

Effect of Lake Management Efforts on the Trophic State of a Subtropical Shallow Lake in Lakeland, Florida, USA

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Abstract For more than a decade, Lakeland, FL, has invested in restoring its urban Lake Hollingsworth from a hypereutrophic state to its natural eutrophic state. The lake bottom was dredged of nearly 2 million m³ of accumulated organic sediments, and treatment wetlands, storm water curb inlet strainers, and a storm water baffle box were installed within the lake's catchment area to reduce the loading of dirt, leaves, and trash to the lake. After dredging ceased, the lake was dosed one time with alum to improve water clarity and reduce phosphorus recycling from its sediments. Water quality surrogates for algal biomass—Secchi disk transparency and water column total nitrogen, total phosphorus, and chlorophyll- α concentrations—were reviewed to assess Lakeland's progress towards its goal. In the years since dredging has stopped, algal biomass concentration in Lake Hollingsworth has significantly declined. Even with these improvements, however, the lake still remains hypereutrophic.

Keywords Hypereutrophic · Nonpoint source pollution · Dredging · Storm water · Limiting nutrient

1 Introduction

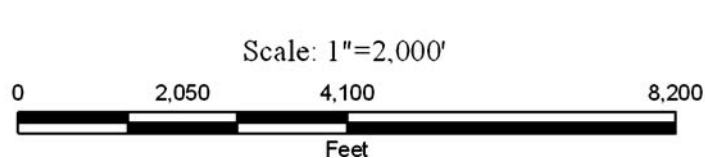
Lake Hollingsworth is a 144-ha lake in Lakeland, Polk County, FL, USA (Fig. 1) with a mean postdredging depth of 2.7 m (Harper and Medley 2004) and a reference stage of 40 m above mean sea level. For more than 100 years, this lake has been popular with residents and tourists for a range of activities including water sports and bird watching. During the twentieth century as the lake's surrounding 668-ha catchment developed, storm water collected from streets and parking lots was discharged through pipes directly to Lake Hollingsworth. Organic-rich sediments accumulated on the lake's floor and recurring nutrient inputs and resuspension caused frequent algal blooms and loss of water clarity (Harper and Medley 2004).

Lake Hollingsworth is classified as hypereutrophic based on average Secchi disk (SD) transparency and on concentrations of total nitrogen (TN), total phosphorus (TP), and chlorophyll- α (CHLA; Forsberg and Ryding 1980). Since 1995, the City of Lakeland has implemented control measures intended to reduce nutrient inputs to the lake and suppress nutrient recycling within the lake (Table 1). We examined the interim impact of these lake management efforts on lake trophic state.

Lake Hollingsworth is located on Lakeland Ridge, an ancient sand dune that once protruded from a sea but today divides the Hillsborough River basin to the west from the Peace River basin to the east (Martin 1998; Sacks et al. 1998). To the west and south of Lakeland Ridge extends Bone Valley, a fossil-rich formation of

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Fig. 1 Lake Hollingsworth, Lakeland, FL (latitude 28° 01'26", longitude -081°56' 42"). The US Census (2009) reported that in 2007, the estimated population of Lakeland was 92,796 persons



~518,000 ha that lies ~10 m below the surface, which is extensively mined for its phosphate (Hoppe 2005). Lake Hollingsworth is typical of a ridge lake in mantled karst topography, and as the nearly round perimeter of the lake suggests, it was created from a sinkhole (Sacks et al. 1998). The lake is underlain by unconsolidated phosphate-rich sands and clay.

Lake Hollingsworth receives inflow from two upstream lakes: Lake Horney and, during heavy rainfall events, Lake Morton (Sacks et al. 1998). Water is discharged from Lake Hollingsworth via Banana Creek and Banana Lake to Lake Hancock and from Lake Hancock via Lower Saddle Creek to the Peace River.

The 1,800-ha Lake Hancock and its 34,000-ha watershed forms the headwaters of the Peace River, which flows to 190 km to the southwest and empties into the Charlotte Harbor estuary at the Gulf of Mexico (see FL Department of Environmental Protection (FDEP) 2007 for maps). Lakes within the Lake Hancock watershed, including Lake Hollingsworth, Banana Lake, and Lake Hancock, are classified by FDEP for designated uses that include “recreation, propagation, and maintenance of healthy well-balanced population of fish and wildlife in fresh water” but are listed as “verified impaired” for nutrients (FDEP 2005). Reductions of water column nutrient concentrations in Lake Hollingsworth were

Table 1 Control measures taken to improve water quality of Lake Hollingsworth (Lakeland 2005; Lakeland 2009)

Project	Description	Construction
Dredging	Removal of 2 million m ³ of organic sediments to restore original lake bottom contours; accumulated organic sediment averaged 2 m or 60% of the lake volume	1997–2001
Curb inlet baskets	Installation of 49 inlet baskets in existing inlets and manholes to reduce dirt, leaves, and trash carried to the lake in storm water; combined, baskets remove ~5,000 kg of influent debris each year	2001
Nutrient removal baffle box	Installation of a baffle box to intercept dirt, leaves, and trash in storm water draining a 10-ha subbasin; baffle box removes ~1,000 kg of influent debris each year	2001
Aquatic plant management	Planting of wetland trees and roots of submerged, emerged, and floating plant species near lake shoreline	2001–present
Public education & outreach	Sponsorship of an Adopt-a-Lake program: lake cleanup, water quality monitoring, establishing and maintaining aquatic plants, removing invasive plants, and installing signs on storm water curb inlets to indicate storm water drains to lake; educational workshops; speaker's bureau; lake water quality and nonpoint source pollution brochures, signs, and displays.	2001–present
Alum addition	Application to lake of 330 m ³ of alum to improve water clarity and reduce phosphorus release from sediments	December 2003
Treatment wetland	Construction of 0.5-ha wetlands to treat runoff from a 27-ha subbasin; codevelopment of an integrated park for education and research	November 2004
Storm water treatment	Construction of 10 baffle boxes to intercept and treat storm water runoff from 217 acres within lake catchment area	Planned for April 2009

part of a broader management strategy for restoring the ecosystem of the Peace River basin and ultimately the health and productivity of the Charlotte Harbor estuary (FDEP 2007).

