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Freshwater harmful algal bloom (FHAB) suppression with solar powered circulation (SPC)

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ABSTRACT

Freshwater harmful algal blooms (FHABs) incidence is increasing worldwide, presenting risks for human and animal health, aquatic-ecosystem sustainability and economic vitality. Increasing nutrient input to freshwater, increasing temperatures and decreasing flow rates that create quiescent or stagnant waters are primary causes of increasing incidence. Ecological approaches to FHAB control target these causes to reduce FHAB incidence without adversely impacting aquatic ecosystems. Artificial circulating increases water flow, and is reported to suppress FHABs in the literature on habitat disturbance. This report evaluates the efficacy of a new technology, solar powered circulation (SPC), designed to create long-distances circulation of the epilimnion (>200 m) to suppress FHABs. Three nutrient-enriched, source-water reservoirs periodically seeded with cyanobacteria from influent served as case studies. Utility personnel systematically and consistently collected limnological data before and during SPC deployment, thus enabling valid within-site comparisons. SPC units were deployed at densities of approximately 0.15 km^2/unit. Pre- to post-SPC initiation changes in cyanobacterial density indicated that SPC strongly suppressed FHABs through a process that strengthened over time. Densities of green algae increased significantly during SPC at the only site where algaecides were never used, and zooplankton density increased significantly at another site. Diatom densities approximately doubled following SPC initiation, although the increases were not statistically significant. Copper sulfate usage declined by 85% at one site during SPC, whereas applications declined from approximately 12/year to 1–2/year at the other site where algaecides were used. SPC provided an effective approach to FHAB control that was ecologically benign and environmentally sustainable.

1. Introduction

Freshwater harmful algal blooms (FHABs; Hudnell, 2008) pose serious risks for human and animal health (Hawkins et al., 1985; Azevedo et al., 2008; Falconer, 2008; Hudnell, 2008a; Hudnell et al., 2008; Pilotto, 2008; Stewart et al., 2008; Backer et al., 2008), aquatic-ecosystem sustainability (Havens, 2008; Ibelings et al., 2008; Ibelings and Havens, 2008) and economic vitality (Steffensen, 2008; Dodds et al., 2009). Cyanobacteria (a.k.a. blue–green algae) are the predominant FHAB organism, although other phytoplankton such as the euryhalinic chrysophyte *Prymnesium parvum* (a.k.a. golden algae) also causes FHABs. Dozens of cyanobacterial species produce highly potent toxins (Humpage, 2008). Cyanobacterial toxins, cyanotoxins, cause lethal and sub-lethal effects in humans and other organisms, and bloom biomasses adversely impact aquatic biota. There is widespread agreement among scientists and water quality managers that the incidence of blooms in fresh-to-estuarine waters is increasing in the U.S. and worldwide (Carmichael, 2008). Every year, FHABs occur where they were not observed previously, and FHAB durations increase. Global climate change, rising freshwater usage demand and excessive nutrient input to freshwater are driving much of the increase (Paerl et al., 2007; Paerl, 2008). The economic costs of FHABs and eutrophication in U.S. freshwaters are conservatively estimated to be $2.2–4.6 billion annually (Dodds et al., 2009). Several reports call for research to improve FHAB prevention, suppression and termination methods (Donohue et al., 2008; Dortch et al., 2008; Hudnell, 2009; Lopez et al., 2008). Innovative approaches to near-term FHAB prevention and control are needed to protect human health, aquatic ecosystems and economies (Hudnell, 2009; Hudnell and Dortch, 2008).

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Approaches to FHAB control are generally classified as ecological or chemical (Sraskraba, 1996). Ecological approaches target factors that promote FHABs to decrease incidence, intensity and duration with ecologically benign and sustainable methods (Dortch et al., 2008; Hudnell and Dortch, 2008; Hudnell, 2009). FHABs occur most often when four stimulatory factors are present—nutrients, warmth (>20 °C), sunlight and quiescent or stagnant water (Paerl et al., 2007; Paerl, 2008; Paul, 2008). Temperature cannot be controlled in large water bodies, and is energy intensive in smaller water bodies. Colorants can be added to water bodies to reduce the amount of light available for phytoplanktonic photosynthesis, but indiscriminately inhibit beneficial and harmful algae, thereby adversely impacting aquatic ecosystems (Spencer, 1984). Only the factors of nutrients and quiescent or stagnant water can be targeted with ecologically sustainable FHAB control methods in most cases. Nutrient input reduction is essential for sustaining aquatic ecosystems from freshwater to marine. However, limiting nutrient inputs often does not control FHABs in the near term. The implementation of nutrient input-reduction strategies is usually a long-term undertaking, and nutrient loads already in sediment frequently stimulate FHABs when resuspended into the water column (Paerl, 2008; Perovich et al., 2008; Pieler, 2008).

Freshwater flow rates are decreasing as drought frequency and duration increase due to global climate change, and withdrawals increase due to rising usage demand (Paul, 2008; Paerl and Huisman, 2008). Decreased flow rates create quiescent, stagnant waters, conditions preferred by FHABs that can be altered through hydrologic manipulations. Increasing flow rates and decreasing water residence time can eliminate FHABs even in nutrient-rich freshwaters (Paerl, 2008). Artificial circulation of water bodies is an approach to FHAB control that can be implemented when flow rates cannot be increased. The scientific basis for FHAB control through artificial circulation is described in the literature on cyanobacterial-habitat disturbance (Reynolds et al., 1983; Steinberg, 1983; Visser and Ibelings, 1996; Donaghay and Osborn, 1997; Jungo et al., 2001; Huisman et al., 2004). Intermediate levels of habitat disturbance suppress FHABs and promote maximum planktonic diversity (Elliott et al., 2001).

This report evaluates new solar powered circulation (SPC) technology for FHAB suppression and prevention. Three case studies are presented in which municipal water utilities collected longitudinal limnological data before and during SPC deployment for FHAB control.

2. Methods

2.1. Case selection

Case study sites were selected based on a survey of SPC users. The survey was sent to the primary representatives at the first 121 freshwater bodies where SPC was deployed during March 2007. Circulation was initiated at these sites between 2000 and June 2006, and continued at least through the summer of 2006. The sites were located in 31 U.S. states ($n = 117$) and Canada ($n = 4$). Representatives at 83 sites agreed to participate in the survey, 64 fully completed the survey and 50 indicated that FHAB control was a primary goal. These 50 sites were screened for inclusion as case studies according to the following criteria.

