 | 10.811 | 157.63 | 202.37 |
| CC3 | 7 | 180.000 | 10.811 | 157.63 | 202.37 |

Metals

We sampled for total and dissolved fractions of iron (Fe), manganese (Mn), arsenic (As), selenium (Se), and mercury (Hg). Dissolved Fe, and both total and dissolved levels of Se and Hg were all below detectable limits.

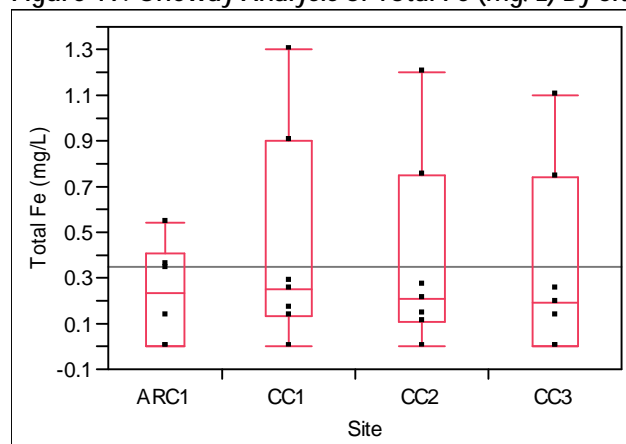
Both iron and manganese are limnologically important metals and exist in either a particulate or dissolved form depending upon levels of dissolved oxygen in the water especially just above the sediment-water interface. Iron is important due to its affinity, in an oxidized state, to combine with phosphorous making it biologically unavailable. In a reduced state, iron loses this affinity with phosphorous with the latter leaching into the water from the sediment and often spurring an algal

bloom which, when it decomposes, decreases dissolved oxygen levels even further resulting in more P released from the sediment and a positive feedback loop is established.

Manganese becomes soluble at DO levels greater than those required for iron but also remains soluble for longer periods. The presence of dissolved Mn but not dissolved iron infers that reducing conditions exist but they are not powerful enough to solubilize iron.

We observed no dissolved iron within either CC or Archer lakes. Levels of total Fe were slightly higher in CC Lake than Archer (Fig. 19). We did find dissolved Mn at relatively low levels within Archer and CC Lake (Fig. 21).

Figure 19. Oneway Analysis of Total Fe (mg/L) By Site



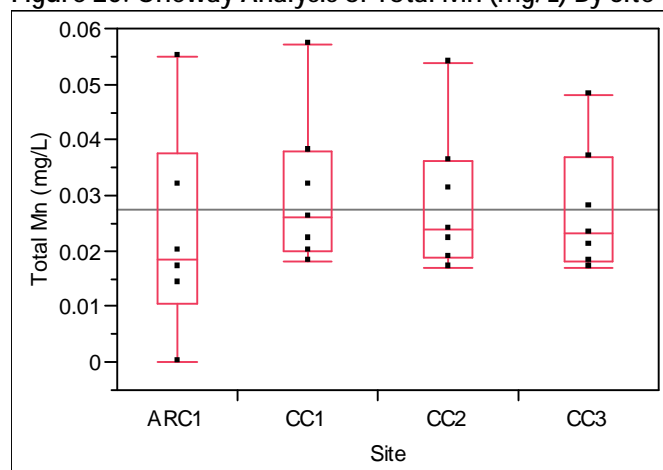
Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Site | 3 | 0.1446003 | 0.048200 | 0.2929 | 0.8301 |
| Error | 23 | 3.7845405 | 0.164545 | | |
| C. Total | 26 | 3.9291407 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|-------|--------|----------|-----------|-----------|-----------|
| ARC1 | 6 | 0.228333 | 0.16560 | -0.1142 | 0.57091 |
| CC1 | 7 | 0.432857 | 0.15332 | 0.1157 | 0.75002 |
| CC2 | 7 | 0.382857 | 0.15332 | 0.0657 | 0.70002 |
| CC3 | 7 | 0.344286 | 0.15332 | 0.0271 | 0.66145 |

Figure 20. Oneway Analysis of Total Mn (mg/L) By Site



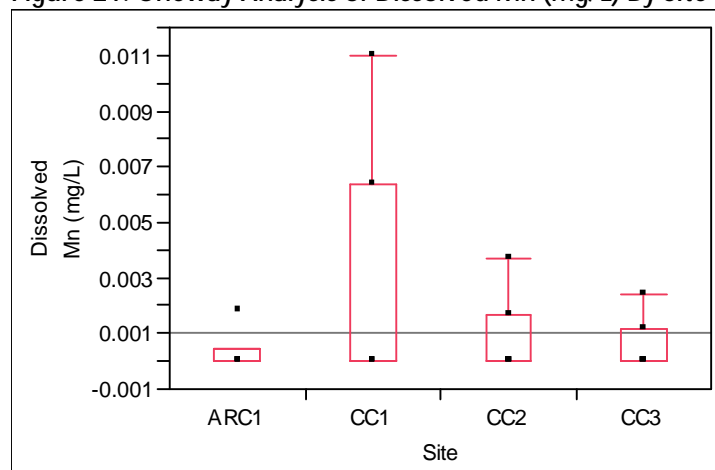
Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Site | 3 | 0.00019687 | 0.000066 | 0.3246 | 0.8075 |
| Error | 23 | 0.00464943 | 0.000202 | | |
| C. Total | 26 | 0.00484630 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|-------|--------|----------|-----------|-----------|-----------|
| ARC1 | 6 | 0.023000 | 0.00580 | 0.01099 | 0.03501 |
| CC1 | 7 | 0.030429 | 0.00537 | 0.01931 | 0.04155 |
| CC2 | 7 | 0.029000 | 0.00537 | 0.01788 | 0.04012 |
| CC3 | 7 | 0.027429 | 0.00537 | 0.01631 | 0.03855 |