Tables 2 and 3 summarize water quality indicators for Lake Hollingsworth. Alkalinity, conductivity, and pH were substantially higher for lake water than in water from the surficial aquifer for samples taken from wells near the lake (Sacks et al. 1998). Concentrations of bioavailable forms of nitrogen, e.g., ammonia, nitrite, and nitrate nitrogen were low, but organic nitrogen was high. Concentrations of organic nitrogen were on the average 99% of the total nitrogen. Lake water conditions were consistent with phytoplankton-dominated

photosynthesis that consumes available inorganic nitrogen and carbon, increases pH, and thus stimulates phosphorus release from sediments (Reynolds 1998; Hullebusch et al. 2003; Xie et al. 2003).

Warm, shallow, poorly buffered, and phosphate-rich lake waters, low nitrogen to phosphorus ratios, and the presence of organic-rich sediments had favored growth of cyanobacteria in Lake Hollingsworth. Smith (1983) suggested that cyanobacteria out-compete other algal species when water column TN/TP <29.

In freshwater, the type and distribution of algae, intensity of algal blooms, and production of toxins depend either directly or indirectly on nutrient and light levels, temperature, and possibly metal concentrations

Table 2 Water quality indicators for Lake Hollingsworth, Lakeland, FL: 1984–2009 (USF 2009)

Parameter	Mean	Standard deviation	Unit
Alkalinity	43	12	mg l ⁻¹ as CaCO ₃
Color	38	19	platinum cobalt
Conductivity	170	54	μS cm ⁻¹
Dissolved oxygen	9.1	2.4	mg l ⁻¹
Ammonia-N	22	22	μg l ⁻¹
Nitrate + Nitrite-N	120	510 ^a	μg l ⁻¹
pH	8.7	0.69	-log(molar)
Temperature	26	3.5	°C
TKN-N	2,900	1,500	μg l ⁻¹
Total suspended solids	30	18	mg l ⁻¹
Turbidity	19	11	Nephelometer turbidity

^a Overdispersion indicates a skewed distribution

Table 3 Summary statistics for trophic state parameters

Statistic	SECCHI (m)	CHLA ($\mu\text{g l}^{-1}$)	TP ($\mu\text{g l}^{-1}$)	TN ($\mu\text{g l}^{-1}$)
No. of cases	291	293	292	290
Minimum	0.10	7.84	33.0	735
Maximum	1.42	425	873	8,060
Median	0.39	84.4	185	2,570
Mean	0.42	110	219	2,980
Standard error	0.01	4.73	8.97	87.8
Standard deviation	0.20	80.9	153	1,500

(de Figueiredo et al. 2004; Camargo and Alonso 2006). Species of cyanobacteria, e.g., *Microcystis* and *Anabaena*, are known to release toxins that pose a health threat to both humans and animals (de Figueiredo et al. 2004; Camargo and Alonso 2006), although the risk posed by these toxins is not well characterized. Bigham (2008) reported that a small percentage of water samples drawn from hypereutrophic FL lakes contained the toxin microcystin above a concentration of $20 \mu\text{g l}^{-1}$, which is a World Health Organization guideline concentration based on a moderate adverse health risk during recreational contact.

Brenner et al. (1999) presented evidence from stable isotope ratios, radioactive isotope dating, and diatom composition in lake sediment cores that prior to the twentieth century, Lake Hollingsworth was eutrophic and possibly macrophyte-dominated. Algal pigments in lake sediments cores revealed that blooms of cyanobacteria likely occurred prior to the 1900s; however, peak concentrations appeared between 1960 and 1990 (Riedinger-Whitmore et al. 2005). Further nutrient enrichment of Lake Hollingsworth evolved after 1930 as land use shifted from citrus groves to residential and urban development, an inference based on sustained increases in upper sediment core layers of total chlorophyll concentration, diatom-marked trophic state, and $\delta^{13}\text{C}$ of organic matter (Riedinger-Whitmore et al. 2005).

Building on the work of Brenner et al. (1999), Paul and Gerritsen (2002) developed nutrient criteria for FL lakes based not only on paleolimnological surveys but also on statistical distributions of water column concentrations, trophic lake condition indices, and multiple linear regression analyses of trophic state parameters including total nitrogen, total phosphorus, chlorophyll- α , and Secchi disk transparency. Nutrient criteria were based on one of five lake classifications, and for an alkaline-colored lake such as Lake Hollingsworth (Tables 2 and 3), total nitrogen and total phosphorus criteria, respectively, were 1,100 and $40 \mu\text{g l}^{-1}$, which corresponded to eutrophic conditions as defined by Forsberg and Ryding (1980; Table 4).

2 Methods and Materials

Observations of trophic state parameters including Secchi disk transparency, chlorophyll- α , total nitrogen, and total phosphorus were obtained from the Polk County Water Atlas (USF 2009). For these parameters, the study dataset combined the data records (i.e., sampling dates) from 1984 to 2009 that were reported by three different entities: LAKEWATCH (2001–2008, $N=32$), Polk County (1984–2009, $N=73$), and City of Lakeland (1984–2009, $N=205$). A few records had

Table 4 Proposed trophic state based on transparency (SD), CHLA, TP, and TN, expressed as summer average values (June–September)

Trophic state	SECCHI (m)	CHLA ($\mu\text{g l}^{-1}$)	TP ($\mu\text{g l}^{-1}$)	TN ($\mu\text{g l}^{-1}$)
Eutrophic	1.0–2.5	7–40	25–100	600–1,500
Hypereutrophic	<1.0	>40	>100	>1,500

Adapted from Forsberg and Ryding (1980)

SECCHI Secchi disk transparency, CHLA chlorophyll- α , TP total phosphorus, TN total nitrogen

missing data, and no data qualifiers were present in the dataset.

LAKEWATCH, Polk County, and City of Lakeland sampling and analyses differed on some protocols. LAKEWATCH methods for sampling and analyses are described by Canfield et al. (2002). Sampling frequencies varied within and between agencies, but one or more agencies sampled water from Lake Hollingsworth at least once per quarter from 1988 to present. In general, all three agencies collected water samples by boat during daylight hours at multiple (e.g., three to five) midlake middepth locations. For each sampling date and parameter, the reported value was the average value of measurements from samples taken at the several stations. Secchi disk measurements were made in accordance with a FDEP protocol (FDEP 2004).