- SPC was deployed for epilimnetic circulation to suppress FHABs
- The whole water body was treated (surface area/SPC unit $\leq 0.16\ km^2$)
- Water body personnel systematically assessed phytoplanktonic density
- Internal analytical methods were validated, standardized and consistent
- Densities of total plankton, cyanobacteria and green algae were available
- Phytoplankton data were available ≥ one spring-fall season pre-SPC
- Phytoplankton data were available ≥ one spring-fall season during SPC

Three sites met the criteria for inclusion as a case study. Each site was a municipal, source-water reservoir. Operations personnel at each site systematically collected limnological data before and during implementation of SPC for FHAB control that were sufficient to evaluate efficacy. Each utility used sampling methodology thought best for operational purposes. The critical feature is that sampling was consistent across time, thus enabling valid within-site comparisons. Comparisons of absolute values should not be made across sites due to methodological differences and the use of copper sulfate at two of the three sites.

2.2. Crystal Lake, Iowa

Crystal Lake, located in Des Moines, IA, is a water-filled gravel pit that serves as a raw-water reservoir for the adjacent McMullen Drinking water-treatment plant. Water is continuously introduced from the Raccoon River into Crystal Lake at a rate of 18.93 million L/day, and the same amount is withdrawn into the water-treatment plant. Recreational activities are not allowed on the lake. Morphological characteristics are shown in Table 1.

The Raccoon River water is high in nutrients with total nitrogen and phosphorus levels occasionally exceeding 18 mg/L and 8 mg/L, respectively. Diversion of river water into Crystal Lake enables microbial denitrification processes to reduce nitrogen levels for a mean period of 40 days prior to use. Crystal Lake regularly experienced intense cyanobacterial blooms during summers and falls that caused taste, odor and biomass problems. Copper sulfate or other algaecides were never applied in Crystal Lake; the utility elected to use alternative source waters during blooms because of concerns about ecosystem degradation with long-term algaecide usage.

Two solar-powered SB10000 units were installed in March 2006. Intake hoses were set at a depth of 2.4 m (Table 1). The units' placement locations and the utility's water-sampling site are shown in Fig. 1a.

The utility withdrew water from the lake at a depth of approximately 3 m, and took water samples from the intake line because water quality at that depth was most critical for operations. During each sampling period, 1 L of water was collected and delivered immediately to the utility laboratory. Concentrations of total phytoplankton, green algae and cyanobacteria were measured microscopically using the Standard Methods procedure 10200 F (APHA, 2005). The centrifugation method was used rather than settling because some cells do not settle, cells may die during the settling period (APHA, 2005) and settling requires too long an analysis period for the utility to avoid water quality problems. The sample was mixed, and a 12 mL aliquot was poured into a 15 mL centrifuge tube. The sample was centrifuged for 20 min at 1050 RCF to concentrate the phytoplankton. The supernatant was aspirated, leaving a 0.5 mL concentrated sample in the tube that was vortexed to create a homogenous resuspension.

40 μL of sample was placed onto a microscope slide and covered with a 22 mm × 22 mm cover slip. The slide was scanned and the organisms were visually counted. A conversion factor was applied to derive the number of organisms per mL. The genera of cyanobacteria were noted and listed in order of their relative proportion, highest to lowest.

Table 1
Reservoir, data collection and treatment parameters.

	Crystal Lake	EGL 4	Lake Palmdale
Algaecides used	No	Yes	Yes
Surface area (km^2)	0.26	0.47	0.89
Max depth (m)	7.6	10.7	7.6
Mean depth (m)	3.0	7.6	5.5
Water volume (km^3)	7.65×10^{-4}	3.53×10^{-3}	4.90×10^{-3}
Water mean residence time (days)	40	270	91
Data collection period	March–December 2005–2008	January–December 2001–2007	January–December 2002–2004
SPC initiation date	March 2006	April 2003	November 2002
# SPC units	2	3	6-7[a]
Surface area km^2/SPC unit	0.13	0.16	0.15–0.13[a]
Mean intake depth (m)	2.4	6.7–4.3[b]	4.6
Water volume circulated (km^3)	6.1×10^{-4}	3.1×10^{-3}–2.0×10^{-3}[b]	4.1×10^{-3}
Water km^3 circulated/SPC unit	3.05×10^{-4}	1.04×10^{-3}–6.67×10^{-4}[b]	6.82×10^{-4}–5.85×10^{-4}[a]
SPC circulation rate (km^3/day)	5.5×10^{-2}	5.5×10^{-2}	5.5×10^{-2}
Total circulation rate (km^3/day)	0.11	0.17	0.33–0.39[a]
Turnover duration (days)[c]	5.6	19.0–12.2[b]	12.4–10.6[a]

[a] A seventh SPC unit was installed in June 2003.
[b] Water intake depths were varied as the reservoir surface elevation and water clarity varied over time.
[c] The duration required for the SPC units to circulate all the water between the surface and mean intake depths one time.

