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Environmental Sciences Division
St. Johns River Water Management District
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Water Quality Changes in Lake Apopka, Florida
St. Johns River Water Management District's Restoration Program

Summary

The primary step in the comprehensive restoration program for Lake Apopka is a large reduction in external phosphorus (P) loading. This is being achieved through step-wise restoration of former farms on the North Shore Restoration Area (NSRA) to wetlands as residual pesticides are remediated to ecologically safe levels. We expect to meet the total maximum daily load (TMDL) target loading (15.9 metric tons P per year) and TMDL target concentration of total phosphorus (TP) in lake water (0.055 mg P/L) after the NSRA has been restored to wetlands and rainwater can be impounded in those wetlands rather than discharged to the lake.

Because of increased areas of wetland restoration but also drought conditions, annual external P loading averaged 18 metric tons over the past five years, compared with 69 metric tons during the pre-restoration period. Despite temporary perturbations during droughts, water quality improved in Lake Apopka in response to reduction in external P loading. Lake water TP concentrations over the past five years averaged 41% lower than restoration baseline (1987 – 1992), algal chlorophyll-*a* declined 29%, and Secchi transparency improved 34%. Reduced P loading during drought years did not result in lower TP concentrations, in part because of reduced lake volume.

Concentrations of TP, total nitrogen (TN), and chlorophyll-a, and Secchi transparency showed improving trends over the entire 23-year District data set. These overall trends were statistically significant for all water quality variables evaluated except total suspended solids (TSS). Improving trends in water quality were interrupted by worsening conditions during two periods of extreme drought (lowest sustained lake levels in the period of record). In each case, water quality improved again when lake level recovered. The long-term improvements persisted despite short-term wind effects caused by multiple hurricanes in 2004 and 2005, which is evidence for a controlling role of external loading rather than wind resuspension for long-term lake water TP concentration.

Examination of the water-column mass of nutrients in L. Apopka in addition to concentrations revealed important dynamics of the changes during drought conditions. Mass of TP initially declined in parallel with lake water concentration in response to decreased loading. During droughts, TP mass increased only slightly, whereas TP concentration increased greatly. The increase in TP concentration was due in large part to the concentrating effects of declining lake volume at a constant TP mass. This conservation of TP mass likely explained both the rapid increase in TP concentration at low lake stage but also the rapid recovery (decline in TP concentration) as the lake refilled. The same pattern was evident for water-column masses of TN and TSS. Declining trends for masses of TP, TN, and TSS were statistically significant.

We predicted a cascade of ecological changes in Lake Apopka, where reduced P loading leads to reduced TP concentrations in lake water and lower algal levels. Lower algal biomass leads to improved water

transparency that allows submersed plants to colonize the bottom. Re-growth of submersed plants provides improved habitat, and sport fish populations increase to levels needed for successful recreational fishing. Although reduction in P loading to L. Apopka still is a work in progress, the steps in this cascade of restoration effects down to initial colonization by submersed plants currently are operating. We found a strong linear relationship between TP concentration and chlorophyll-*a* concentration. This relationship supports our conclusion that continued reduction in TP concentrations will translate to continued reduction in phytoplankton biomass. There was a good linear relationship between the concentration of TSS and the concentration of chlorophyll-*a* over a three-fold range in chlorophyll. This relationship suggests that the majority of TSS in L. Apopka was algae or algal detritus. As nutrient control limits algal biomass, TSS should decline as well, and light conditions for submersed vegetation should improve. District staff counted almost 400 small beds of desirable native submerged vegetation in 2009. We expect these initial volunteer patches to expand and provide improved habitat for fish and wildlife.

Introduction

Lake restoration work worldwide provides evidence that eutrophication of lakes can be reversed by reduction in external nutrient loading (Jeppesen et al. 2005). Large shallow lakes are especially important case studies, because the close contact between water and sediments promotes the recycling of sediment nutrients that might delay recovery. The St. Johns River Water Management District (District) has developed and is implementing a restoration program for Lake Apopka, a shallow, 125 km^2, eutrophic lake located near Orlando, Florida (Hoge et al. 2003).