For total phosphorus and total Kjeldahl nitrogen (TKN) analyses, Polk County and Lakeland collected water samples in high density polyethylene (HDPE) 500-ml bottles rinsed with lake water. Samples were preserved with sulfuric acid and returned to the laboratory on ice. Analyses of total phosphorus and total Kjeldahl nitrogen were by US Environmental Protection Agency (US EPA) methods 365.4 and 351.2, respectively (US EPA 1974, 1993b). Polk County and Lakeland collected water for ammonia nitrogen, nitrite/nitrate nitrogen, and chlorophyll- α analyses in a 2-l HDPE bottle and a 1-l amber Nalgene bottle, respectively, without preservation. Bottles were rinsed with lake water before sampling. Samples were returned to the laboratory on ice. Measurement of ammonia nitrogen and nitrite/nitrate nitrogen in lake water samples were by US EPA methods 350.1 and 353.2, respectively (US EPA 1993a, c). Total nitrogen was calculated as the sum of total Kjeldahl nitrogen and nitrate/nitrite-nitrogen. All agencies determined chlorophyll- α in lake water samples by standard method 10200 H (APHA 1992). Polk County corrected chlorophyll- α concentrations for pheophytin- α concentrations while LAKEWATCH and Lakeland did not.

Table 3 provides summary statistics for each of the trophic state parameters and histograms of parameter data are shown in Fig. 2. A one-sample Kolmogorov–Smirnov test at the 95% confidence level confirmed that parameter observations were not normally distributed. Log-transformed observations were, however, normally distributed (Fig. 3). Outlier analyses and statistical testing were accomplished with log-transformed distributions.

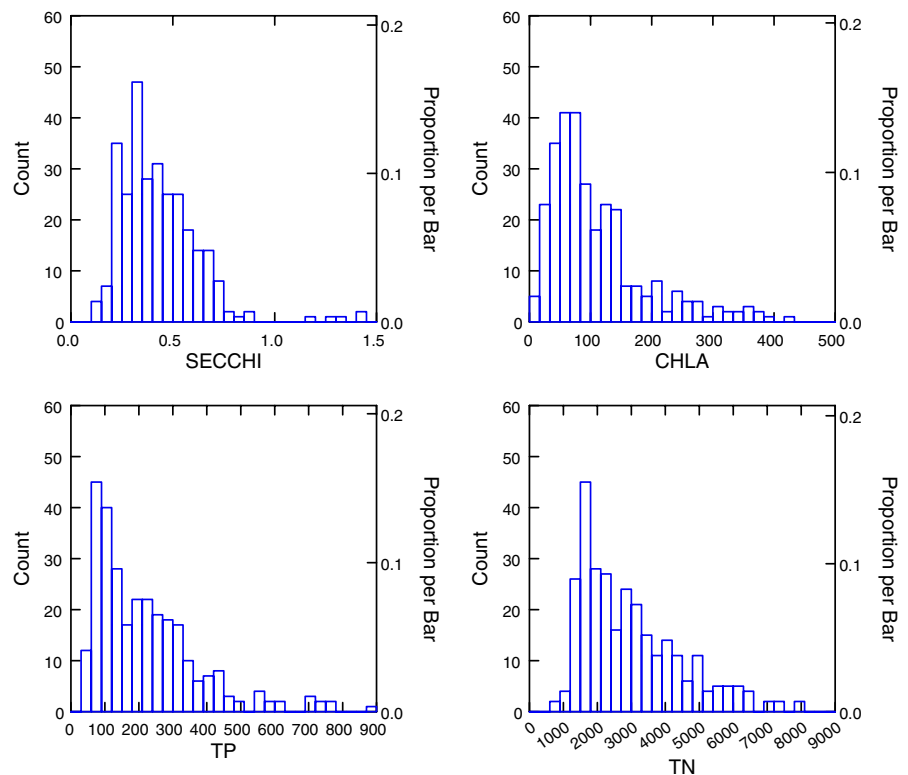
Nonlinear relationships between SD transparency and CHLA, TP, and TN concentrations are shown in Figs. 4, 5, and 6. Pearson product moment correlation coefficients for log-transformed data were $r=-0.87$, -0.54 , and -0.85 between Secchi disk transparency and CHLA, TP, and TN concentrations, respectively. Trophic state parameters agreed reasonably well between sampling entities Lakeland, LAKEWATCH, and Polk County, with two notable exceptions: Lakeland's total phosphorus concentrations between 1997 and 2005 and LAKEWATCH's chlorophyll- α concentrations between 2002 and 2004 diverged from general trends, as can be seen in Fig. 7.

To identify possible outliers, “studentized residuals” were calculated in SYSTAT® for a least squares fit of a linear model to log-transformed data of paired parameters (e.g., SECCHI versus CHLA, SECCHI versus TP, SECCHI versus TN, CHLA versus SECCHI, CHLA versus TP, CHLA versus TN, etc.). Observations with a studentized residual $>|3|$ were removed as outliers and the process was repeated until no observations were flagged as outliers by this method. A total of 12 outliers were removed by this method: two outliers of Secchi disk transparency, three of chlorophyll- α , one of total phosphorus, and six of total nitrogen concentrations.

For hypothesis testing, our study dataset was divided into two periods: 1984–2001 and 2002–2009, as all of the dredging occurred before 2002 and much of the storm water capture and treatment equipment was installed between 2001 and 2002 (Table 1). Our study's null hypothesis was that no change in the mean algal biomass concentration occurred between the two periods. The alternate hypothesis was that mean algal mass biomass changed between the two periods. We used a student's two-sided t test assuming unequal variances on log-transformed observations to test the null hypothesis at the 95% confidence level. Removal of outliers did not change either the direction or significance of the hypothesis testing results.