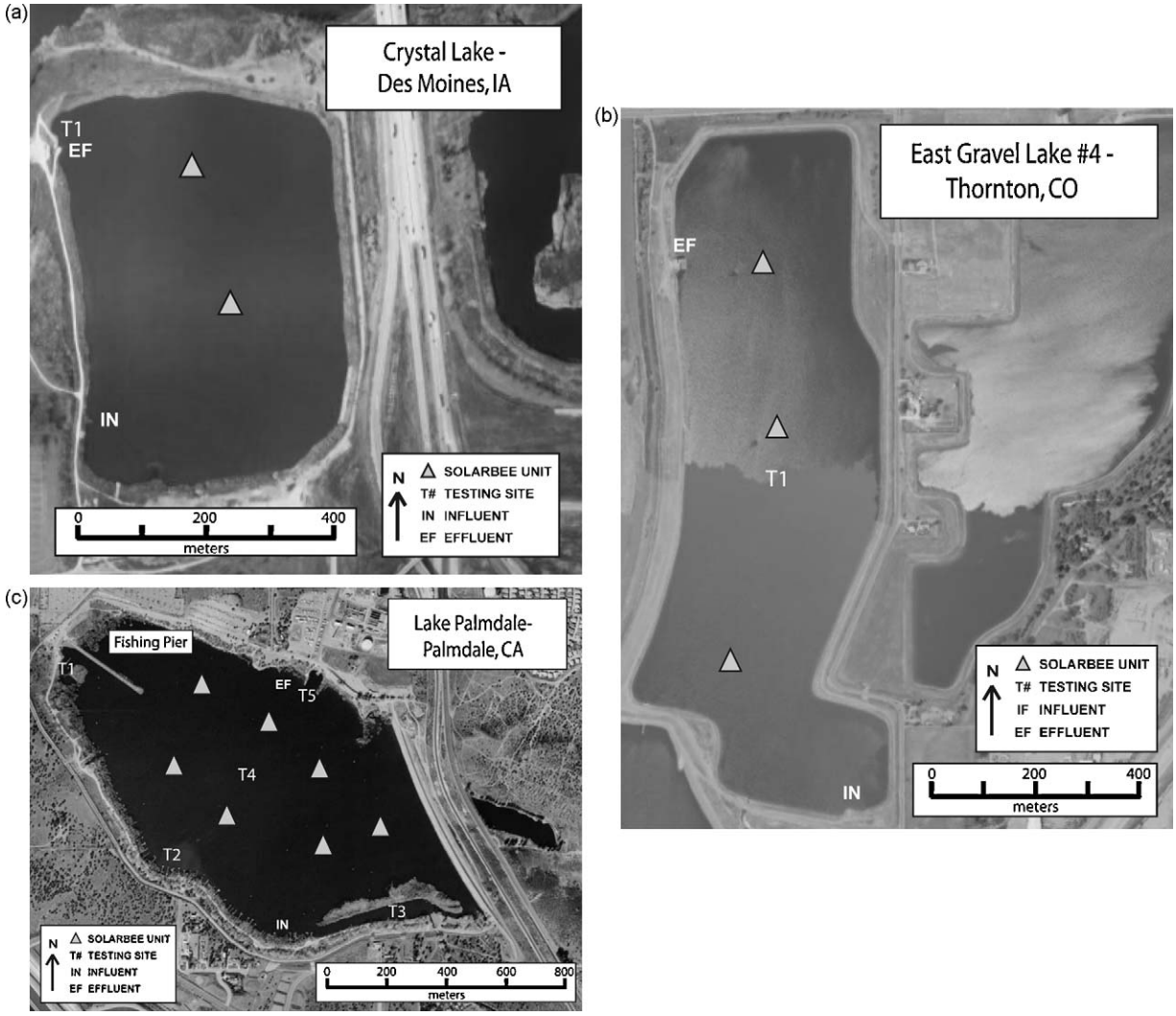

Fig. 1. (a) Crystal Lake, surface area = 0.26 km^2, is a source-water reservoir in Des Moines, IA. Water samples were collected from the utility intake pipe (T1) that withdrew water at a depth of about 3 m. (b) East Gravel Lake #4, surface area = 0.47 km^2, is a source-water reservoir in Thornton, CO. Water samples were collected at the approximate middle of the lake from the surface (T1). (c) Lake Palmdale, surface area = 0.89 km^2, is a source-water reservoir in Palmdale, CA. Water samples were integrated from samples collected at a depth of about 1 m at 5 sites (T1–5).

2.3. East Gravel Lake 4, Colorado

East Gravel Lake 4 (EGL 4), located in Thornton, CO, is part of multi-lake, raw-water storage complex. Source water is primarily from the Burlington Ditch that is strongly dominated by secondary effluent from the Denver Metropolitan Area. Nitrate and total phosphorus influent levels occasionally exceeded 10 and 1.3 mg/L, respectively. EGL 4 is the final lake in the series that supplies source water to the treatment plant. Recreational activities are not allowed on the lake. Morphological characteristics are shown in Table 1.

EGL 4 regularly experienced FHABs seeded by influent transfers during summers even after initiating a policy of applying algaecides whenever weekly samples indicated excessive levels of cyanobacteria. The FHABs created taste and odor compounds, leading to many customer complaints. The utility used copper sulfate to terminate the FHABs. Powdered activated carbon was used to remove the taste and odor compounds, both in the lake after copper sulfate treatments and in the in-plant treatment process.

Three solar-powered SB10000 units were installed in April 2003. Intake hoses were set at an average depth of 7.6 m (Table 1). The average intake depth was varied over time to a minimum of 4.3 m as water level and clarity varied (Table 1). All units were upgraded during April 2005 to a newer model that incorporated batteries to operate the units continuously.

SPC units were not placed in the lakes that supply water to EGL 4. FHABs occurred frequently in those lakes, and cells were transported into EGL 4 during continuous water transfers. Although FHABs were not thought to have originated in EGL 4 since circulation was initiated, copper sulfate was applied after water transfers when cells were apparent. The units' placement locations and water-sampling site are shown in Fig. 1b.

Water samples were collected from the surface of the lake in 1 L containers. Aliquots of 200 mL were filtered through a Sedgwick–Rafter sand filter to concentrate the algae for analyses. A wide-bore pipette was used to place 1 mL aliquots of the concentrate into a Sedgwick–Rafter counting cell. Plankton was examined using a compound microscope set to 100× magnification and fitted with an ocular micrometer. The number of single cells and cellular clumps appearing in 10 fields (1 strip) were counted. The number of cells and clumps counted was converted to units/mL.

2.4. Lake Palmdale, California

Lake Palmdale, located in Palmdale, CA, serves as a raw-water reservoir that supplies the adjacent Palmdale water-treatment plant. The lake regularly experiences high wind velocities, but supports boating, fishing, hunting, and pontoon aircraft navigation. The lake is designated as a "no body contact" water body. Morphological characteristics are shown in Table 1.

The California Aqueduct supplies Lake Palmdale with water containing nitrate at concentrations occasionally exceeding 6 mg/L, and total phosphorus at 0.22 mg/L, due to agricultural drainage and waster water-treatment plant discharges. The aqueduct regularly experienced intense algae blooms that triggered blooms in Lake Palmdale. The utility initiated a policy of applying algaecides whenever chlorophyll *a* levels were $\geq$15 μg/L at any site. The utility regularly applied copper sulfate from April through September in 2002 when cyanobacteria predominated the phytoplankton. The cyanobacterial secondary metabolites, geosmin and 2-methylisoborneol, caused adverse taste and odor events and customer complaints.

Six solar-powered SB10000 units were installed in November 2002. Intake hoses were set at an average depth of 4.6 m (Table 1). A seventh unit was installed in June 2003. All units were upgraded in February 2005 to a newer model that incorporated batteries to operate the units continuously. The units' placement locations and water-sampling sites are shown in Fig. 1c.

The utility collected data on plankton concentrations to assess water quality at five test sites from January 2002 until March 2004 when funding for the monitoring program ended, although some monitoring continued into October 2004. The five test sites were marked with anchored buoys throughout the study period to ensure consistency in sampling locations. Water samples were collected at least twice a month between March and September and at least once a month between October and February.

Water samples for algal analyses were collected from each test site at a depth of about 1 m (the usual Secchi depth) using a Van Dorn sampler. A volume of 200 mL water from each test site was mixed to form a composite sample of 1000 mL. A 125 mL sample of the well-mixed composite was preserved with 25 drops of Lugol's iodine solution and sent to a laboratory at Northern Kentucky University for analysis. Composite samples were placed in sedimentation chambers for settling prior to algal analyses. Settled samples were analyzed using Standard Methods 10200 F (APHA, 2005) to determine total algae, cyanobacteria, green algae and diatom densities in cells/mL.

