Managing Algal Blooms at a Botanical Garden Lake: **A Success Story**

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Blooms of microscopic cyanobacteria and algae have become a major concern for inland water quality across the country and throughout the world (Brooks et al. 2016). These species are vital components of aquatic food webs, but excessive growth can lead to aesthetically unpleasing accumulations, disruption of food webs, and increased oxygen demand. Additionally, the growth of some toxic species can create conditions that may be harmful to aquatic wildlife and terrestrial animals (including humans) exposed to the blooms or contaminated water or food sources. Effective management of water quality to mitigate or prevent the development of such Harmful Algal Blooms (HABs) has become a top priority in the stewardship of U.S. inland waters.

The study site up to 2011

The Huntington Library, Art Collection and Botanical Gardens, San Marino, California is a private, non-profit institution founded in 1919 and open to the public in order to promote research and education in the arts, humanities, and botanical sciences. The botanical gardens of The Huntington cover 120 acres, and its collections are organized into more than a dozen specialized gardens. One of these, the Garden of Flowing Fragrance was opened to the public in 2008, and is one of the largest Chinese-style gardens outside China, including an artificial lake constructed with a concrete bottom in 2006 with a surface area of ≈1 acre. The lake holds approximately 877,000 gallons of water (≈3.3 million liters), and has a mean depth of 4.4 ft. (1.3 m). The lake was built with no natural inputs or outlets, and evaporative losses of water for most years constitute 2-3X the volume of the lake. These losses are compensated by the addition of water drawn from local deep wells. The lake is equipped with a gravel biofilter that controls ammonium levels in the lake by stimulating nitrification of ammonia to nitrate, but this process does not affect overall nitrogen and phosphorus loading.

Identifying the problem: nutrient inputs and outputs

Observations in the summer of 2011 indicated a massive accumulation of planktonic algal/cyanobacterial biomass in the lake three years after it was open to the public (Figure 1A-E,G; Table 1). While substantial amounts of microalgae were apparent in previous years, chlorophyll values in excess of 300 μg/liter were observed in some areas of the lake during 2011, indicating hypereutrophic conditions (Figure 1D; Table 1). Moreover, the plankton community at that time was strongly dominated by the cyanobacterium, *Cylindrospermopsis raciborskii* (Figure 1F), a cyanotoxin-producing species that is also capable of converting N_2 into cellular nitrogen (nitrogen fixation). Toxin analysis by HPLC, and confirmed by standards, demonstrated the presence of the cyanotoxin cylindrospermopsin, as well as saxitoxin and the saxitoxin analogue, 21-sulfosaxitoxin.

Total nitrogen and phosphate concentrations in the lake were high (Table 1), with the overwhelming percentages of those elements present as particulate material (biomass of suspended cyanobacteria, algae, and detritus). Dissolved nutrients were very minor components of the total concentration of those elements. Significantly, the water source for replenishing the ponds (from the Garden's deep wells) is low in phosphorus (6.2 μg/liter) but high in nitrogen (5,600 μg/liter). Despite the low phosphorus concentration in the well water, total phosphorus in the lake was ≈930 μg/liter, 150X the concentration in well water. This situation implied that more important sources of phosphorus must exist for the lake.

The concrete lining of the Chinese Garden Lake effectively keeps major nutrients entering the system within the water, biota, and sediment of the lake, with the obvious exception that nitrogen fixation and/or denitrification (conversion of ammonia to N_2) may occur. As a consequence, internal loading of nutrients has steadily progressed since the construction of the lake. There have been multiple sources of nutrients to the lake, in addition to nutrients entering from well water replenishment, and the rare and highly episodic rain events that characterize Southern California (regional rainfall is <15 inches, or 38 cm per year). Care was taken during design and construction to limit nuisance runoff from the lawn and botanical holdings within the drainage basin of the lake, and fertilizer is used sparingly in the catch area. Resident and transient populations of waterfowl and California Gulls also frequent the lake (it is estimated that ≈30 birds visit the lake daily). They are not intentionally fed, but contribute an unknown and possibly significant amount of excreta to the lake summed over multiple years.