Carlson (1977) developed a trophic state index (TSI) on the premise that a doubling of algal biomass defined a change in trophic state. His TSI for Secchi disk transparency (TSIS; Eq. 1) was based on the range over which transparency was measured and scaled such that a 10-unit change would reflect a change in trophic state. He then expanded this concept to two other surrogates for algal biomass, chlorophyll- α and total phosphorus concentrations, by replacing log-transformed

Fig. 2 Histograms of Secchi disk transparency (*SECCHI*) in units of meter and chlorophyll- α (*CHLA*), total phosphorus (*TP*), and total nitrogen (*TN*) concentrations in units of microgram per liter for observations from Lake Hollingsworth, Lakeland, FL: 1984 to 2009



Secchi disk transparency in Eq. 1 with an equation derived from a least squares fit of a linear model to log-transformed data, e.g., chlorophyll- α versus Secchi disk transparency and total phosphorus versus Secchi disk transparency, as shown in Table 5. Kratzer and Brezonik (1981) expanded this series to include total nitrogen.

$$\text{TSIS} = 10 \left(6 - \frac{\ln \text{SECCHI}}{\ln 2} \right). \quad (1)$$

Carlson (1977) recognized that none of the algal biomass surrogates were a perfect measure of algal biomass. For example, along with algal biomass concentration, a lake's water color or suspended non-algal particle burden could attenuate light, in which case the Secchi disk transparency (TSIS) would overestimate the trophic state. In this study, Carlson's steps in TSI development are repeated with trophic state parameter data from Lake Hollingsworth (Figs. 4, 5, and 6; Table 5) to improve inferences regarding limiting nutrients.

3 Results and Discussion

Secchi disk transparency increased, and chlorophyll- α , total nitrogen, and total phosphorus average concentrations decreased over the 25-year study period (Table 6; Fig. 7). Moreover, for chlorophyll- α , total nitrogen, and total phosphorus concentrations, the amplitude of annual cycling also declined (Table 6; Fig. 7). For each of these surrogate measures of algal biomass, changes in mean transparency or concentration between the two periods were statistically significant (Fig. 3). Trophic state parameters, however, were still in the range of hypereutrophic as defined by Forsberg and Ryding (1980; Table 5). Nutrient criteria of 1,100 and 40 $\mu\text{g l}^{-1}$ for total nitrogen and total phosphorus appropriate for an alkaline and colored lake (Paul and Gerritsen 2002), respectively, had yet to be sustained in Lake Hollingsworth.

Pre- and post-dredging, annual cycling of algal biomass is evident from time series plots (Fig. 7). For Secchi disk transparency, transparency minima and maxima occurred in March through May and July through October, respectively, and for chlorophyll- α and total nitrogen concentrations, minima and maxima

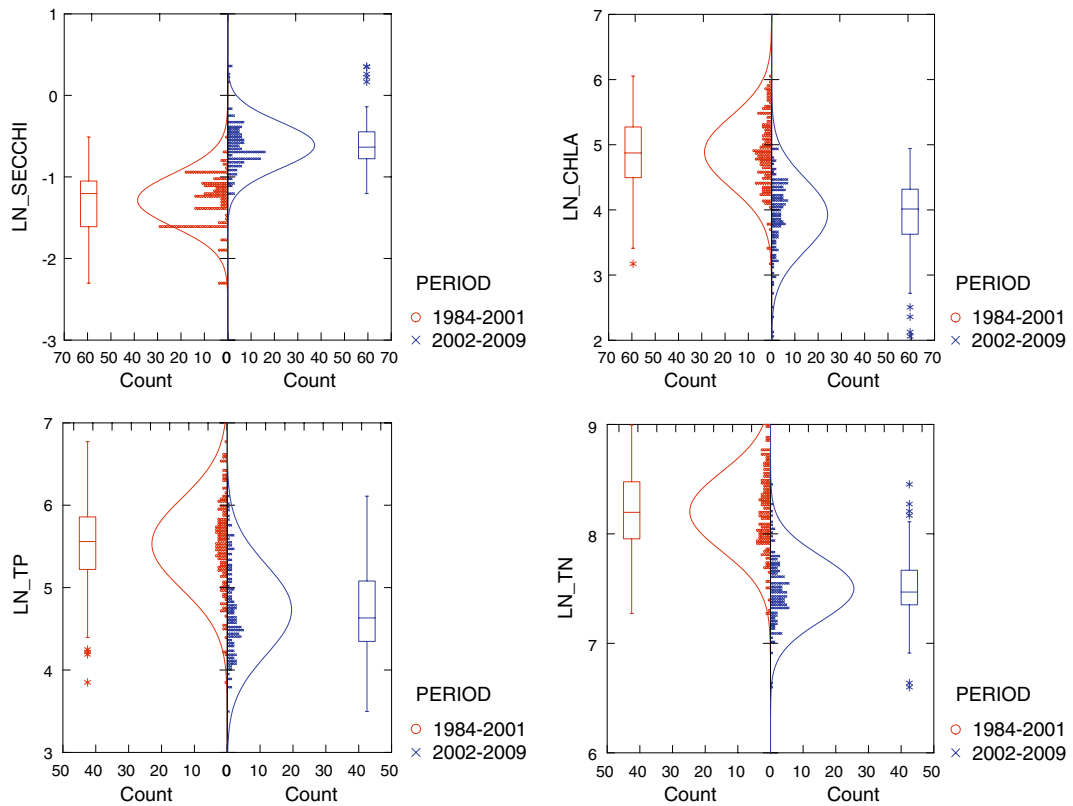


Fig. 3 Box plots and histograms of log-transformed Secchi disk transparency (LN_SECCHI) and chlorophyll- α (LN_CHLA), total phosphorus (LN_TP), and total nitrogen (LN_TN) concentrations for Lake Hollingsworth, Lakeland, FL

Fig. 4 Chlorophyll- α versus Secchi disk transparency for observations from Lake Hollingsworth, Lakeland, FL: 1984 to 2009