Composite samples for crustacean zooplankton analysis were collected by towing a 153 μm simple conical tow net submerged horizontally just below the water surface for about 90 m away from each test site. A volume of 200 mL from each test site was mixed to form a composite sample of 1000 mL. Composite samples were concentrated by filtering through the net to 250 mL samples that were preserved with 4% sugar buffered formaldehyde. Preserved zooplankton samples were shipped to Lake Superior State University for analysis. Aliquots were extracted from the samples using a wide-bore pipette, dispensed in counting chambers and examined at 10–40× magnification using a stereozoom dissecting microscope. Sufficient sub-sample volume was used to ensure that either 200 individuals or 10% of the total sample was quantified according to Standard Methods 10200 G (APHA, 2005). The results were reported as the number of zooplankton per cubic meter.

2.5. SPC technology and deployment for FHAB control

The SolarBee©, Inc., SB10000 units each consisted of three pontoons supporting a platform comprised of above water, near surface and under water components. Solar panels, an electronic control box, a low-voltage, high-efficiency brushless motor and accessories were mounted on an above-water frame. A distribution dish, impeller and battery were attached to the frame and suspended just below the surface. A 0.914 m diameter, flexible, intake hose was attached to the base of the impeller. A steel plate suspended 0.305 m beneath the hose caused water in that density layer to be drawn in radially with near-laminar flow. Water intake depth was adjusted using chains attached to the hose and secured to the frame. Two moorings attached to the frame with chains maintained the spatial position of the unit. The impeller operated continuously at 80 rpm in battery-equipped units unless the controller was programmed to vary by time of day, or prolonged periods of low light incidence caused the electronic controller to reduce the RPM or deactivate the system temporarily. The units transported approximately 37,850 L/min of water to the surface. Approximately 11,355 L/min of direct flow was transported through the hose, and another 26,495 L/min of induced flow was transported external to the hose. Water smoothly departed from the units radially at low velocity, both above and below the dish positioned just under the surface.

The intake depth was set at the base of the photic zone for FHAB control, usually just above the thermocline. Only the epilimnion

was circulated. The thermocline remained intact, thereby preventing hypolimnetic nutrients from entering the photic zone and further promoting FHABs. The SPC unit density was approximately 1/0.15 km^2 (Table 1),

2.6. Data analysis

Descriptive and inferential statistics were performed using Statistix 9 by Analytical Softwater, Inc., Talahassee, FL. Pre- and post-SPC initiation differences in algal densities were assessed using analysis of variance techniques with $\alpha = 0.05$.

3. Results

The surface areas per SPC unit, total water volumes circulated, water volumes circulated per SPC unit, total circulation rates and turnover durations for the three reservoirs are shown in Table 1.

3.1. Crystal Lake, Iowa

The Crystal Lake water-utility management maintained a policy against algaecide usage. The reservoir experienced FHABs during summer and fall months prior to 2006. Total algal densities increased from near zero in May 2005 to over 300,000 cells/mL during late July and August 2005 (Fig. 2a). The bloom was dominated by cyanobacteria (Fig. 2b). The utility ceased withdrawing source water from Crystal Lake in July 2005 due to taste and odor events, and used alternative source water during the remainder of the year. Densities of green algae remained below 2000 cells/mL during 2005, except for a brief peak at 4100 cells/mL during July (Fig. 2c). Although cyanobacteria densities remained elevated throughout the summer of 2005, the predominant genera shifted from *Aphanizomenon*, to *Cylindrospermopsis*, then *Pseudanabaena*, and finally *Oscillatoria*/*Planktothrix*.

After installation of two SPC units in March 2006, total algal (Fig. 2a) and cyanobacterial densities (Fig. 2b) were much lower than in 2005 ($p < 0.05$), although nutrient concentrations in the source water were unchanged. Total algal and cyanobacterial densities exceeded 25,000 cells/mL only in one week during August of 2006, reaching a peak of about 50,000 cells/mL, and declined further during 2007 and 2008. Total algal densities demonstrated a downward trend during SPC; mean values were 10,962 cells/mL in 2006, 8149 cells/mL in 2007 and 5928 cells/mL in 2008. Cyanobacterial densities also declined annually during SPC; mean values were 8040 cells/mL in 2007, 3407 cells/mL in 2007 and 2865 cells/mL in 2008. Although cyanobacterial densities were far lower during the treatment period, the dominant genera shifted between *Aphanizomenon*, *Cylindrospermopsis*, *Pseudanabaena*, and *Oscillatoria*/*Planktothrix* in patterns similar to that observed during 2005. As opposed to cyanobacteria, green algal densities increased sharply during SPC (Fig. 2c); both mean and peak values in 2006–2008 were 2–5+ times those of 2005 ($p < 0.05$). The yearly changes in algal densities are summarized