The lake has also supported a substantial population of ornamental fish (≈100 koi) from the beginning, and fish food was identified as a potentially major source of nutrients to the lake, particularly for phosphorus. Phosphorus is generally a key element limiting the overall productivity of lakes (Elser et al. 2007). Although its concentration is relatively low in the well water used to replenish

Figure 1. The Huntington Garden's Chinese Lake in summer 2011. Hypereutrophic conditions dramatically affected water color and reduced transparency (A-C). Chlorophyll concentrations in lake water exceeded 300 µg/liter (D) due to the presence of high abundances of the toxin-producing cyanobacterium, Cylindrospermopsis raciborskii *(F). Resident and transient birds populations (E), ornamental fish (G) and their wastes contributed to nutrient loading in the lake.*

Table 1. Characteristics of the Huntington Garden's Chinese Lake in summer, 2011. Chlorophyll concentrations indicated hypereutrophic conditions in the lake. Most (≈99%) of the total nitrogen and phosphorus in the water column of the lake were contained in suspended particulate material (microalgae, cyanobacteria and detritus).

Sample Location in Lake	Chlorophyll Concentration (μg/liter)	Particulate Nitrogen (μg/liter)	Inorganic Nitrogen (μg/liter)	Particulate Phosphate (μg/liter)	Inorganic Phosphorus (μg/liter)
North end	252	6,500	83	900	8.0
South end	310	4,020	31	250	5.6

the lake as noted above, approximately 3.5 kg/week of fish food was added up to 2011, contributing 32 g phosphorus/week. That amount of phosphorus constitutes ≈465 μg/liter phosphorus addition annually to the lake, if distributed evenly throughout the lake volume. Therefore, fish food alone might account for total phosphorus concentrations in the water column of the lake within three years, although some immobilization in the sediments undoubtedly occurs.

Mechanical attempts to remediate the lake failed or proved unfeasible

As noted above, the biofilter installed in the lake at the time of construction did not maintain low algal biomass in the water column, but it was not designed to do so. A sand filtration platform containing the finest sand was deployed in the lake for several months in an attempt to reduce algal/cyanobacterial biomass, but water samples collected at the intake and output of the filter showed that *C. raciborskii* passed through the filter with very little reduction in abundance, presumably due to the narrow diameter of the cells. A bag filtration system equipped with 1 μm mesh bags did reduce algal/cyanobacterial abundances in the water passing through the filter, but the process was deemed financially impractical because hundreds of bags and considerable effort would be required to significantly impact overall abundance in the lake. Similarly, at the scale required to reduce and maintain low algal/cyanobacterial biomass, an industrial diatomaceous earth filtration system was also deemed impractical. The filter removed as much as 85 percent of the standing stock of algae and cyanobacteria from the lake water, but installation and maintenance would be expensive as a long-term solution.

Other solutions were considered but discarded: the application and removal of hay, sonication, UV light, flocculation and sedimentation, chemical treatments, increased shading, oxygenation, and enhanced circulation. It was deemed that these activities or additives might negatively impact the lake flora or fauna, its aesthetic value, and, more importantly, ultimately not address the basic issue of nutrient loading.

An evolving solution to nutrient loading: A three-pronged approach

Given that the filtration approaches tried in the lake proved either ineffective or impractical, a management strategy was devised for reducing nutrient loading and specifically targeting phosphorus loading in the lake (because the dominant cyanobacterium, *C. raciborskii*, is a nitrogen-fixing species, it was assumed that controlling nitrogen would be ineffective). The approach relied on (1) mechanically reducing existing nutrient loads in the lake, (2) reducing the rate of nutrient inputs by addressing the largest probable source (input of fish food), and (3) redesigning water handling for the lake to enact periodic removal of lake water as a means of achieving an acceptable steady-state nutrient concentration in the lake.