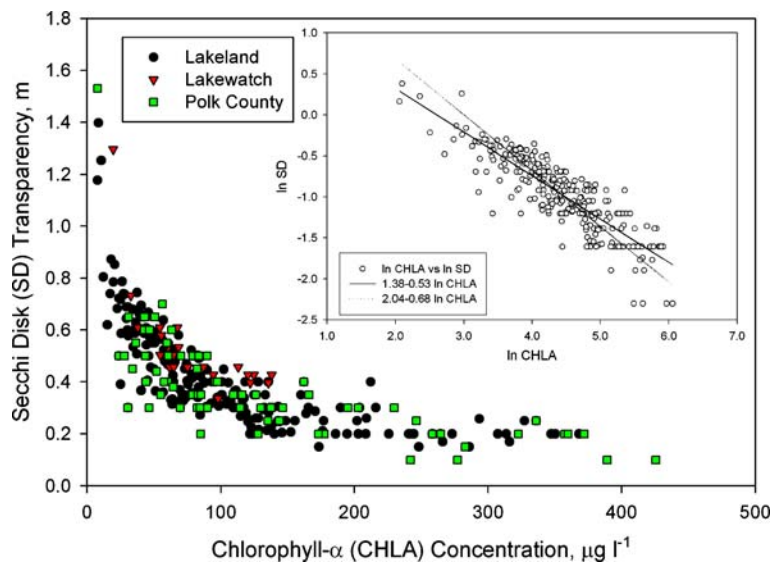
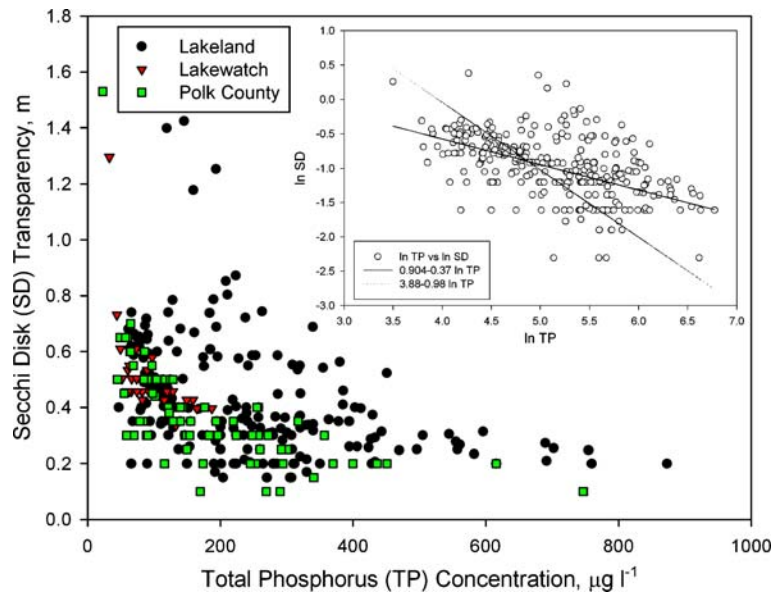


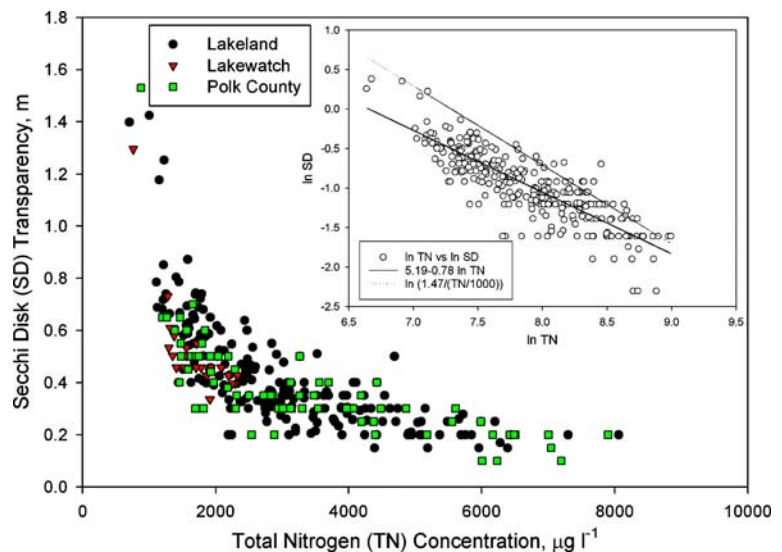
Fig. 5 Total phosphorus versus Secchi disk transparency for observations from Lake Hollingsworth, Lakeland, FL: 1984 to 2009



correspondingly occurred in July through October and March through May, respectively. Such cycling is consistent with higher springtime temperatures and dilution effects or higher flushing rates from rainfall during summer and early fall. Annual cycling of total phosphorus concentrations was not as strongly evident, possibly obscured by wind-induced resuspension of lake sediment (Bachmann et al. 2000). Brown et al. (1998) did not find a compelling seasonal cycle for trophic state indicators across FL's hypereutrophic lakes.

From 2000 to 2001, an extended drought caused water levels in Lake Hollingsworth to fall by 2 m and dredging that had begun in 1997 was stopped. Storm water controls were put into place in 2001 (Table 1) and by the end of 2002 when lake levels returned to normal, trophic state parameters responded to a recontoured lake and reduced nutrient loading (Fig. 7). The effect of a one-time alum addition in December 2003 was evident in the correspondingly high Secchi disk transparency and low chlorophyll- α concentration and, to a lesser

Fig. 6 Total nitrogen versus Secchi disk transparency for observations from Lake Hollingsworth, Lakeland, FL: 1984 to 2009