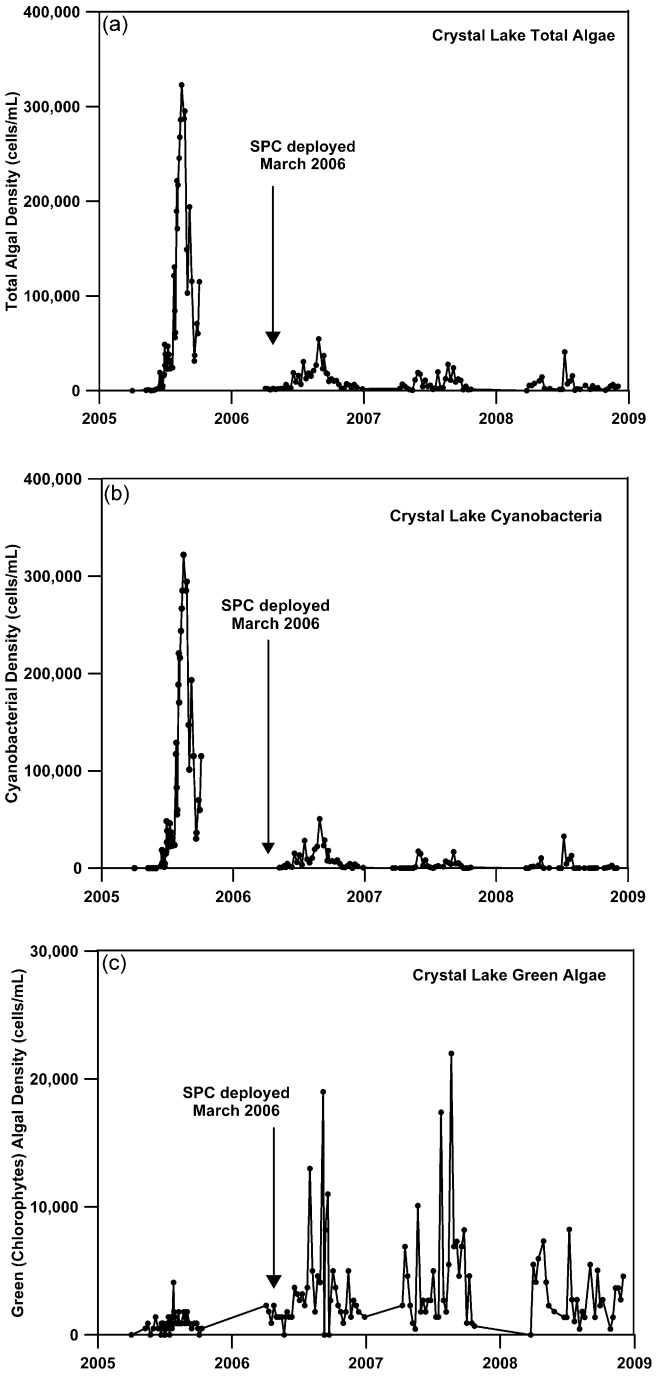

Fig. 2. (a) Crystal Lake total algal concentrations from 2005 to 2007. Algaecides were never used in Crystal Lake. (b) Crystal Lake cyanobacterial concentrations from 2005 to 2007. (c) Crystal Lake green algal concentrations from 2005 to 2007.

Table 2
Planktonic densities pre- and post-SPC initiation.

	Total algae	Cyanobacteria	Green algae	Diatoms	Zooplankton
Crystal pre	**86,302 ± 13,834**	**85,447 ± 13,799**	**871 ± 90**	NA	NA
Crystal post	**8,668 ± 972**	**5,161 ± 524**	**3,665 ± 380**	NA	NA
EGL 4 pre	**1,796 ± 862**	**72 ± 41**	**1,534 ± 850**	135 ± 30	NA
EGL 4 post	**306 ± 87**	**3.9 ± 1**	**45 ± 8**	232 ± 86	NA
Palmdale pre	4,228 ± 848	426 ± 148	1,528 ± 423	2,216 ± 769	**169 ± 56**
Palmdale post	7,977 ± 2,449	967 ± 446	888 ± 214	4,436 ± 2,211	**984 ± 272**

Numbers are means ± standard errors of the means; NA: not available. Units are cell/mL at Crystal and Palmdale, and units/mL at EGL 4. Bolded values are statistically significant at $p \leq 0.05$; between-site comparisons are inappropriate. Algaecides were never used at Crystal, whereas copper sulfate usage declined by 85% at Palmdale and from 1–2/month to 1–2/year at EGL 4 after SPC initiation.

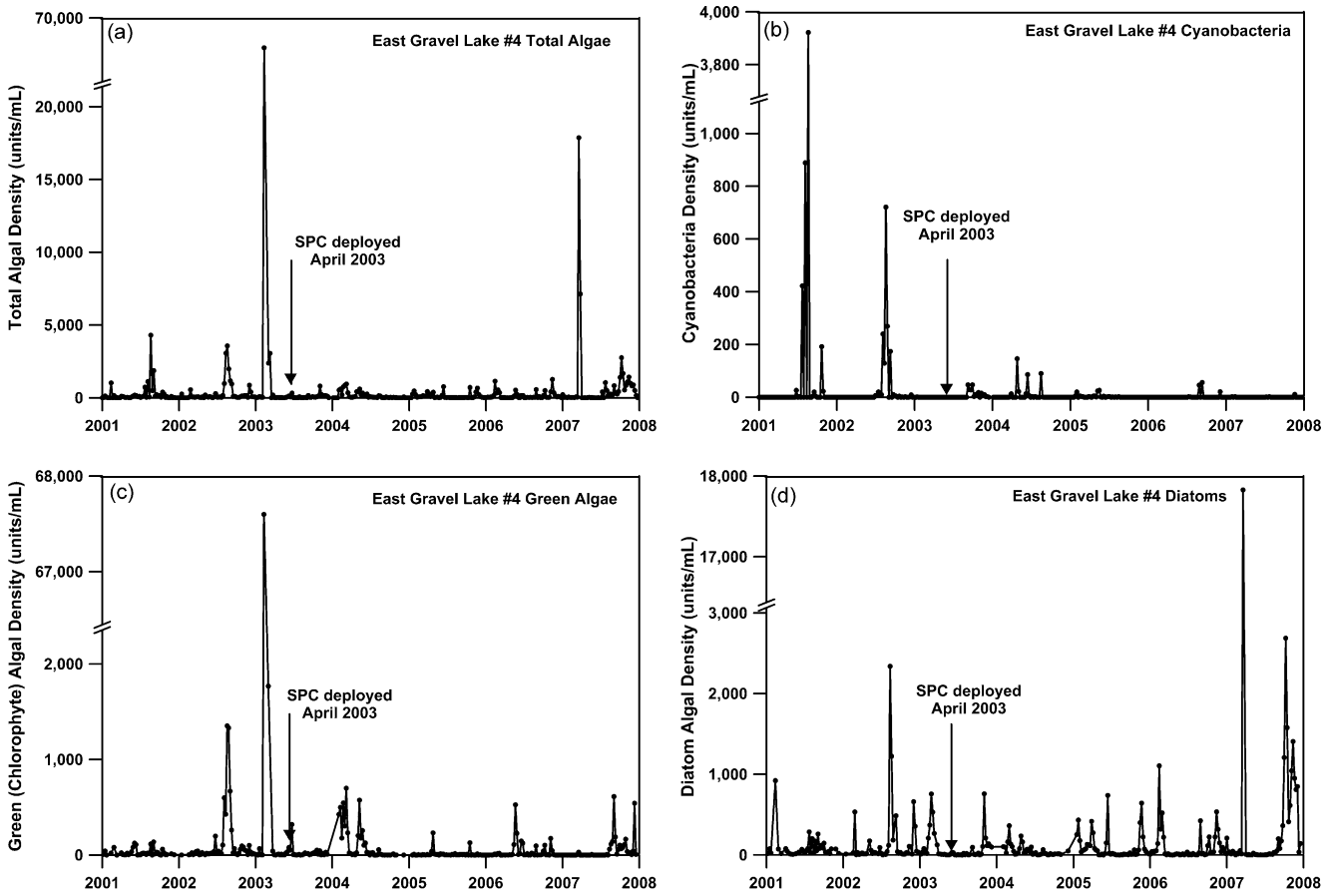

Fig. 3. (a) East Gravel Lake 4 total algal concentrations from 2001 to 2007. Algaecides and powered activated charcoal were used before and during SPC. Although detailed records of algaecide and powered activated charcoal usage were unavailable, the utility's management believes that usage declined sharply after SPC deployment. (b) East Gravel Lake 4 cyanobacterial concentrations from 2001 to 2007. (c) East Gravel Lake 4 green algal concentrations from 2001 to 2007. (d) East Gravel Lake 4 diatom concentrations from 2001 to 2007.

as mean pre- and post-SPC initiation values in Table 2. No taste and odor events were experienced during 2006–2008, enabling Crystal Lake to continuously meet criteria for use as source water.