Figure 21. Oneway Analysis of Dissolved Mn (mg/L) By Site



Analysis of Variance

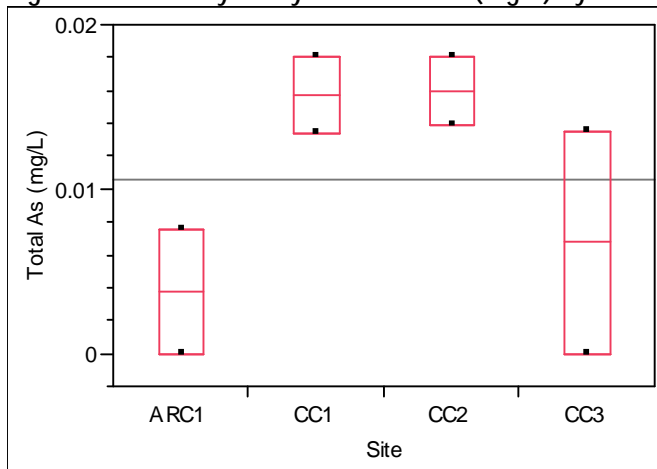
| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Site | 3 | 0.00002036 | 6.7851e-6 | 1.1213 | 0.3610 |
| Error | 23 | 0.00013917 | 6.0509e-6 | | |
| C. Total | 26 | 0.00015953 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|-------|--------|----------|-----------|-----------|-----------|
| ARC1 | 6 | 0.000300 | 0.00100 | -0.0018 | 0.00238 |
| CC1 | 7 | 0.002486 | 0.00093 | 0.00056 | 0.00441 |
| CC2 | 7 | 0.000771 | 0.00093 | -0.0012 | 0.00269 |
| CC3 | 7 | 0.000514 | 0.00093 | -0.0014 | 0.00244 |

We did find total and dissolved arsenic in aqueous samples collected on 06/07/07 and again on 04/22/08 at levels between 0.004 and 0.016 mg/L (Figs 22 and 23). The US EPA criteria level for arsenic in drinking water is 0.01 mg/L. While drinking water is obviously not an issue in CC or Archer, bioaccumulation (but not biomagnification) of organic arsenic compounds, after biogenesis from inorganic forms, does occur in aquatic organisms. No speciation of arsenic was performed and the degree of toxicity of arsenic is dependent on the form (e.g. inorganic or organic) and the oxidation state of the arsenical. It is generally considered that inorganic forms are more toxic than organic forms, and within these two classes, the trivalent forms are more toxic than the pentavalent forms, at least at high doses. Trying to determine potential toxicity of aquatic organisms at the levels found, without speciation, is not possible; however, the fact that any level was found warrants concern about toxicity.

Figure 22. Oneway Analysis of Total As (mg/L) By Site



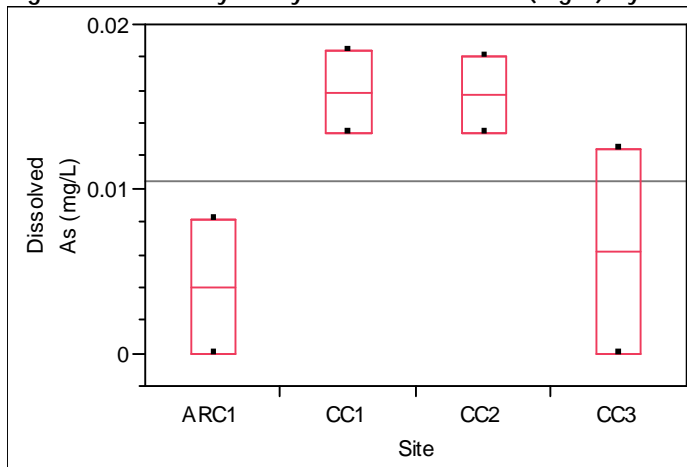
Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Site | 3 | 0.00023272 | 0.000078 | 2.2447 | 0.2253 |
| Error | 4 | 0.00013824 | 0.000035 | | |
| C. Total | 7 | 0.00037096 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|-------|--------|----------|-----------|-----------|-----------|
| ARC1 | 2 | 0.003750 | 0.00416 | -0.0078 | 0.01529 |
| CC1 | 2 | 0.015700 | 0.00416 | 0.0042 | 0.02724 |
| CC2 | 2 | 0.015950 | 0.00416 | 0.0044 | 0.02749 |
| CC3 | 2 | 0.006750 | 0.00416 | -0.0048 | 0.01829 |

Figure 23. Oneway Analysis of Dissolved As (mg/L) By Site



Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Site | 3 | 0.00023363 | 0.000078 | 2.3381 | 0.2150 |
| Error | 4 | 0.00013323 | 0.000033 | | |
| C. Total | 7 | 0.00036686 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|-------|--------|----------|-----------|-----------|-----------|
| ARC1 | 2 | 0.004050 | 0.00408 | -0.0073 | 0.01538 |
| CC1 | 2 | 0.015900 | 0.00408 | 0.0046 | 0.02723 |
| CC2 | 2 | 0.015750 | 0.00408 | 0.0044 | 0.02708 |
| CC3 | 2 | 0.006200 | 0.00408 | -0.0051 | 0.01753 |

Sediment

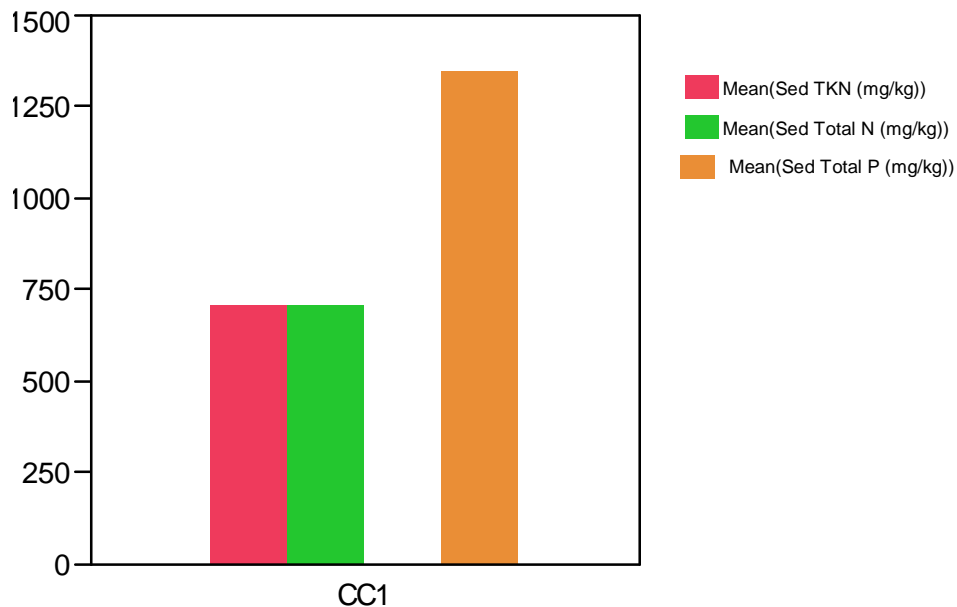
We collected sediment samples from site CC1 on 5/24 and 8/02/07. Samples were collected using an Ekman dredge and analyzed on 5/24/07 for nutrients and on 8/02/07 for nutrients and selected metals.