As a first step, during November 2011, the lake was drained and its sediment removed (Figure 2A). Nutrient loading of lake sediments, and subsequent release into the water column and bloom stimulation or prolongation, is a common phenomenon of shallow lakes. Sediment removal can be an effective strategy for reducing total phosphorus loading, if such activity is feasible (Bormans et al. 2015). Phosphorus removal as sediment was approximated from the depth and areal extent of the sediment, and estimated phosphorus content of the sediment (Søndergaard et al.), at >20 kg phosphorus. If the sediment-bound phosphorus were completely available to be remobilized into the water column of the lake, phosphorus in the sediment corresponded to an overall phosphorus concentration in the lake volume on the order of 1 mM phosphorus. Not all of the phosphorus in the sediment would be bioavailable to the algae and cyanobacteria in the lake, but sediment removal clearly constituted a massive reduction in phosphorus available to support planktonic algae in the lake (compare value to values in Table 1). The lake was refilled in late November 2011.

Our estimation of the amount of fish food added weekly to the lake (and subsequent excretion of nutrient wastes by the fish) clearly indicated an important source of nutrient loading. As a consequence, koi numbers were reduced by approximately half (≈50) in the lake, and the amount of fish food was reduced by a similar amount.

Periodic removal of lake water was also enacted to help reduce plankton and nutrient loads in the lake. The original design of the lake had no outlets, so internal nutrient buildup was inevitable. Removal was accomplished through the design and construction of a simple piping system that pumped lake water into the supply line used to irrigate the botanical holdings of The Huntington. Water pumped from the lake by this system has averaged approximately two-three lake volumes per year, with the water replaced with well water also used for restoring evaporative losses. Assuming a concentration of total phosphorus in the lake's water column during 2011 (930 μg/liter), removal of the lake water containing planktonic microorganisms, detritus and dissolved substances in the water could remove >10 kg phosphorus/year, less if clearer water persisted in the lake.

Lake status and lessons learned

The Chinese Garden Lake at The Huntington is a clear lake today with a minimal standing stock of suspended microalgae and cyanobacteria (Figure 2B). The initial status of the lake and overall changes enacted are depicted in Figure 3, indicating removal of sediment, reduction in fish and fish food, and periodic exchange of lake water. The combined effect of these activities has resulted in sustained high water quality and clarity. Moreover, the composition of the plankton community has shifted from dominance by toxin-producing cyanobacteria to a community dominated by innocuous green microalgae (specifically desmids), reducing health risks to fish and birds living in or frequenting the lake.

The experiences of The Huntington in addressing issues with their lake serve as an example of the multiple pathways and approaches that are available in developing and enacting effective lake management practices. A preliminary assessment of nutrient inputs to the lake identified several potentially important sources of nutrient elements, and a wide array of procedures and practices for reducing them. Preliminary efforts were able to quickly rule out many of these possible approaches as either ineffectiveness or impractical. In particular, physical removal by filtration was thwarted by the small cell diameter of the dominant cyanobacterium, and the cost associated with maintenance of the systems. Additionally, the Garden chose to avoid chemical treatments that might be effective in treating bloom outbreaks but would not address long-term internal nutrient loading. As a result, they adopted an approach that involved a combination of activities to address nutrient loading in the lake.

The small size of the Chinese Garden Lake (≈1 acre) was unquestionably an advantage in allowing activities that might not be feasible in larger artificial or natural lakes. Nevertheless, some approaches evaluated by the Garden were deemed impractical or too costly even for the relatively small aquatic ecosystem of their lake. Their situation also benefited from the unique need for substantial amounts of irrigation water for their botanical holdings. That enabled removal of the lake water (and the nutrient elements present as biota, dissolved organic compounds, and inorganic forms of nitrogen and phosphorus) to help counteract nutrient buildup in the lake, while also providing a use for that water that avoided the cost of treatment or disposal of the lake water.

These unique features place caveats on the extrapolation of the results from the Chinese Garden Lake of The Huntington to other lakes and ponds.

Each lake must be evaluated in light of its unique physical, chemical, and biological characteristics in order to develop and apply best management practices. However, we feel that the example presented here could be applied, in some form, to numerous water bodies of botanical gardens, zoos, parks, and other holdings that are manageable in size and suffer many of the same aspects of nutrient loading.

Figure 2. Drainage of the lake and sediment removal in November 2011 (A) enacted to reduce nutrient loading in the lake. Five years following sediment removal and changes in nutrient management practices, the Chinese Lake (B) remains clear and virtually free of harmful algae and cyanobacteria.