3.2. East Gravel Lake 4, Colorado

Total algal densities peaked at 4298, 3566 and 67,958 units/mL during August 2001 and 2002, and February 2003, respectively (Fig. 3a), prior to deployment of SPC. The algal assemblage consisted almost entirely of cyanobacteria in August 2001, reaching a peak density of 3922 units/mL. The peak in 2002 contained a mixture of cyanobacteria, green algae and diatoms, whereas that in early 2003 was predominated by green algae (Fig. 3b–d). Total algal density peaked above 1000 units/mL during 7 months of the pre-SPC period. Cyanobacterial densities exceeding 700 units/mL were observed during July–August of 2001 and 2002 (Fig. 3b) in spite of approximately biweekly applications of copper sulfate. Other notable spikes in algal density prior to SPC deployment were a green algae peak of 67,600 units/mL during February 2003 (Fig. 3c), and diatom peaks of 533–922 units/mL during February 2001–2003, 2339 units/mL during August 2002, and 660 units/mL during December 2002 (Fig. 3d).

Total algal and cyanobacterial densities were significantly lower following SPC deployment in April 2003 ($p < 0.05$, Table 2). Total algal densities exceeded 1000 units/mL only during 2006 and 2007 when diatom populations expanded. Multiple total algal densities between 400 and 1000 units/mL were observed throughout the year during 2003–2007 (Fig. 4a). Densities of cyanobacteria never exceeded 100 units/mL in 2003–2007 except during April 2004 when densities peaked at 146 units/mL (Fig. 4b). Peak cyanobacteria densities of 50–90 units/mL occurred during June and August 2004, and August–September 2006. Cyanobacterial densities remained at or near zero at all other times during 2003–2007.

Populations of green algae exceeded 200 units/mL each year following SPC deployment, and peak densities above 500 units/mL were observed during all years except 2003 and 2005 (Fig. 4c). However, mean green algal density during SPC treatment was significantly lower than that observed during the pre-treatment period due to a peak of 67,600 units/mL shortly before SPC deployment ($p < 0.05$, Table 2). Diatom densities exceeded 350 units/mL each year from 2003 to 2007 (Fig. 4d). Peak diatom densities exceeded 600 units/mL during 4 of those 5 years, including peaks above 1000 units/mL in 2006 and 17,000 units/mL in 2007. The increase in mean diatom density during SPC treatment (Table 2), however, was not statistically significant ($p > 0.05$). These data and low cyanobacteria densities indicated an overall healthier profile of phytoplankton during SPC deployment.

Although detailed records of copper sulfate and powdered activated carbon applications during 2001–2007 were unavailable, managements' impression was that algaecide applications decreased from 1 to 2/month to 1–2/year after SPC initiation. Taste and odor events have not occurred, and cyanobacterial densities have remained suppressed, since completion of the study.

3.3. Lake Palmdale, California

Cyanobacterial densities generally were held below 10,000 cells/mL due to the utility's policy of applying copper

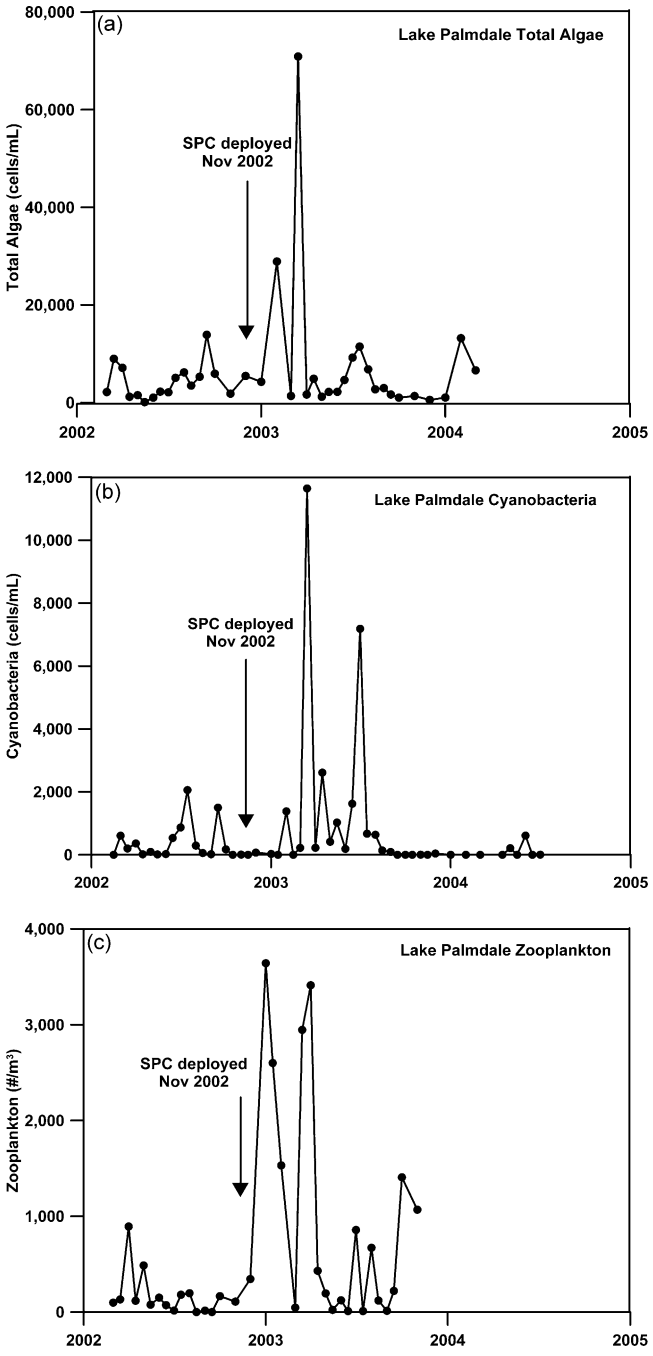

Fig. 4. (a) Lake Palmdale total algal concentrations from January 2002 to March 2004 when most of the monitoring terminated due to funding deficiency. Algaecide usage in both 2003 and 2004 was approximately 85% below that of 2002. (b) Lake Palmdale cyanobacterial concentrations from January 2002 to July 2004. (c) Lake Palmdale zooplankton concentrations from January 2002 to October 2004.