Sediments act as both a source and sink of nutrients in lakes. During periods of anoxia over the sediment-water interface, binding affinities of certain metals associated with the sequestration of nutrients is reduced resulting in their release from sediments into the water. When oxygenated, sediments act as sinks for these nutrients.

All of the nitrogenous species in the sediments were in the reduced and/or organic form (as measured by TKN). Oxidized forms (nitrate/nitrite) were below detectable limits. Sediments also contained relatively large amounts of total P. Since this nutrient appears to be the one limiting primary production in CC, its sequestration in and release from the sediment likely plays an important role in determining the amount of algae the lake can support at any given time.

Levels of metals detected in sediments were unremarkable. As expected, we found calcium in the greatest concentration (29,000 mg/kg) followed by iron (3700 mg/kg), sodium (420 mg/kg), manganese (84 mg/kg). Zinc and copper were both found at concentrations of 12 mg/kg. Levels of selenium, silver, mercury, beryllium, cadmium, and chromium were all below detectable limits. Based upon our small sampling size, metal toxicity within lake sediments does not appear to be a major issue in CC Lake.

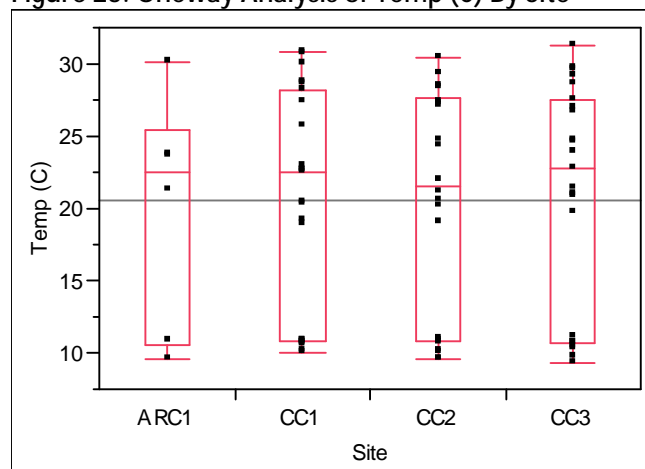
Figure 24. Concentration (mg/kg) of Nutrients in Sediment in CC Lake



Physico-chemical

Water temperature within CC and Archer lakes ranged from very warm during the summer (at times exceeding 30°C) to ~ 10°C during the coldest periods of winter (Fig. 25). Water temperature has an effect on overall lake metabolism, nutrient biogenesis, rate of primary production, and a host of other factors important to lake function. Generally, lakes within the region have increased primary production and algal biomass with lower levels of nutrients than lakes in more temperate areas due to increased water temperatures and abundant light for photosynthesis.

Figure 25. Oneway Analysis of Temp (C) By Site



Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Site | 3 | 5.4509 | 1.8170 | 0.0301 | 0.9929 |
| Error | 70 | 4230.3728 | 60.4339 | | |
| C. Total | 73 | 4235.8238 | | | |

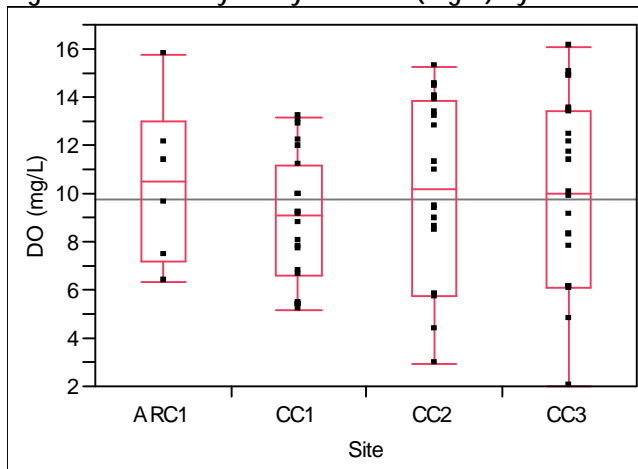
Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|-------|--------|---------|-----------|-----------|-----------|
| ARC1 | 6 | 19.8733 | 3.1737 | 13.544 | 26.203 |
| CC1 | 23 | 20.5670 | 1.6210 | 17.334 | 23.800 |
| CC2 | 22 | 20.5059 | 1.6574 | 17.200 | 23.812 |
| CC3 | 23 | 20.8996 | 1.6210 | 17.667 | 24.132 |

Concentrations of dissolved oxygen in CC and Archer lakes never appeared to be problematic during the course of this study (Figs 26 and 27). We caveat this with the fact we did not measure DO levels at night when levels are known to drop due to respiration by algae. DO levels, as is typical, decreased with depth but never to the point where aquatic life was threatened. The very high levels (anything > 110 % saturation) were noted during the summer and associated with a large algal biomass and as a by-product of photosynthesis. DO levels were not significantly different based upon season.

Often in eutrophic waters, DO levels will plummet at depth due to oxygen consumption by respiring algae. This has been found in other lakes within the region that are much deeper than CC Lake. In this particular instance, DO levels are likely maintained by the shallow nature of the lake so that no anoxic pool forms at depth and mixing by wind is adequate to maintain DO levels. DO levels at depth were never < 2.0 mg/L.