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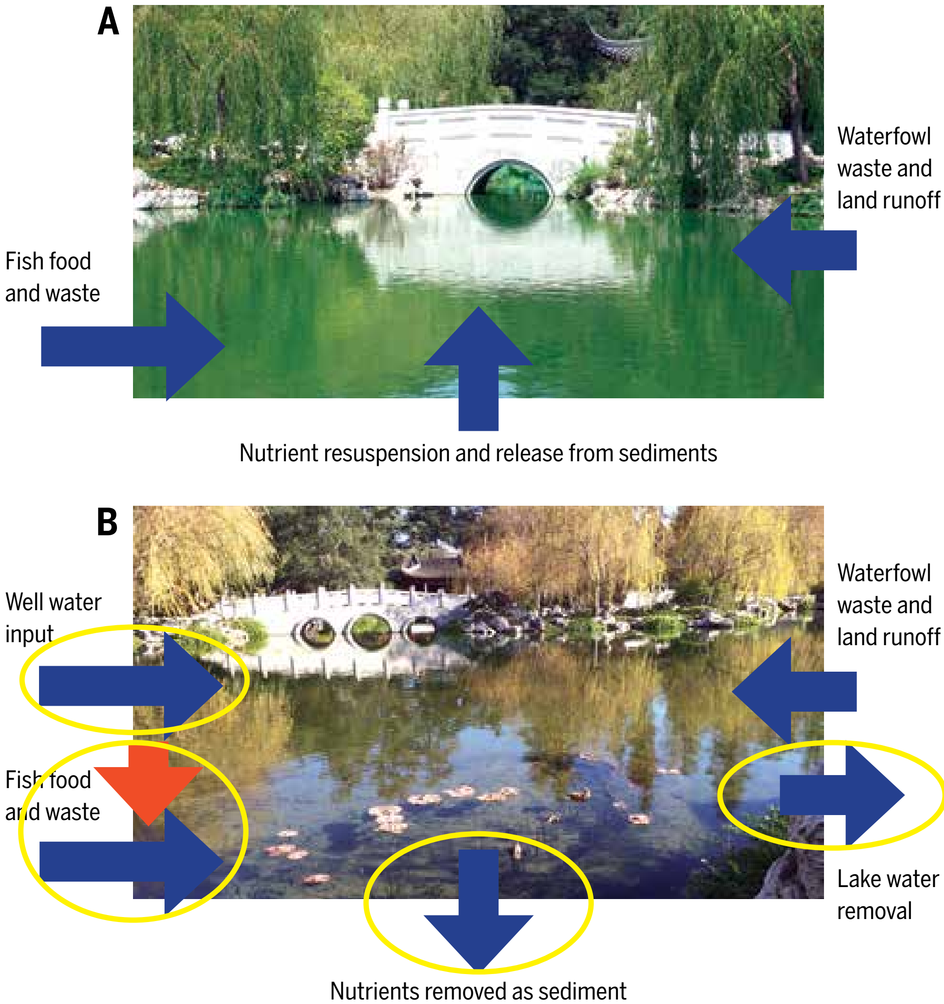

Figure 3. (A) The eutrophic state of The Huntington Garden's Chinese Lake resulting from internal loading of nutrients contained in fish, fish food, wildfowl, and land runoff. (B) Reductions in fish and fish food, removal of sediment to address accumulated internal nutrient loads, and periodic exchange of water are highlighted in the yellow circles.

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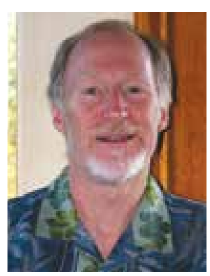

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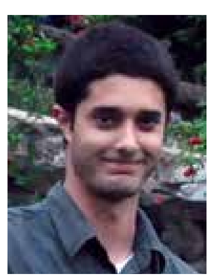

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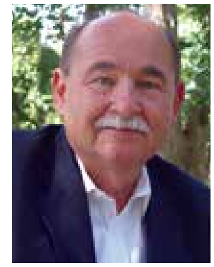

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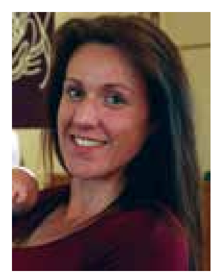

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