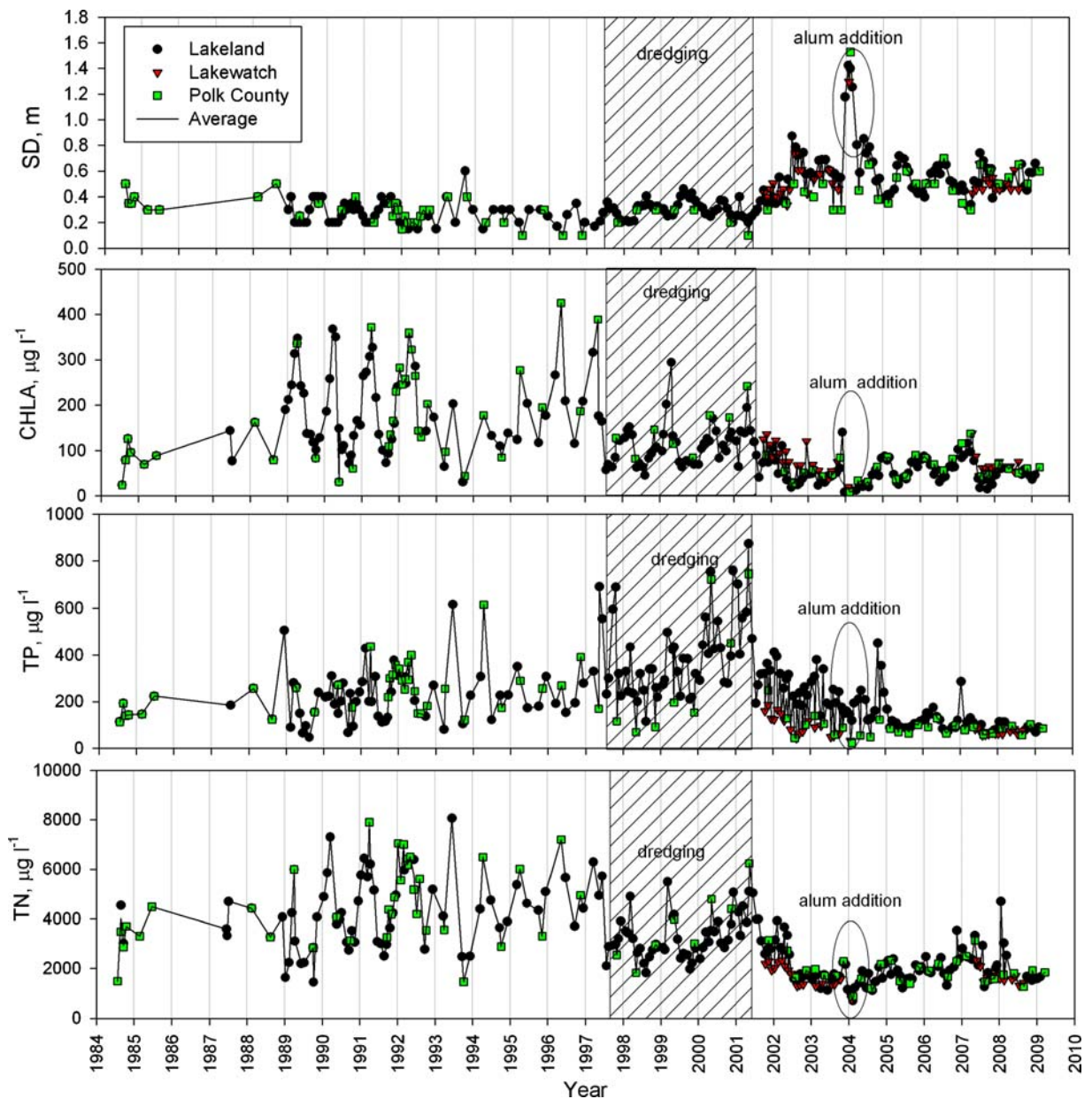


Fig. 7 Temporal trends in Secchi disk (*SD*) transparency and concentrations of chlorophyll- α (*CHLA*), total nitrogen (*TN*), and total phosphorus (*TP*) in Lake Hollingsworth, Lakeland, Florida

extent, low total nitrogen and total phosphorus concentrations observed in January 2004 (Fig. 7). This suggested that alum was effective over the short term in removing suspended algal biomass but in the highly productive environment not at permanently binding phosphorus in the sediments (Hullebusch et al. 2003).

Figure 8 shows the change in TSIs pre- and post-dredging. According to Carlson, a lake with a TSI of 50 is mesotrophic and 60 eutrophic; presumably, a

lake with a TSI of 70 is hypereutrophic. Note that when Carlson's (1977) TSI for chlorophyll- α (TSIC) and TSI for phosphorus (TSIP) and Kratzer and Brezonik's (1981) TSI for nitrogen (TSIN) were used, the results show a 10-unit change or by Carlson's definition a change in trophic state. Such a large change was not seen when TSIs produced from regressions of Lake Hollingsworth data were used (Figs. 4, 5, and 6). The latter results were more

Table 5 Summary of equations used to calculate trophic state indices

Trophic state index	Literature	This study
Chlorophyll-a	$2.04-0.68 \ln \text{CHLA}^a$	$1.38-0.53 \ln \text{CHLA}$
Total phosphorus	$3.88-0.98 \ln \text{TP}^a$	$0.904-0.37 \ln \text{TP}$
Total nitrogen	$\ln (1.47/(\text{TN}/1,000))^b$	$5.19-0.98 \ln \text{TN}$

Units on SECCHI, CHLA, TP, and TN are meter, microgram per liter, microgram per liter, and microgram per liter, respectively

^a Carlson (1977)

^b Kratzer and Brezonik (1981)

Table 6 Summary statistics for trophic state parameters pre- and post-dredging of Lake Hollingsworth

Statistic	SECCHI (m)		CHLA ($\mu\text{g l}^{-1}$)		TP ($\mu\text{g l}^{-1}$)		TN ($\mu\text{g l}^{-1}$)	
	1984–2001	2002–2009	1984–2001	2002–2009	1984–2001	2002–2009	1984–2001	2002–2009
No. of cases	158	133	160	133	158	134	157	133
Mean	0.291	0.567	153	57.8	292	133	3,900	1,890
Standard deviation	0.088	0.191	85.0	27.5	161	84.6	1,400	609