Prior to the 1940s, Lake Apopka had abundant submersed, rooted vegetation and was nationally famous for its clear water and abundant game fish (Clugston 1963; Lowe et al. 1999). Large-scale draining for agriculture of about 80 km^2 floodplain marshes at the north end of L. Apopka began in the 1940s. Drainage increased nutrient loading, water color, and lake stage, and precipitated a shift from submersed macrophyte to phytoplankton primary production (Schelske et al. 2010). Submersed macrophytes declined rapidly and disappeared in the 1950s. Drainage water discharges from farm lands increased phosphorus (P) loading sevenfold from 0.08 to about 0.56 g P m^{-2} yr^{-1} and were the primary cause of eutrophication (Battoe et al. 1999, Lowe et al. 1999). Because of oxidation of the drained muck soils, surface levels in the former farm areas subsided up to 1.8 m (6 ft) below lake level.

Legislation passed in 1985 and 1987 directed the District to restore Lake Apopka to Class III water quality. Planning, diagnostic, and feasibility studies for the lake began under the 1985 Lake Apopka Restoration Act, and the 1987 Surface Water Improvement and Management (SWIM) Act included the lake as a priority water body for restoration. The 1996 Lake Apopka Improvement and Management Act authorized the District to set a phosphorus concentration target for the lake and provided funding to initiate a mandated buyout of the remaining floodplain “muck” farms on the north shore of the lake. The District adopted the phosphorus target by rule in 1996 and completed buyout of most of the muck farms by 1999 using both state and federal funds.

The District established a restoration P loading target for L. Apopka of 15.9 metric tons P per year (0.13 g P m^{-2} yr^{-1}), which represents a 77% reduction from pre-restoration conditions (Coveney et al. 2005). This loading target was derived through input-output modeling to meet a restoration goal for total phosphorus (TP) concentration in lake water of 0.055 mg/L (Coveney 2000). We set the concentration goal through a weight-of-evidence approach that estimated TP levels prior to large-scale farming (Lowe et al. 1999). FDEP and USEPA adopted the District’s loading limit as a Total Maximum Daily Load (TMDL) for P (Magley 2003). FDEP formed a Basin Working Group and adopted a Basin Management Action Plan for the Upper Ocklawaha River Basin, including Lake Apopka (FDEP 2007). Through the Basin Working Group, local stakeholders are involved with the District and FDEP in the efforts to improve Lake Apopka.

The primary step in the comprehensive restoration program for Lake Apopka is a large reduction in external P loading which is being achieved through gradual restoration of the former farms to wetlands. The District's program also includes operation of a treatment wetland (Marsh Flow-Way) on a part of the former farmlands to remove suspended particles and nutrients from lake water, the large-scale removal of gizzard shad (*Dorosoma cepedianum*) from L. Apopka to remove P and to reduce P recycling, and some planting in the littoral zone.

Because we cannot control many sources of P (e.g. atmospheric deposition and spring input), loading from the former farms must be decreased by almost 90%. However, high mortality of fish-eating birds occurred during initial reflooding in winter 1998 – 1999. These deaths were attributed to organochlorine pesticide (OCP) residues bound to the organic, peat soils. The District along with federal and state partners began a decade-long project to study the distribution and bioaccumulation of weathered OCP residues in muck soils and to remediate contaminants to ecologically safe levels.

Reduction in P loading to L. Apopka still is a work in progress. Controlled, step-wise reflooding is underway, and OCP levels in fish are monitored at each step to ensure safe conditions. Currently, about 65% of the former farm area is under restoration, and drainage water from remaining portions still must be discharged to L. Apopka. Although schedules are dependent on monitoring results and on regulatory agencies, the District may complete flooding for wetland restoration as early as 2012.

Two periods of extreme drought in recent years resulted in temporary increases in lake water TP concentrations. Despite these temporary perturbations, TP concentrations over the past five years averaged 41% lower than restoration baseline (1987 – 1992), algal chlorophyll-*a* declined 29%, and Secchi transparency improved 34%.

This report provides a brief summary of changes in important water quality variables in L. Apopka during the past 23 years.

Water Quality Changes

Phosphorus Loading

Beginning with the initial purchases of farmlands by the District and continuing with regulatory efforts and complete acquisition of the farms in 1999, the restoration program has reduced P loading to L. Apopka (Fig. 1). Watershed modifications (e.g. farm retention ponds) to reduce loading began in 1993 and are ongoing today as further parcels on the former farms are flooded and drainage water discharges are reduced.