Figure 26. Oneway Analysis of DO (mg/L) By Site



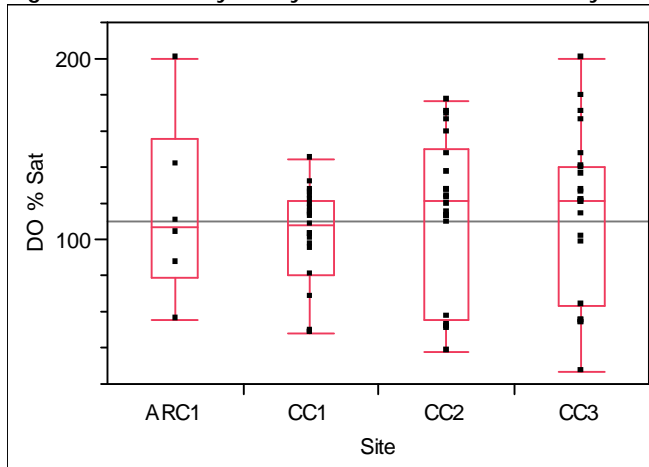
Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Site | 3 | 27.09329 | 9.0311 | 0.7493 | 0.5264 |
| Error | 70 | 843.69752 | 12.0528 | | |
| C. Total | 73 | 870.79081 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|-------|--------|---------|-----------|-----------|-----------|
| ARC1 | 6 | 10.4033 | 1.4173 | 7.5766 | 13.230 |
| CC1 | 23 | 8.8452 | 0.7239 | 7.4014 | 10.289 |
| CC2 | 22 | 10.0973 | 0.7402 | 8.6210 | 11.574 |
| CC3 | 23 | 10.1148 | 0.7239 | 8.6710 | 11.559 |

Figure 27. Oneway Analysis of DO % Saturation By Site



Analysis of Variance

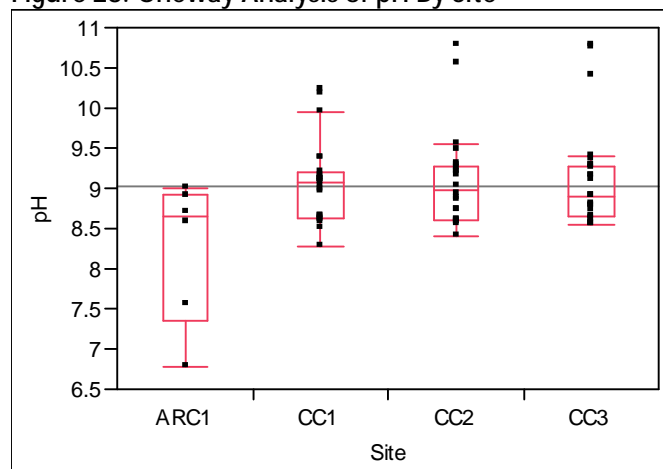
| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Site | 3 | 3306.52 | 1102.17 | 0.6503 | 0.5854 |
| Error | 70 | 118632.62 | 1694.75 | | |
| C. Total | 73 | 121939.14 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|-------|--------|---------|-----------|-----------|-----------|
| ARC1 | 6 | 116.083 | 16.807 | 82.564 | 149.60 |
| CC1 | 23 | 99.709 | 8.584 | 82.588 | 116.83 |
| CC2 | 22 | 113.191 | 8.777 | 95.686 | 130.70 |
| CC3 | 23 | 114.357 | 8.584 | 97.236 | 131.48 |

Levels of pH within CC Lake were very high with annual means of > 9.0 standard units (SU) (Fig. 28). Levels were often approaching 11 SU during the summer and, like DO, are an artifact of an excessive amount of photosynthesis during which algae will sequester carbon dioxide from the water leaving calcium carbonate in excess driving pH levels up. At night, the carbon dioxide sequestered by algae during the day is released back into the water driving pH levels back down. We performed no night sampling from CC Lake so these pH swings cannot be quantified however; AzDEQs NNC considers a lake impaired at pH levels > 9.0 SU. Levels higher than this are known to be harmful to aquatic life. Archer Lake generally had less algal biomass than CC so pH levels were not as high.

Figure 28. Oneway Analysis of pH By Site



Analysis of Variance

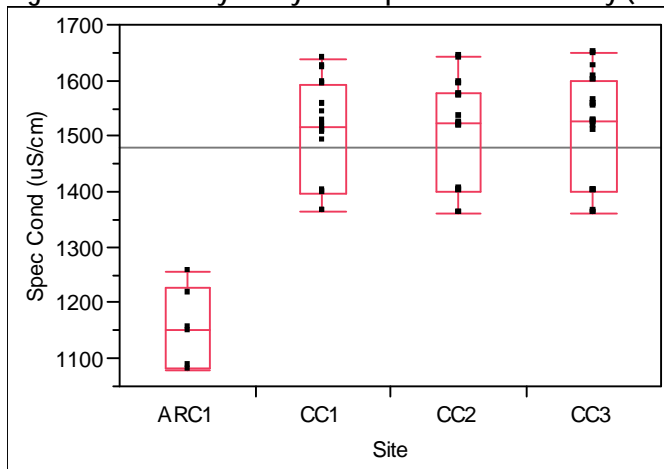
| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Site | 3 | 4.084195 | 1.36140 | 3.5359 | 0.0190 |
| Error | 70 | 26.951303 | 0.38502 | | |
| C. Total | 73 | 31.035499 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|-------|--------|---------|-----------|-----------|-----------|
| ARC1 | 6 | 8.24667 | 0.25332 | 7.7414 | 8.7519 |
| CC1 | 23 | 9.06000 | 0.12938 | 8.8020 | 9.3180 |
| CC2 | 22 | 9.09636 | 0.13229 | 8.8325 | 9.3602 |
| CC3 | 23 | 9.14130 | 0.12938 | 8.8833 | 9.3994 |

Levels of specific conductivity (a measure of the waters ability to carry an electrical current and a proxy for salinity) were high in CC Lake and Archer with the latter having lower levels than the former. Currently, the CC/Archer Lake complex is a closed hydrologic system with water only exiting via evaporation or seepage through the lake into the local aquifer. The higher the degree of evaporation, the higher the levels of specific conductivity. The relatively high levels of conductivity witnessed in both CC and Archer lakes are not necessarily harmful to aquatic life, rather, they emphasize the relatively high residence time of water within the lake (the higher the residence time, the more nutrients will be recycled within the lake) and evaporation.