sulfate whenever weekly testing indicated chlorophyll *a* levels exceeded 15 μg/L. The utility applied 26,077 kg of algaecide during 2002 prior to initiating SPC. Total algal concentration exceeded 10,000 cells/mL only during September 2002 (Fig. 4a). Cyanobacterial densities peaked at 2058 cells/mL during July 2002 (Fig. 4b). Densities of green algae remained below 2000 cells/mL except on three occasions during August–October 2002 when densities peaked between 4268 and 5112 cells/mL. Diatom densities also remained below 2000 cells/mL except during March and September 2002 when levels peaked at 6830 and 11,133 cells/mL, respectively. Zooplankton densities were below 500 units/mL except during a peak of 893 units/mL in April 2002 (Fig. 4c). Even with frequent algaecide applications in 2002, the utility received customer complaints of foul tastes and odors in potable water due to production of geosmin and 2-methylisoborneol during the cyanobacterial peak period.

The utility deployed SPC for FHAB control in November 2002. The 15 μg/L chlorophyll *a* criterion for algaecide application was reached only three times in 2003 and four times in 2004, as opposed to 13 times in 2002. Whereas 26,077 kg of copper sulfate were applied in 2002, only 3992 and 3753 kg were applied in 2003 and 2004, respectively. Both mean total algal and cyanobacterial densities were higher in 2003 than 2002 (Fig. 4a and b), although the increases were not statistically significant ($p > 0.05$). Mean total algal densities increased from 4249 cells/mL in 2002 to 8378 cells/mL in 2003. Total algal densities exceeded 10,000 cells/mL on three occasions in 2003, peaking at 28,897 cells/mL in February, 70,874 cells/mL in March, and 11,465 cells/mL in July (Fig. 4a). Cyanobacterial densities exceeded 2700 cells/mL twice in 2003 (Fig. 4b), but remained well below the World Health Organization's Level One FHAB criterion of 20,000 cells/mL (Burch, 2008). Cyanobacterial densities in 2004 were significantly below those observed during 2002 ($p < 0.05$). Other than a peak at 611 cells/mL in June 2004, cyanobacterial densities remained at or near zero into July 2004 when sampling ended due to lack of funding. Mean green algal densities were comparable in 2002, 1490 cells/mL, and 2003, 996 cells/mL ($p > 0.05$). Mean diatom densities of 4466 cells/mL in 2003 exceeded those of 2171 cells/mL in 2002, but not significantly ($p > 0.05$). Diatom densities in 2003 peaked at 26,567 cells/mL in February, 57,221 cells/mL in March and 5045 cells/mL in July 2003. The mean zooplankton density of 1017 individuals/mL in 2003 (Fig. 3c) was significantly greater than that of 2002, 180 individuals/mL ($p < 0.05$). Zooplankton densities exceeded 500 individuals/mL only once in 2002, but on nine occasions in 2003. Similar planktonic results were observed in pre- and post-SPC comparisons (Table 2).

Although most monitoring was suspended between March 2004 and late 2006, FHABs were not believed to have initiated in Lake Palmdale since SPC deployment. The utility experienced only a few minor taste and odor events since SPC initiation. Those events were attributed by the utility to cyanobacterial cells entering the reservoir from the aqueduct.

4. Discussion

4.1. An ecological approach

Meeting the challenge of freshwater FHABs requires methods for suppressing blooms that are effective in the near term, ecologically benign and environmentally sustainable over the long term. The goal of ecological approaches to FHAB control is to restore conditions that enable beneficial phytoplankton to out compete cyanobacteria. Water circulation counteracts decreased flow rates, shifting the competitive advantage from cyanobacteria to chlorophytes and diatoms (Reynolds et al., 1983; Visser and Ibelings, 1996; Donaghay and Osborn, 1997; Elliott et al., 2001; Jungo et al., 2001; Huisman et al., 2004). FHABs disrupt the normal flow of nutrients up the food chain through algae palatable to zooplankton and then fish, a condition that is reversed when FHABs are suppressed (Havens and East, 1997; Auer and Arndt, 2004; Havens, 2008).

The three case studies were selected for presentation because sufficient data were collected before and during SPC treatment to assess FHAB suppression efficacy. Comparably extensive datasets were not available from other water bodies using SPC. A time-series assessment was considered more appropriate than a case–control assessment because all freshwater bodies differ in

morphological, physical, chemical and biological parameters. Furthermore, nearby sites with sufficient limnological data that did not use SPC for FHAB suppression were unavailable for use as control sites. Comparisons with sites that used other methods of FHAB suppression would not add information to an assessment of SPC control of FHABs. The data from the case studies, in combination with discussion of conditions at sites where SPC failed to suppress FHABs, described below, provide a reasonable indication of conditions under which SPC would and would not be likely to suppress FHABs.

The data from each case study indicated that SPC strongly suppressed FHABs. Each of the case studies showed a trend of increased cyanobacterial suppression with years of SPC deployment. Crystal Lake provided the most unambiguous data because of a policy against algaecide usage. Intense cyanobacterial blooms were observed during the summer prior to implementing SPC. Cyanobacterial peak density declined by about 82% during the first year of SPC deployment and by about 95% the second year, coincident with large increases in green algae. Taste and odor events were not experienced, and Crystal Lake continually met criteria for use as source water during SPC deployment. EGL 4 experienced intense FHABs seeded during influent transfers, and associated taste and odor events, during summer months in the 2 years immediately preceding SPC deployment even though algaecides were applied approximately biweekly. Cyanobacteria densities decreased dramatically during the subsequent 5 years of SPC deployment. Algaecide applications decreased to approximately 1–2/year, and profiles of total algae, green algae and diatoms indicated a well-balanced planktonic assemblage. Lake Palmdale experienced taste and odor events prior to SPC deployment even with frequent algaecide application due to seeding from the California Aqueduct. Cyanobacterial densities increased during the first year of SPC; the peak densities of $<$12,000 cells/mL during March and July 2003 exceeded the peak densities observed in 2002. However, algaecide usage decreased by about 85% in 2003 (26,077 kg in 2002 to 3992 kg in 2003), probably accounting for cyanobacterial density increase. Cyanobacterial densities deceased in 2004 below those of 2002 even as algaecide usage remained about 85% below the 2002 level (3753 kg in 2004). This observation indicated that the process(es) through which SPC suppresses FHABs strengthened over time. Mean densities of green algae remained stable, and mean densities of diatoms and zooplankton increased during SPC, indicating a more balanced planktonic assemblage.