P loading from the watershed depends greatly on rainfall, and the decline in loading has not been monotonic. To date, P loading has met the TMDL target (15.9 metric tons (10^6 g) P per yr) only during drought years (2000 – 2001 and 2006 – 2007) and in 2009 (Fig. 1). The increase in P loading to L. Apopka in 2008 resulted in part from the need to keep large portions of the former farms dry to operate heavy equipment to remediate soil pesticide residues. Remediation is complete, and reflooding can continue. We expect to meet the TMDL target loading after the entire area of former farms has been restored to wetlands and rainwater can be impounded in those wetlands rather than discharged to the lake. In the long run (i.e. steady state), models predict that L. Apopka will meet the target TP concentration (0.055 mg/L) when loading meets the TMDL target. In the short run, many other variables affect the relationship between P loading and TP concentration. For example, low loading during drought years may not result in low TP concentrations because of reduced lake volume.

Although nitrogen (N) loading to L. Apopka has not been calculated, reductions in water discharges from the farms to target P loading likely reduced N loading as well.

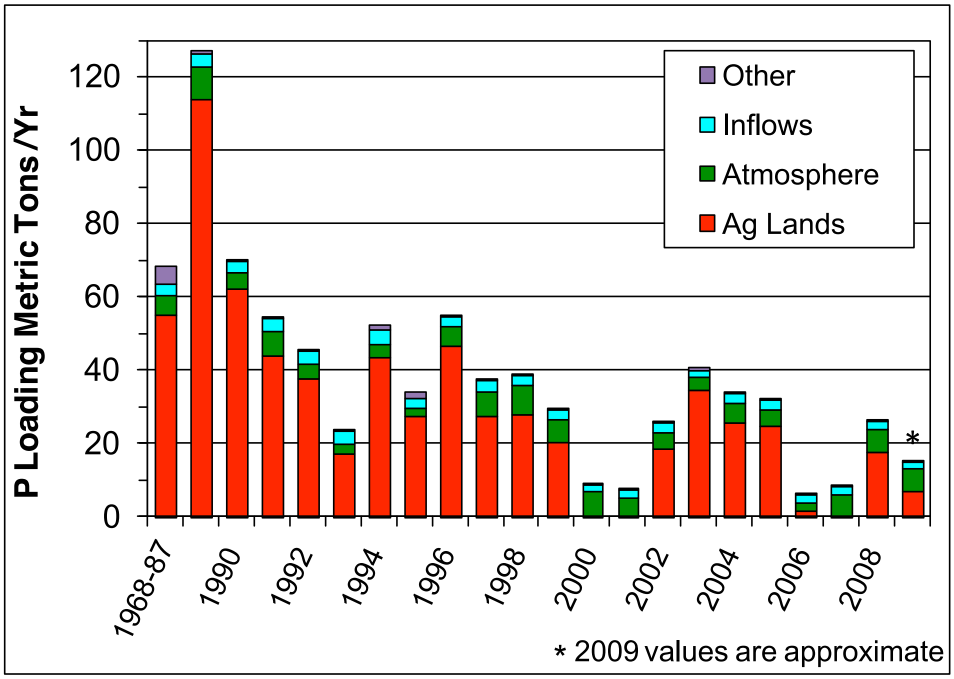


Figure 1. Phosphorus loading from all sources to L. Apopka for period of District monitoring. “Agricultural Lands” category describes the North Shore Restoration Area. Land use in that area shifted gradually from agriculture prior to 1989 to fallow fields and restored wetlands in 2009. The TMDL target for P loading is 15.9 metric tons (10^6 g) P per yr. Mean loading for 1968-87 was derived from analyses of sediment stratigraphy (Coveney 2000). Loading values from 1989 on were measured directly. Values for 2009 are the best current estimates.