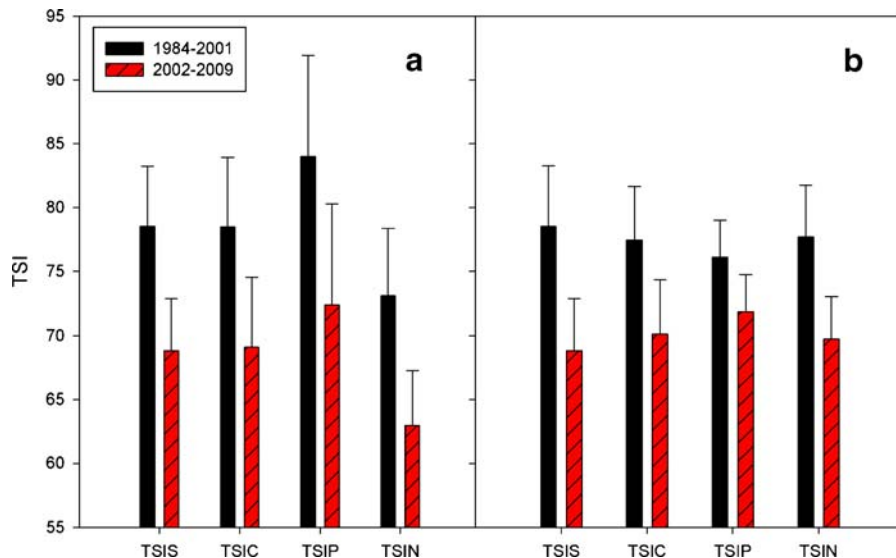
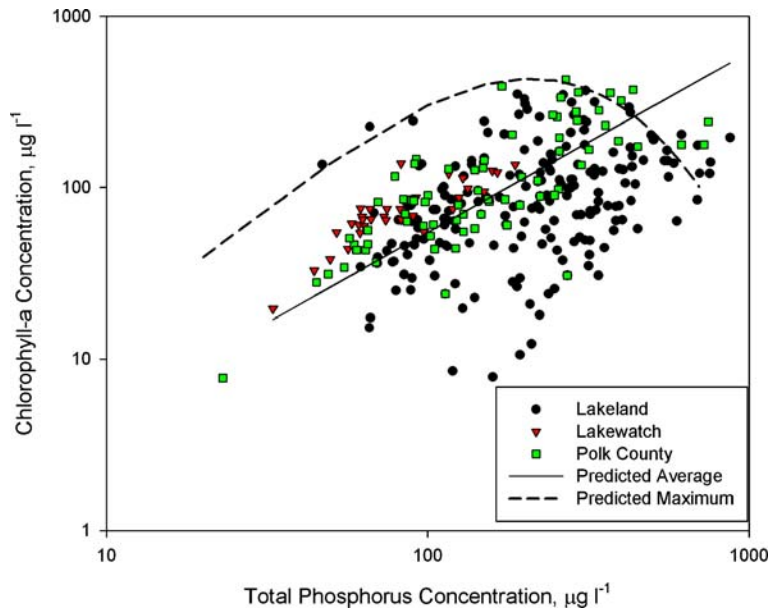


Fig. 8 Change in trophic state index (*TSI*) pre- and postdredging of Lake Hollingsworth, Lakeland, FL. In both graphics **a** and **b**, *TSIS* is calculated according to Carlson (1977). In graphic **a**, *TSIC* and *TSIP* are calculated according to Carlson

(1977) and *TSIN* according to Kratzer and Brezonik (1981); in graphic **b**, *TSIC*, *TSIP*, and *TSIN* were determined by a least squares fit of a linear model to log-transformed paired data from Lake Hollingsworth

Fig. 9 Chlorophyll- α versus total phosphorus concentration in Lake Hollingsworth. Predicted average and maximum chlorophyll- α concentrations were based on an analysis of FL lakes by Brown et al. (2000)



consistent with transparency and concentration data (Table 6).

Both nitrogen and phosphorus appeared to limit primary production in Lake Hollingsworth, a preliminary conclusion that is consistent with previous assessments for shallow hypereutrophic FL lakes (Canfield 1983; Havens 1995). Water column chlorophyll- α in Lake Hollingsworth was compared with average and maximum concentrations seen for FL lakes (Fig. 9).

According to Brown et al. (2000), average and maximum chlorophyll concentrations can be predicted from total phosphorus concentrations by Eqs. 2 and 3. Chlorophyll (e.g., biomass) production is not limited by phosphorus alone if observations plot below the predicted maximum chlorophyll line, as shown in Fig. 9, although factors other than nitrogen or phosphorus—temperature, light intensity, carbon (e.g., dissolved carbon dioxide), flushing or mixing rate, and

Fig. 10 Temporal trends in differences between trophic state indices TSIN–TSIP and TSIC–TSIS for Lake Hollingsworth. Trend lines were loess-smoothed with 5% proportional sampling

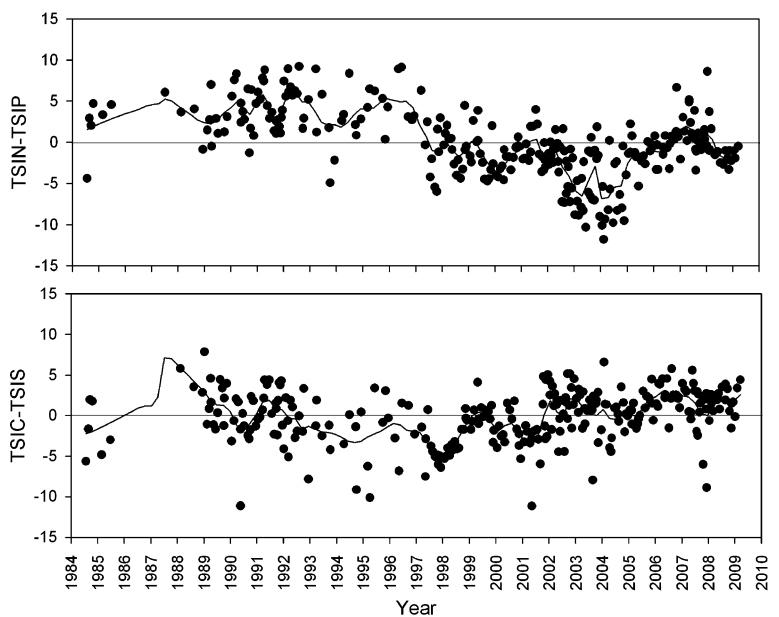


Table 7 Average concentration \pm standard deviation of chlorophyll- α for combinations TN and TP concentrations above and below their median concentrations

Nutrient level	TP <185 $\mu\text{g l}^{-1}$	TP >185 $\mu\text{g l}^{-1}$
TN >2,570 $\mu\text{g l}^{-1}$	66.7 \pm 69.3 (N=32)	166 \pm 86.8 (N=108)
TN <2,570 $\mu\text{g l}^{-1}$	71.7 \pm 51.8 (N=117)	109 \pm 46.8 (N=21)