Figure 29. Oneway Analysis of Specific Conductivity (uS/cm) By Site



Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Site | 3 | 676344.8 | 225448 | 26.6972 | <.0001 |
| Error | 70 | 591125.4 | 8445 | | |
| C. Total | 73 | 1267470.2 | | | |

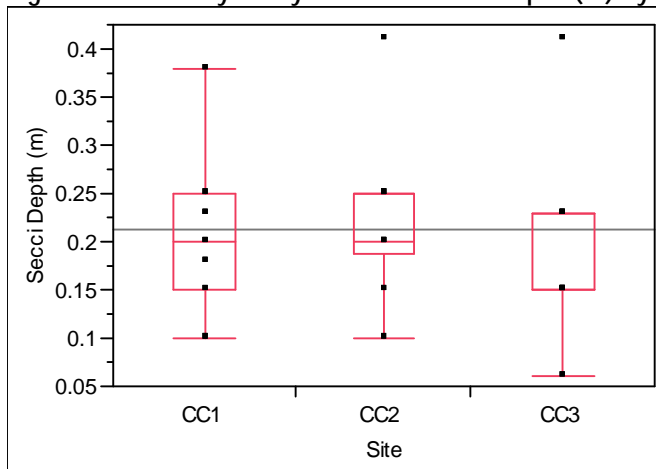
Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|-------|--------|---------|-----------|-----------|-----------|
| ARC1 | 6 | 1157.00 | 37.516 | 1082.2 | 1231.8 |
| CC1 | 23 | 1503.09 | 19.161 | 1464.9 | 1541.3 |
| CC2 | 22 | 1507.14 | 19.592 | 1468.1 | 1546.2 |
| CC3 | 23 | 1510.96 | 19.161 | 1472.7 | 1549.2 |

Turbidity and Water Transparency

Turbidity is a quantifiable measure of the amount of particles in water that scatter light (measured in nephelometric turbidity units or NTUs) and water transparency was measured in the field using a weighted Secchi disk (a standardized 20 cm in diameter disk lowered into the water to the point where it can no longer be seen). Turbidity levels were quite high and, correspondingly, Secchi disk depth was usually quite low indicating that water within CC and Archer Lakes contain a large amount of suspended particulate matter and that transparency within CC Lake (Archer was too shallow to sample using a Secchi disk) is very low (Figs 30 and 31). Most of the particulate matter in the water is likely due to algae. Indeed, often the only thing limiting algae growth is light availability this being caused by self-shading of algae cells nearer the surface.

Figure 30. Oneway Analysis of Secci Disk Depth (m) By Site



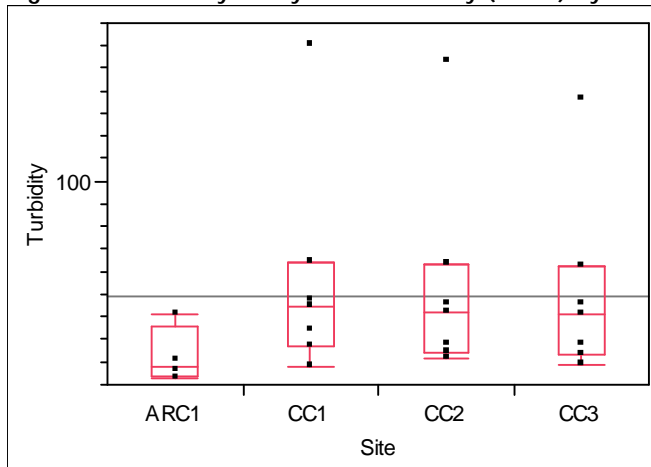
Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Site | 2 | 0.01160721 | 0.005804 | 0.7193 | 0.4909 |
| Error | 65 | 0.52446779 | 0.008069 | | |
| C. Total | 67 | 0.53607500 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|-------|--------|----------|-----------|-----------|-----------|
| ARC1 | 0 | . | . | . | . |
| CC1 | 23 | 0.213043 | 0.01873 | 0.17564 | 0.25045 |
| CC2 | 22 | 0.228636 | 0.01915 | 0.19039 | 0.26688 |
| CC3 | 23 | 0.196522 | 0.01873 | 0.15912 | 0.23393 |

Figure 31. Oneway Analysis of Turbidity (NTUs) By Site



Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|----------|----|----------------|-------------|---------|----------|
| Site | 3 | 3376.507 | 1125.50 | 0.6411 | 0.5971 |
| Error | 21 | 36869.394 | 1755.69 | | |
| C. Total | 24 | 40245.902 | | | |

Means for Oneway Anova

| Level | Number | Mean | Std Error | Lower 95% | Upper 95% |
|-------|--------|---------|-----------|-----------|-----------|
| ARC1 | 4 | 22.6000 | 20.950 | -20.97 | 66.169 |
| CC1 | 7 | 56.4857 | 15.837 | 23.55 | 89.421 |
| CC2 | 7 | 54.0429 | 15.837 | 21.11 | 86.978 |
| CC3 | 7 | 50.6857 | 15.837 | 17.75 | 83.621 |

Nutrient Loading

We sampled from the well head on 10/09/07 to calculate the amount of nutrients being delivered to the lake and then extrapolated this to annual loading. The volume of the CC/Archer Lake complex is ~ 114 acre feet. The pump has a capacity of 400 gallon per minute but only runs at full capacity for 3 months (May - July). August - November it runs at approximately 200 gpm then the remainder of the year it is usually turned off. Results from this one-time sampling were 2.9 mg/L for total N and 0.019 for total P. Given the average volume of water delivered to the lake via the wellhead, annual loading amounts to approximately 1153 kg of N and 7.56 kg of P per year.

The N:P ratios would suggest the lake is P-limited; however, the concept of nutrient limitation should only be applied when limitations in primary production (algae growth) are observed. Clearly, the amount of algal biomass observed in CC/Archer lakes indicates that no nutrient truly limits growth.

General Recommendations

Eutrophication and the concept of "pushing back" a lake to an earlier trophic state is one of the most complex environmental issues facing resource managers today. Lakes become eutrophic due to an accumulation of nutrients and/or heavy nutrient loading to the system. While many lake treatments exist, some often fail due to a lack of not resolving the core problem; removing/reducing nutrient levels both within and being delivered to the system. Caution should be exercised in selection of treatment/management options available as many are without scientific merit and have no peer review. Treatments such as adding barley straw, "beneficial" bacteria, and using ultrasound technology are just a few of many self-proclaimed lake panaceas on the market today. Simply put, experience has shown that the vast majority of these "treatments" do little if anything to increase water quality in lakes and this report will not consider them as viable treatment/management options.