Nutrient Concentrations and Other Water Quality Indicators

Reduction in external P loading to Lake Apopka resulted in improved water quality. Concentrations of total phosphorus, chlorophyll-*a*, and total nitrogen (TN) as well as Secchi transparency showed improving trends (Fig. 2 & 3). Concentration of total suspended solids (TSS) did not show an overall improving trend because of high levels during the recent drought. Worsening effects of extreme low lake stage on all water quality variables were evident (Fig. 2 & 3), and these are discussed below. Although time-courses for water-quality variables were not necessarily linear because of effects of drought and other features, we used simple linear models to test the significance of overall trends in water quality for the period (1987-2009) of District monitoring. Improving trends were significant for all water quality variables except TSS (Table 1). Neither internal recycling of sediment P nor wind-driven resuspension of sediments prevented improvements in these water quality measures, including chlorophyll-*a* and Secchi transparency, even in this shallow, eutrophic lake (Coveney et al. 2005).

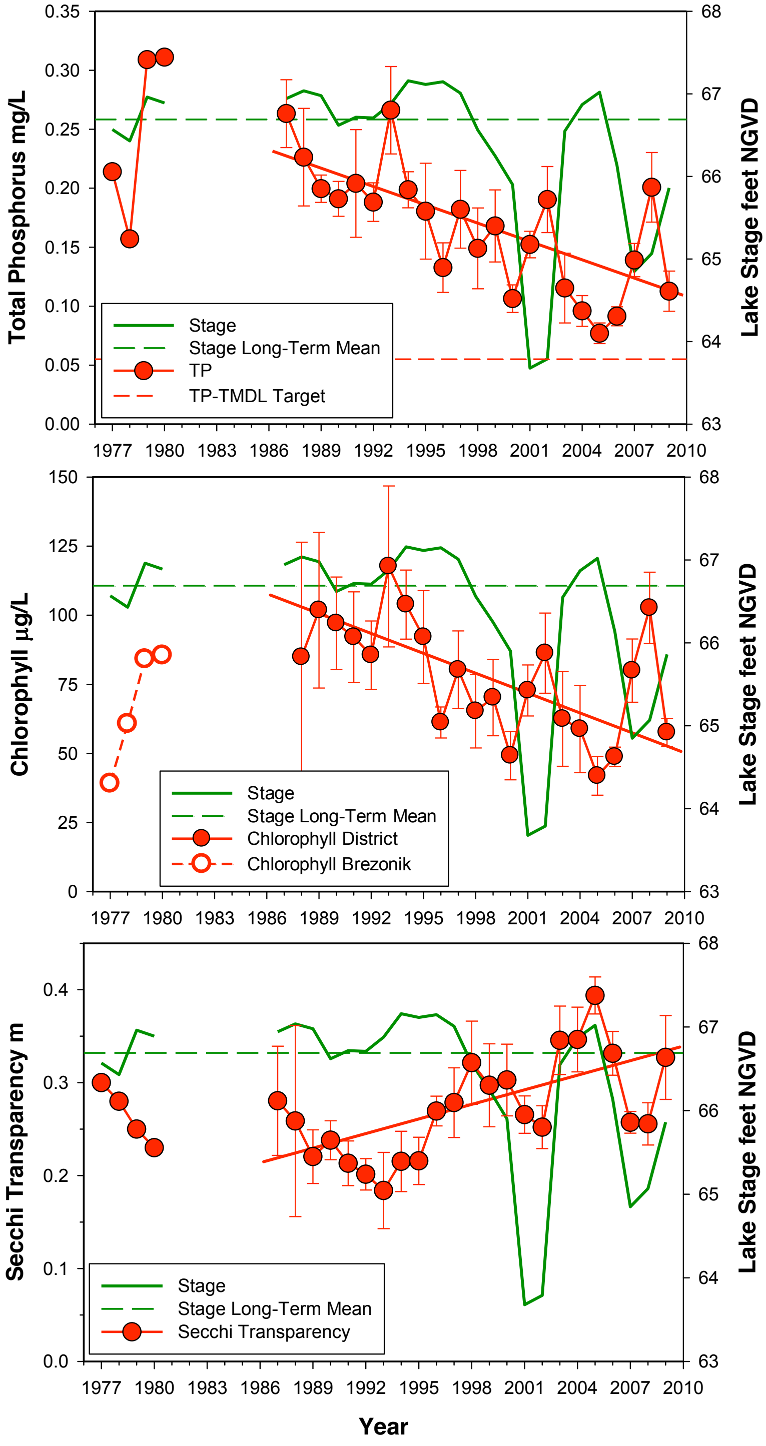


Figure 2. Mean annual values for total phosphorus (TP) concentration (top), chlorophyll-*a* concentration (middle) and Secchi transparency (bottom) in L. Apopka for the entire 23-yr period (1987-2009) of District monitoring. Data for 1977-1980 from Brezonik et al. (1981), mean annual lake stage, long-term mean stage, and the TMDL target concentration for P are included. Error bars are 96% confidence limits around means (±2SE). Linear trends are shown for District data. Brezonik et al. and the District used different methods for analysis of chlorophyll-*a*.

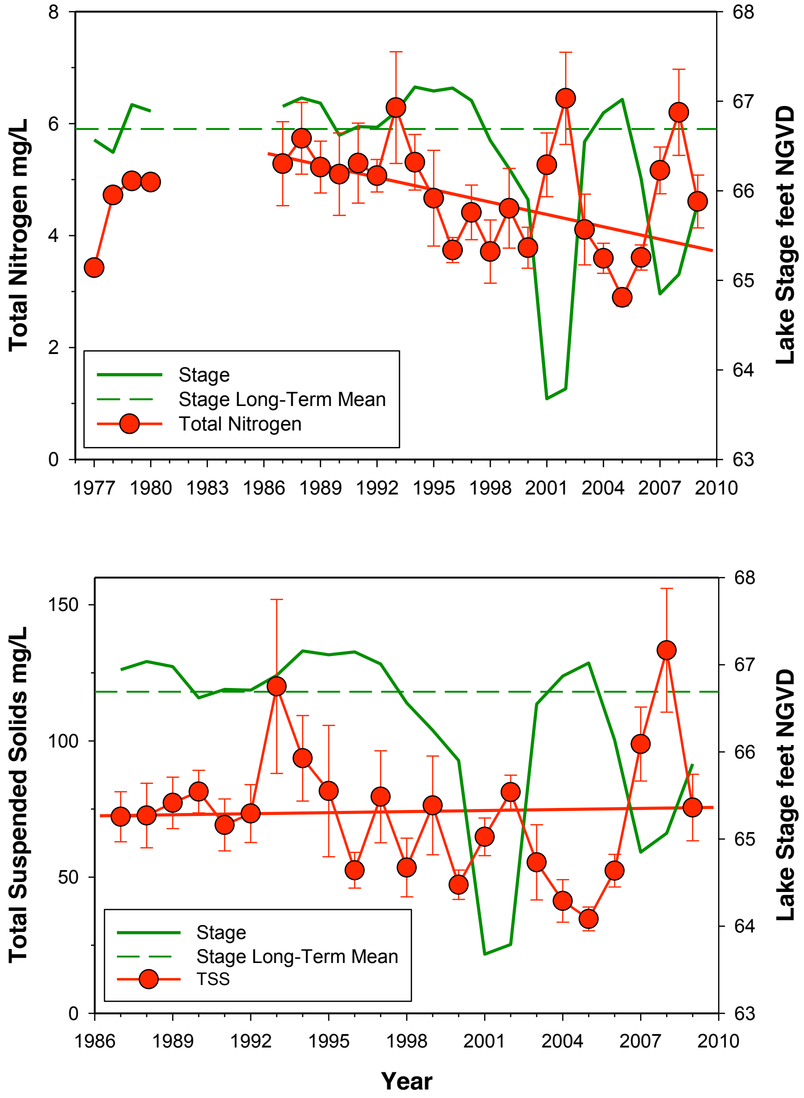


Figure 3. Mean annual values for total nitrogen (TN) concentration (top) and total suspended solids (TSS) concentration (bottom) in L. Apopka for the entire 23-yr period (1987-2009) of District monitoring. TN for 1977-1980 from Brezonik et al. (1981), mean annual lake stage and the long-term mean stage are included. Error bars are 96% confidence limits around the means (±2SE). Linear trends are shown for District data. Brezonik et al. (1981) did not report TSS.