The SPC units were designed to intake water at the density levels present between the intake hose and plate suspended below the hose. This design enabled near-laminar flow intake from radial directions at velocities that decrease with distance from the unit. The unit's output flow apparently combined with influent flow and thermal- and wind-driven surface currents to redistribute the water across the treatment zone. The combination of artificial and natural currents created long-distance circulation of the epilimnion sufficient for FHAB suppression during repeated turnover cycles within the contiguous 0.15 km^2 treatment zones (Table 1).

4.2. Hypotheses and research needs

SPC is an ecological approach to restoring homeostatic balance within water bodies that is not fully understood. The case studies demonstrated that although SPC strongly suppresses FHABs, all cyanobacterial cells were not eliminated from the water bodies. The case-study reservoirs occasionally experienced episodes of increasing cyanobacterial densities that were usually of low magnitude and brief duration. Outcomes may be optimized through research that describes relationships between SPC parameters such as circulation rate and area, unit location, spacing between units and water intake depth, and the physical, chemical, biological and morphological characteristics of water bodies. Mechanisms through which SPC suppress FHABs are hypothesized to be: (1) promotion and distribution of cyanobacteria pathogens, cyanophage (Honjo et al., 2006) and bacteria that lyse cyanobacteria cells (Mayali and Azam, 2004); (2) promotion of bacteria and beneficial algae that reproduce much more rapidly than cyanobacteria (Kratz and Myers, 1955; Sorokin and Krauss, 1958), thereby transporting nutrients up the food chain and limiting bloom growth and; (3) interference with cyanobacteria's ability to optimize position in the water column through buoyancy control to meet nutrition and sunlight requirements (Wallace et al., 2000). Research ultimately may indicate that SPC inhibits FHABs through multifactorial processes. If cyanobacteria pathogens have an important role in terminating environmental blooms, research is needed to identify and culture the pathogens demonstrating the highest levels of virulence for a variety of cyanobacterial taxa. Studies could evaluate the potential for cultured pathogens to be released in combination with SPC to prevent bloom pulses or rapidly terminate existing blooms, as well as the potential for adverse effects.

4.3. Failures to suppress FHABs

SPC failed to achieve FHAB control during several whole waterbody treatment trials. A test in four 0.001 km^2 aquaculture ponds with maximum depths of about 1 m failed to suppress FHABs. Although the cause is unknown, natural lake dynamics were altered due to high fish density, the absence of zooplankton due to predatory fish and perhaps other factors. Failure also occurred in several other small ponds with maximum depths of less than 1 m, particularly when adjacent to wetlands supporting FHABs. FHAB control was also not achieved in a lake that received influent from a river experiencing a FHAB. The average residence time of the lake water was only 5 days, apparently not enough time for SPC to suppress cyanobacteria in the lake. Current application parameters may be insufficient for SPC suppression of FHABs in very shallow water bodies with short residence times.

SPC also failed to suppress FHABs during several partial waterbody treatments; applications that comprise approximately 20% of the more than 300 water bodies using SPC for FHAB control. FHABs were well controlled in most, but not in a 7.2 km^2 bay in a very large lake when less than 6% of the bay was treated. Three SPCs were deployed near an influent and wetlands delivering cyanobacterial cells and high phosphorus concentrations to the bay. Cyanobacterial cell density was moderate in the treated zone, but high beyond the treated zone in the open water. A similar lack of control was observed in a large reservoir where high volume, cool influent rich in phosphorus dove under the warmer surface water in the reservoir. Surface FHAB cells were blown into the treated zone by the prevailing wind. Another failure to control FHABs occurred in a lake where the photic zone extended beyond the thermocline. *Anabaena* bloomed slightly below the thermocline, and to a lesser extent in the epilimnion, during late summer and fall, prior to whole lake turnover. The bloom in the epilimnion was not suppressed when the SPC intake was just above the thermocline. Penetrative convection (a.k.a. nightly thermal-driven transfers; Fischer et al., 1979), similar to nightly convective mixing in ocean science literature (Soloviev and Klinger, 2001), may have caused the failure. Penetrative convection transfers are successive declines of thin surface-water layers to the thermocline or hypolimnion due to cooling of the surface water by evaporation and convective transfer with the colder nighttime air. As cold water descended, the bloom was elevated into the treated zone where it re-seeded the epilimnion nightly. Several other failures were reported, but did not involve cyanobacteria. SPC did not

suppress a dinoflagellate bloom in one water body, nor did SPC suppress blooms of green algae or diatoms that occurred in early spring when water temperatures were too cold for zooplankton to thrive and graze the blooms. The current data also indicate that chlorophytes and diatoms flourish during SPC.

4.4. Other forms of artificial circulation

Forms of artificial circulation that produce turbulent mixing, such as down-flow, diffused air and paddlewheel systems, also suppressed FHABs in small water bodies and increased beneficial algal populations (Steinberg, 1983; Elliott et al., 2001). However, FHAB suppression through turbulent mixing required electrical-grid power (Reynolds et al., 1983; Visser and Ibelings, 1996; Jungo et al., 2001; Huisman et al., 2004). Utilities that burned fossil fuels to produce electricity released greenhouse gasses that promoted global climate change (Hoffert et al., 2002), a factor contributing to the increasing incidence of FHABs (Paerl et al., 2007) and perhaps cyanotoxin production (Davis et al., 2009). Furthermore, turbulent mixing stimulated FHABs when destratification of the water column transported nutrients from the nutrient-rich hypolimnion to the photic zone (Singleton and Little, 2006). Other disadvantages included a small area of influence for each air diffuser and applicability limited to smaller water bodies due to cost. Artificial waterfalls or fountains may also provided good FHAB control in smaller water bodies, but continually required electric-grid power (Clevely and Wooster, 2007).

5. Conclusion

The current studies demonstrated that SPC of the epilimnion strongly suppressed FHABs even in nutrient-rich waters. Densities of chlorophytes and diatoms increased as those of cyanobacteria decreased. Suppression of FHABs within the approximately 0.15 km^2/unit treatment zones indicated that SPC-upflow and natural surface currents combined to create long-distance circulation of the epilimnion. Although the mechanism(s) through which SPC suppressed FHABs remains unknown, the evidence indicated that the magnitude of suppression increased over time. SPC provided an effective approach to FHAB suppression that was ecologically benign and environmentally sustainable.

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