While there is usually no single treatment that will achieve all the desired outcomes, there are some that will provide better outcomes than others; however, selection of treatments/management alternatives should always be lake-specific and what works in one lake might not in another so that a boiler-plate approaches usually result in a waste of time, energy, and money.

In every situation; however, active management and monitoring is the key component to lake restoration success or failure. Lakes are highly dynamic systems changing on an hourly, daily, weekly, monthly, seasonal, and annual basis. The worst thing is to be reactive rather than proactive because often by the time a situation has become bad enough to warrant action, it is too late for any treatment option due to concerns about lowering dissolved oxygen or pH levels or creating an even worse situation than the one currently at hand. For example, the consideration of what lake conditions and treatment options might exist in June requires fore-thought and data collected in January, not in June. It is beyond the scope of this work to develop a specific lake management plan but one definitely needs to exist in order for any of the following recommendations to work.

To re-iterate, without first reducing nutrient loading to or in the lake (discussed later in this report), the success of any particular in-lake recommendation is greatly minimized.

Dredging/Lake Re-structuring

CC is an extremely shallow lake and in such areas, overgrowths of emergent aquatic vegetation are common and heating of water throughout the lake is to be expected. Dredging is at the extreme end of lake restoration techniques due to expense and logistics. There are several ways to dredge/re-structure a lake representing a spectrum of difficulty and price. The most expensive, and usually most effective, method is to drain the entire lake, bring in heavy equipment to remove sediments (once dry) and deepen the lake, re-line using bentonite clay or some other suitable liner, install any necessary infrastructure, and re-fill. Obviously, this is a difficult and very expensive task. Alternatives to this exist including lowering the lake level (as compared to completely draining) and deepening the sides so that aquatic plants cannot become established along the littoral (sides) edge. Another alternative in lakes with a large amount of organic material is to employ suction barges (Pic 1) with floating pipes and an underwater adjustable cutting/suction head that effectively vacuums the lake of the most nutrient-enriched, superficial sediments. This dredge performs some deepening but obviously not to the degree that draining and bringing in heavy equipment does. It also does not remove aquatic plants and does not work well along the shallow edge.

Picture 1. Suction Dredge in La Cebadilla Lake, Tucson Arizona



To varying degrees, the amount of turbidity and algal biomass in CC and Archer somewhat limit the growth of aquatic plants by reducing the amount of light able to reach the sediment. While there are aquatic plants at both lakes, and it appears an active program aimed at their control, the biomass of aquatic plants might increase if water clarity increases. The problems associated with a high amount of algal biomass and aquatic plants are really separate but related issues. Aquatic plants derive most of their nutrients from their extensive root structure buried within the sediment whereas algae derive nutrients directly from the water column. Therefore, any restorative action aimed at decreasing the amount of algal biomass and clarifying the water must be cognizant of possibly increasing the growth of aquatic plants.

During this study, CC Lake did not suffer from dissolved oxygen depletion to any appreciable extent. This is likely due to the shallow nature of the lake allowing water to become re-aerated and avoiding an anoxic pool of water commonly found at depth in deeper lakes. Additionally, sediments within the lake, while having some nutrients sequestered within them, were not as bad as other lakes within the region regarding nutrient or metal concentrations. At this time, draining and/or dredging would likely not result

in an appreciable increase in water quality within the lake as a stand-alone operation. Since it is the single most expensive and logistically difficult alternative, its recommendation is not warranted at this time. This opinion may change due to changing lake conditions.

Algaecides/Herbicides

Various algaecides, usually forms of chelated copper, have been used as a lake management tool for decades. Indeed, some lake management strategies rely solely on the application of algaecides. They are effective in killing algae but less effective in preventing its growth in the first place and do not make an effective pre-emergent. Additionally, if improperly applied at the wrong time, as in the middle of an algae bloom, dissolved oxygen depletion can (and often does) occur. Some fish kills can be directly tied to the mis-use of algaecides.

Algaecides are toxic not only to algae but also other forms of aquatic life such as zooplankton and fish. It is also possible for copper levels to accumulate in sediments to toxic levels. While not nearly as expensive as other alternatives, such as dredging, algaecides require a licensed applicator, must be constantly applied throughout the growing season, and require frequent monitoring to ensure no toxicity occurs. Over time, these costs accumulate to a point often greater than any initial outlay of capital for a longer-term solution. While their occasional use should not be dismissed, algaecides in and of themselves should not be a viable stand-alone option for lake management. Granular forms of algaecide can serve as effective deterrents against the proliferation of filamentous algae and aquatic plants.

Herbicides (usually forms of glyphosate) can be used on aquatic emergent plants should these become problematic once water quality (and clarity) in the lake has increased. Since these treatments are more localized than treating the entire water column, toxic effects are reduced compared to algaecides; however, careful monitoring and timing of application is crucial to avoid any toxicity in the lake.

I would not recommend the use of algaecides as a long-term, stand alone treatment in CC or Archer Lakes due to the potential of negative effects, cost, and logistics of application. However, algaecides should never be completely dismissed and could be used as an occasional short-term management technique. The same is true of herbicides.

Aeration/Circulation

It is a common misnomer that lake "aerators" are used to increase dissolved oxygen levels in lakes. Increasing dissolved oxygen levels in water is difficult and more dependent upon the amount of oxygen-consuming particles in the water being removed than trying to force oxygen into water; an almost impossible task given that dissolved oxygen levels and water temperature are inter-dependent. The warmer the water the more energy required to go into solution and for the ability of the water to "hang onto" the oxygen molecule. Given the extremely warm water temperatures, and high oxygen demand of the water in both CC and Archer Lakes, it is not likely that an aerator would actually increase dissolved oxygen levels during the summer. Also, as previously mentioned, dissolved oxygen levels do not appear to be problematic in CC Lake.