Water Quality Variable	Probability (p) of No Trend
Total Phosphorus	<0.001
Chlorophyll-*a*	0.004
Secchi Transparency	0.015
Total Suspended Solids	0.885 NS
Total Nitrogen	0.037

Table 1. Linear trend models for water quality variables for Lake Apopka 1987-2009. The probability of the null hypothesis (no trend, slope = 0) is shown. All trends were significant ($p < 0.05$) except TSS. Linear trends were evaluated using a robust non-parametric least absolute distance regression technique. NS: not significant.

TP concentration in L Apopka declined more-or-less steadily from the start of District monitoring with three important exceptions (Fig 2). The first perturbation coincided with an unusually violent spring storm in March 1993. Concentrations of TP, TSS, and TN increased suddenly, likely through storm-driven sediment resuspension. However, the downward trend resumed the following year. The second perturbation occurred in 2001 and 2002 at the end of a severe drought, when TP concentrations increased markedly. Once again, the improving trend continued the following year. Annual TP concentrations in 2004 – 2006 were under 0.1 mg P/L and approached the TMDL target of 0.055 mg/L (Fig. 2). These long-term improvements persisted despite short-term wind effects caused by multiple hurricanes in 2004 and 2005, which is evidence for a controlling role of external loading rather than wind resuspension on long-term lake water TP concentration. The most-recent perturbation occurred during a second severe drought in 2007 and 2008. TP concentration again increased sharply at low lake stages, but TP declined again in 2009 as lake stage began to increase (Fig. 2).

Other water quality variables (concentrations of chlorophyll-*a* and total nitrogen and Secchi transparency) followed the same general pattern as TP, with long-term improvements punctuated by temporary perturbations (Fig. 2 & 3). One exception was TSS concentration (Fig. 3), where the increase during the second drought (2007-2008) was sufficiently high to mask the earlier declines. TSS concentration subsequently declined but did not recover sufficiently by 2009 to result in a long-term improving trend. It is notable that Secchi transparency improved long-term (Fig. 2) even while TSS did not (Fig.3).

Although TP concentration in lake water declined in response to reduced loading, annual TP concentration was not closely related to annual P loading (Coveney et al. 2005). Because of the relatively long residence times for water and for P in L. Apopka, loading and TP concentrations must be averaged over multiple years to establish a relationship. Furthermore, hydrologic characteristics (e.g. lake volume and hydraulic residence time) changed through time and especially during drought years. These changes must be considered to compare properly the effects of various nutrient loading rates.

Comparison with water quality data from 1977-1980

Brezonik et al. (1981) measured various water quality constituents in L. Apopka during 1977-1980 (Fig. 2 & 3). We compared these data with District monitoring data prior to the start of watershed restoration activities (restoration baseline data, 1987-1992) to determine whether water quality changed in the intervening years (Table 2). Median TP and Secchi transparency values were not significantly different between the two data sets. Median TN differed significantly, but only slightly (9%) (Table 2).

Water Quality Variable	Median 1977-1980 Brezonik	Median 1987-1992 District	Comparison Brezonik vs District (p value)
Total Phosphorus mg/L	0.262	0.202	0.456 NS
Chlorophyll-*a* ug/L	72.4	94.6	0.030
Secchi Transparency m	0.265	0.229	0.241 NS
Total Nitrogen mg/L	4.83	5.25	0.014

Table 2. Comparison between median values for 1977-1980 (Brezonik et al. 1981) and median values for the District restoration baseline period 1987-1992 (1989-1992 for chlorophyll-*a*). Mann-Whitney two-sample rank test with significance at $p < 0.05$. NS: not significant.

In contrast to the other analytes, median chlorophyll-*a* in 1989-1992 was 31% higher than the median for 1977-1980 (Fig. 2, Table 2). However, analytical methodologies used for chlorophyll-*a* differed in the two data sets. Brezonik et al. (1981) collected lake seston on Whatman GF/A filters, extracted pigments in 100% acetone, and measured chlorophyll-*a* “corrected” for pheopigments. The District used finer Whatman GF/C filters, extracted with the more-effective 90% acetone-water solvent mixture, and reported “total” chlorophyll-*a*. Each of these methodological differences, and especially the extraction solvent, would contribute to higher values in the District’s data set. Taken together, these methodological differences, rather than a real difference in median chlorophyll-*a*, likely explained the higher values reported for 1989-1992.