TN total nitrogen, TP total phosphorus

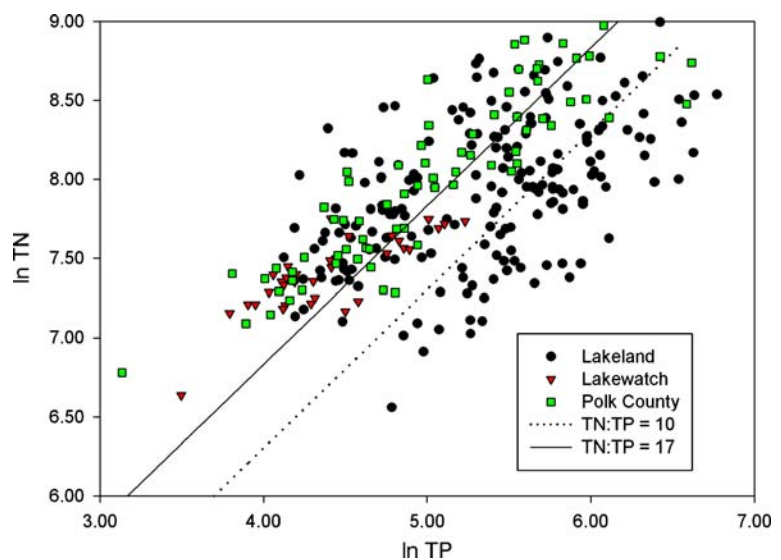
predation by zooplankton, as examples—can limit algal growth (Reynolds 1998).

$$\log \text{CHLA} = -0.369 + 1.053 \log(\text{TP}) \quad (2)$$

$$\begin{aligned} \log(\max)\text{CHLA} = & 0.528 + 0.18 \log(\text{TP}) \\ & + 0.33 \log(\text{TP})^2 + 0.29 \\ & \times \log(\text{TP})^3 - 0.128 \\ & \times \log(\text{TP})^4. \end{aligned} \quad (3)$$

Temporal plots of TSIN–TSIP and TSIC–TSIP (Fig. 10) revealed time-dependent changes in limiting nutrients, as was discussed by Havens (1995) for a subtropical nitrogen-limited lake and validated for that lake with nutrient bioassay experiments. The temporal trend of TSIN–TSIP suggested that phosphorus limitation occurred through 1997 with a shift

Fig. 11 Log-transformed total phosphorus (TP) versus log-transformed total nitrogen (TN) concentrations



toward nitrogen limitation after 1997, the trend of TSIC–TSIS that a light limitation abated after 1997. This apparent shift in limiting factors is a likely consequence of the removal by dredging of ~ 1 m of organic layer of sediment from the lake's bottom. The deepened lake is now less susceptible to wind-induced sediment resuspension (Bachmann et al. 2000).

Table 7 shows average concentrations of chlorophyll- α for combinations total nitrogen and total phosphorus concentrations above and below their median concentrations. The highest average chlorophyll- α concentration occurred when both total nitrogen and total phosphorus concentrations were high.

A plot of log-transformed total nitrogen versus log-transformed total phosphorus is presented in Fig. 11, along with TN/TP ratios identified by Forsberg and Ryding (1980) and Sakamoto (1966, cited therein) as thresholds for nitrogen (TN/TP <10) and phosphorus limiting (TN/TP >17) algal growth. TN/TP ratios observed in Lake Hollingsworth ranged from 4.32 to 50.7, with an average of 17.1, and spanned both phosphorus- and nitrogen-limiting conditions. Use of such ratios, however, oversimplifies the nutrient–chlorophyll relationship in a lake system (Smith 1983; Reynolds 1998; Lewis and Wurtzbaugh 2008). Phytoplankton thrive at optimal nitrogen to phosphorus ratios as low as 4.1 for *Microcystis* species and as high as 38 for *Scenedesmus* species (Smith 1982), and the distribution of phytoplankton species within a lake may depend not only on the immediate shortage of

one or more growth factors but on historical dominance (Reynolds 1998). Moreover, measures of total nitrogen and total phosphorus include both bioavailable and refractory compounds and offer no information regarding the time-dependent cycling between soluble and insoluble, organic and inorganic, fractions (Lewis and Wurtzbaugh 2008).

Can Lake Hollingsworth switch from a turbid state to a clear state? It is difficult to predict if and under what conditions such a switch could occur (Beisner et al. 2003). Observations and modeling reinforce the theory that shallow lakes may have two stable states: a turbid phytoplankton-dominated state and a clear macroplankton-dominated state (Moss 1990; Blindow et al. 1993; Scheffer et al. 1993). Data from subtropical FL lakes analyzed by Bachmann et al. (2002) generally support the theory that shallow lakes have both a turbid and a stable state, but stop short of defining a critical turbidity threshold. Altering the number and type of biota in a lake—biomanipulation—has been proffered as a way to catalyze the change from one stable state to another (Moss 1990; Hilt et al. 2006; Jeppesen et al. 2007). Reducing nutrient loads to a lake can reduce turbidity, but reestablishing submerged aquatic vegetation may be necessary for a shallow lake to reach and maintain its clear state (Moss 1990; Scheffer et al. 1993; Bachmann et al. 2002). Blindow et al. (1993) postulated that lakes may have a third, labile or transition, state that is dominated by angiosperms (such as hydrilla). Submerged aquatic macrophytes appear to play a key role in maintaining water clarity, as examples, they serve as a nutrient reservoir, reduce sediment resuspension, and provide protection for algae-eating zooplankton against predators (Blindow et al. 1993; Jeppesen et al. 2007; Takamura et al. 2003).

4 Conclusions

Strategies employed to improve the water clarity of Lake Hollingsworth included substantial reductions in external nutrient loading by capturing influent detritus, suppressing internal cycling of nutrients by removing organic sediments, replanting submerged and emergent aquatic vegetation, and settling suspended particles including algal cells through alum addition (Table 1). These strategies straddled dramatically lower lake water levels during a 2-year drought.

The trophic state of Lake Hollingsworth in Lakeland, FL, has significantly improved in response to reductions in both external and internal loading of phosphorus and nitrogen. Lake water quality data indicated that algal growth is limited by both phosphorus and nitrogen but further reductions in external nutrient loading may be important for the lake to return to its natural state.

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