Aerators should more properly be referred to as circulators. There are great benefits to increasing lake circulation. This can result in an increase of mixing zone depth for algae and lessen effects of stagnation allowing water at depth to be brought to the surface so that natural re-aeration can occur. As discussed

in the section on algae, both CC and Archer lakes are dominated by noxious, and potentially toxic, forms of cyanobacteria which prefer calm, stagnant water. Lakeside was also dominated by cyanobacteria at one time but installation of an effective circulation system in the lake switched the algal assemblage away from cyanobacteria and toward more palatable forms (to zooplankton and small fish) of algae. While overall algal biomass was not affected, anytime numbers of noxious/toxic cyanobacteria can be reduced this opportunity should be taken. Increased circulation, if adequately sized, also has the potential to decrease the amount of emergent aquatic plants growing along the edge.

Given the extremely shallow nature of CC lake, care must be taken in placement and sizing of diffusers. Entrainment of anoxic sediment must be avoided as it is possible to actually decrease dissolved oxygen levels should this occur. It is beyond the scope of this report to engineer and size a specific aeration system; however, several different designs exist. In the case of CC Lake, I would imagine a bottom-draw surface circulation system would work best.

Costs associated with adding a circulation system in CC Lake would be minimal compared to long-term benefits. While increasing lake circulation would result in water quality benefits in CC Lake, it should not be used as a stand-alone operation because it simply will not address all of the current water quality issues in the system. It would, however, alleviate enough problems for this report to recommend installation of a circulation system in CC Lake.

Decreasing Residence Time

Currently, the CC/Archer lake complex operates as a closed hydrologic system. In such a system with a relatively long residence time, nutrients are constantly accumulated and recycled and evaporation increases salinity. There is a direct correlation between residence time and the amount of primary productivity (algae growth) in lake and reservoir systems; the greater the former the greater the latter and vice versa.

Residence time can be reduced by creating some type of outlet from CC Lake. This outlet could either be in the form of an injection well back into the local aquifer or via a canal or pipe back into the Santa Cruz River. Both would require proper permitting from AzDEQ (an APP for the former and AZPDES for the latter). I understand the bureaucratic difficulties involved with additional permitting, however, in this case the benefits to CC Lake would, in my opinion, outweigh any logistical difficulties in obtaining such permitting.

I have performed several research projects on the Santa Cruz River in the recent past (<http://www.azdeq.gov/environ/water/assessment/download/edw.pdf>) and know first-hand of the water quality issues within this system. Water quality within both CC and Archer Lakes is better than it is within the river likely due to recharge through the local aquifer resulting in some nutrient removal. In essence, any water put back into the river would dilute many of the known pollutants already contained within it, especially if additional nutrient removal were to occur within the lakes. I know that a rather impromptu system had been constructed in the recent past to decrease residence time in the lake(s) by making a channel where water from the lake was emptied back into the river. Without proper permitting, this activity is not allowed under state law. Since the benefits to the lake would likely be substantial and once the initial cost of construction was paid it would be relatively inexpensive to maintain in the long-run, the cost of obtaining proper permitting would be well worth the time and effort invested.

Triploid Grass Carp

Triploid (sterile) grass carp are excellent at eating large amounts of aquatic plant material. Currently, CC Lake is permitted for their use by the Arizona Game and Fish Dept. Grass carp are large-bodied (up to 60 pounds), fast-growing (up to 29 g/day under ideal situations), long-lived (15-20 years) species requiring no maintenance and are very tolerant of a wide range of water quality conditions. They are relatively inexpensive so even the initial capital outlay is relatively small. Their use and stocking may be critical once water quality and clarity is increased in the lake.

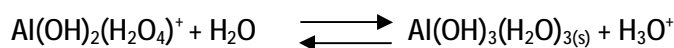
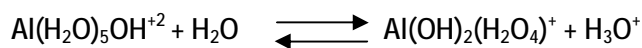
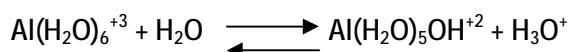
Recommended stocking rates would be anywhere from 15-30, 8-12 inch long fish per acre of aquatic vegetation. Since it may take 3-4 years before their size is such where an effect is noticed, these fish could/should be stocked at any time. While primarily herbivorous, they will rarely, take smaller fish on occasion in the absence of adequate vegetation. Anglers at the lake also may on a rare occasion, incidentally take them. In this case, occasional re-stocking may be necessary.

Nutrient Removal

As previously stated, without first reducing the nutrient load to the lake, the above recommendations will likely be short-lived and the lake would quickly revert back to a eutrophic state. Options for nutrient removal range from construction of a package water treatment plant at the lake utilizing technology such as ozonation, reverse osmosis, protein fractionation, biological nutrient removal, flocculation/coagulation, etc. This approach is almost always cost-prohibitive both in the long- and short-term. Unfortunately, nutrient removal is among the most expensive of all water treatment technologies.

An alternative that offers promise is a treatment we have employed at Lakeside Lake with great success; the use of aluminum sulfate to bind phosphorous thereby making it unavailable for algae growth. Alum is far less toxic than algaecides and does not kill algae outright; rather, by removing phosphorous from the water it limits their growth in the first place.

Free Al^{+3} ions are formed when aluminum sulfate, $\text{Al}_2(\text{SO}_4)_3$ is added to water and these ions are quickly attached to six water molecules to form $\text{Al}(\text{H}_2\text{O})_6^{+3}$. Several hydrolytic species are next formed due to a successive loss of protons to surrounding water molecules.



The final product, $\text{Al}(\text{OH})_3(\text{H}_2\text{O})_3$, is the alum precipitate or "floc" and is usually written as $\text{Al}(\text{OH})_3$.

Under alkaline conditions an additional reaction can occur:



There are three mechanisms of phosphorous removal by alum in water ;

- From the formation of insoluble AlPO_4 ,
- By sorption on the surface of the $\text{Al}(\text{OH})_3$ floc and,
- By entrapment of phosphorous-containing particulate matter in the $\text{Al}(\text{OH})_3$ floc.

This same mode of action by alum to remove phosphorous can also significantly increase the settling rate of suspended particulate material from the water column and has even been shown to remove dissolved organic material adding to color of the water. Since this suspended material carries an oxygen demand with it, the effect of removing an essential nutrient for algal growth (P) combined with removing suspended material would likely result in increased dissolved oxygen levels within the water column.