The relationship between chlorophyll-*a* and TP (Fig. 6) provided further evidence that differences in methodology were responsible for lower chlorophyll values from Brezonik et al. (1981). Chlorophyll-*a* was closely related to TP for all 21 years in the District’s data set. In contrast, three of the four years in the data set from Brezonik et al. were outliers (Fig. 6). Because of the long-term stability in the chlorophyll to TP relationship from 1989 – 2009, a large change in the 1977 – 1980 data set was unlikely. Instead, the large discrepancy in the chlorophyll to TP relationship indicated methodological differences. Comparable methodology for TP was used for both data sets. Therefore, we conclude that higher values for chlorophyll-*a* in 1989 – 1992 resulted from known differences in methodology and that water quality conditions in 1977-1980 were similar to conditions in 1987-1992 prior to restoration activities.

Effects of Drought on Water Quality – Nutrient Concentration and Mass

As mentioned above, the overall improving trends for water quality in L. Apopka were interrupted during extreme droughts. For example, despite low P loading due mostly to low precipitation in 2000-2001, TP concentration in lake water increased to average about 0.2 mg P/L in 2002. In response, chlorophyll-*a* increased, and Secchi transparency declined (Fig. 2). Similar changes occurred during drought in 2007-08. The low lake stages reached in each of these droughts were the lowest sustained levels in the entire data set (since 1936) available for L. Apopka. At the lowest point in 2002, the lake had lost 75% of its mean volume. Maximal loss of volume was about 52% in 2008.

Examination of the water-column masses of nutrients in L. Apopka in addition to concentrations revealed important dynamics of the changes during drought conditions. Mass of TP in L. Apopka declined in parallel with lake water concentration until TP mass reached a new, low level about 2000

(Fig. 4). Both the period of decline in TP mass (1987-2000) and the subsequent fluctuations around the new reduced level were similar to changes in TP loading (Fig. 1). Importantly, whereas TP concentration increased sharply during drought in 2001 – 2002, TP mass increased only slightly (Fig. 4). The increase in TP concentration appeared to be due in large part to the concentrating effects of declining lake volume at a constant TP mass. This conservation of TP mass likely explained both the rapid increase in TP concentration and the rapid recovery (decline in TP concentration) as the lake refilled to normal stage in 2003 (Fig. 2).

A similar pattern was evident during the drought 2007-2008, where TP mass increased modestly from 2006 – 2008, while TP concentration increased greatly. The increase in TP mass in 2008 coincided with increased P loading due in part to the temporary need to keep large portions of the former farms dry for mechanical remediation of soil pesticides.

The median TP mass for 1977 – 1980 calculated from Brezonik et al. (1981) did not differ significantly from the median TP mass for 1987-1992 prior to the start of watershed restoration activities (restoration baseline). Even with drought effects, the overall downward trend in TP mass during 1987-2009 (Fig. 4) was highly significant ($p < 0.001$).

In addition to changes in external loading, other mechanisms might have contributed to small increases in water column TP mass during droughts. These factors included increased sediment-water exchange and release of P from exposed sediments (Coveney et al. 2005). Regardless of the mechanisms, large increases in TP concentrations during droughts were temporary responses to extreme perturbations, and water quality improved rapidly as water levels returned to normal ranges (Fig. 2 & 3).

Water-column masses of TN and TSS (Fig. 4) showed similar changes to TP but also notable differences. As for TP mass, median TN mass for 1977 – 1980 calculated from Brezonik et al. (1981) did not differ significantly from the median TN mass for 1987 – 1992 (restoration baseline). TN mass showed a significant improving (declining) linear trend ($p < 0.001$) for 1987 – 2009 (Fig. 4). Mass of TN increased more during the 2001 – 2002 drought than did TP, although behavior during the 2007 – 2008 drought was comparable.

Mass of TSS also showed a significant declining linear trend ($p = 0.011$) (Fig. 4). This pattern illustrated the confounding effects of changes in lake volume, because the overall trend for TSS concentration was flat over the same period (Fig. 3). TSS mass changed only slightly during the 2001 – 2002 drought but increased substantially in 2007 and 2008 (Fig. 4).