Like many metals, the toxicity of aluminum is not well correlated with levels of total aluminum but is correlated with the biologically-active fraction. The inorganic, monomeric form of aluminum, Al^{+3} , is believed to be the most toxic. Toxicity of aluminum in a waterbody is usually measured as the dissolved fraction of the total and is dependent upon other water quality criteria, especially pH levels. Under typical situations encountered in freshwater environments, the toxic fraction is an extremely small fraction of the total. Increasing toxicity is reported in the literature at pH levels below 5.5 and above 8.5.

There are two ways to use alum to control eutrophication effects in CC/Archer Lakes; treating the water either before or as it enters Archer, or direct application into the water via a boat as we currently do in Lakeside. The water used in Lakeside, however, has lower total P levels than in-coming water into Archer so if the latter is chosen; it would have to be performed frequently throughout the spring, summer, and fall. It is possible that some combination of both (treating the water as it comes in and direct application into the water) would be required to meet designated goals and objectives.

Since water entering the system initially goes into Archer, it might be possible to use this smaller lake as a pre-treatment area for alum application. Alum generally comes in two forms; granular and liquid. The best design would be to install a circulation system in Archer and store liquid alum on-site which could be metered into the water via the circulation system. This would insure adequate mixing, flocculation, and phosphorous removal prior to water entering CC. The amount of alum entering the water could be metered up or down depending upon phosphorous loading and season.

Archer is currently used for model boat/recreational purposes. This design may interfere with this activity depending upon design selection. A surface aerator spraying water into the air would interfere with recreation the most and a subsurface diffuser the least.

Long-term cost of associated with using alum depends on delivery method. Applied via a boat, alum is relatively inexpensive; construction of an alum injection unit into Archer would be more expensive but still moderate relative to other treatment options.

Recommendation Matrix

In order to provide some frame of reference regarding cost and efficacy of the recommended treatments, we provide the following matrix. The relative scale is based on a rating of 1-5 with 1 representing the "least" and five representing the "most".

| Treatment | Long-Term Cost | Initial Capital Outlay | Difficulty | Expected Benefit | Longevity |
|--------------------------------------|----------------|------------------------|------------|------------------|-----------|
| Dredging | 1 | 5 | 5 | 3 | 4 |
| Algaecide/Herbicide | 3 | 2 | 2 | 2 | 1 |
| Aeration/Circulation | 2 | 3 | 3 | 4 | 4 |
| Decreasing Residence Time | 1 | 3 | 3 | 4 | 4 |
| Grass Carp ¹ | 1 | 1 | 1 | 3 | 5 |
| Alum Injection System into Archer | 3 | 3 | 3 | 5 | 2 |
| Alum Applied Directly in CC via Boat | 1 | 1 | 1 | 4 | 2 |

1: Grass carp will not control algal growth. Their recommended use is to treat aquatic plants only.

Specific Recommendations

Obviously, not all of the recommendations are feasible nor is it necessary to apply all of them simultaneously. CC Lake did not achieve its current eutrophic status overnight so attempting to "fix" it will not occur overnight either. It almost always takes a combination of techniques to achieve desired goals and objectives so beginning with some of the simplest, and least costly, recommendations obviously makes sense.

The first and foremost pressing need for the CC/Archer Lake complex is a lake management and monitoring plan. Management of the lakes should be active depending upon dynamic and changing lake conditions on a seasonal and annual basis. Management of dynamic ecosystems, such as urban lakes, is akin to driving a car where constant small inputs are required to avoid crashing. Given the current status of CC/Archer Lakes (potentially toxic to fish, wildlife, and humans), a lake management and monitoring plan, and its implementation, should be enacted as soon as possible.

After a management plan has been enacted, the next logical, and least expensive, step would be to apply alum via a boat directly into CC and Archer to determine if this treatment alone would be enough to alleviate symptoms of eutrophication. This treatment could occur for a period of one year after which time it would be re-assessed in terms of efficacy. This treatment would require bench-scale floc jar tests be performed in the laboratory prior to dosing in the lake to determine needed concentrations and any possible toxicity.

Simultaneous with alum introduction via a boat, an aeration/circulation system should be engineered to aid in mixing of the alum with the water and to try and reduce the amount of noxious, and potentially toxic, cyanobacteria within the lake.

Decreasing algae growth and clarifying the water are the major benefits of using alum. However, this may exacerbate the growth of aquatic plants. The addition of grass carp to CC Lake would greatly reduce the risk of an invasion by aquatic plants. This is a relatively inexpensive and long-lived treatment and, like lake management, should be implemented as soon as possible. The current plan of mechanically removing aquatic plants should continue and herbicides used as a last resort.

Depending upon the success of this first tier of lake management using alum, circulation, and grass carp, obtaining an AzPDES permit for re-introduction of water back into the Santa Cruz River should be explored. The engineering aspect of this should not be too onerous or expensive and the benefits would likely be substantial. Indeed, I would imagine most of the monitoring conditions associated with an AzPDES permit would already be covered in whatever lake management and monitoring program already will be put in place.

Due to phosphorous loading into the system, it might not be possible to control nutrient and algae growth by applying alum directly into the lake. Treatments might have to be applied too frequently to achieve goals and objectives. If this is the case, then pre-treating water in Archer with alum would be the next preferred alternative. This would require the installation of a circulation system, metering pumps, and storage container for liquid alum within Archer. The costs associated with this construction would be moderately expensive but it may be the only feasible method to ever control the amount of nutrients going into CC Lake. There are long-term costs associated with this treatment including the cost of liquid alum, maintenance, and electricity to run the circulators and metering pumps.

The author believes that the costs associated with a dredging/restructuring operation would far outweigh the benefits and such an operation is not warranted nor recommended at this time. This opinion may change due to changing lake conditions.

To summarize, the following recommendations are given in order of prioritization and importance. The selection of subsequent steps are dependent upon the efficacy of earlier steps.

1) Construction and Implementation of a Lake Management and Monitoring Plan

- a. Application of alum via a boat directly into the water.
- b. Installation and engineering of a circulation system.
- c. Introduction of grass carp.

2) Decreasing Residence Time via Releasing Lake Water Back into the Santa Cruz River.

3) Construction of an Alum Injection System within Archer Lake.

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