Water column mass of TP over the most recent five years (2005 – 2009) averaged 56% lower than restoration baseline (1987 – 1992), TSS mass declined 22%, and TN mass declined 36% (Fig. 5).

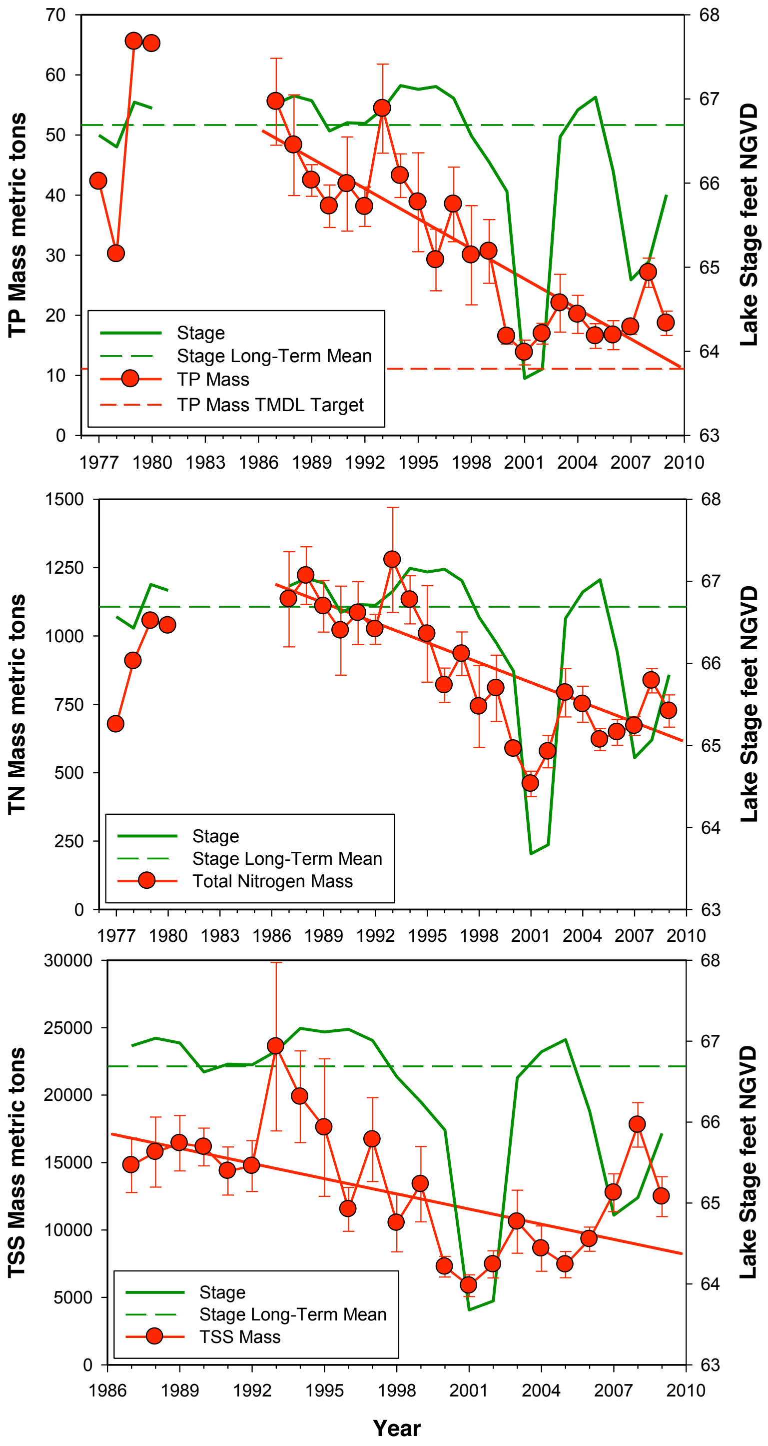


Figure 4. Mean annual values for TP mass (top), TN mass (middle) and TSS mass (bottom) in L. Apopka for the entire 23-yr period (1987-2009) of District monitoring. Data for TP and TN for 1977-1980 from Brezonik et al. (1981), mean annual lake stage, long-term mean stage, and the TMDL target mass for TP are included. Error bars indicate the 96% confidence limits around the means (±2SE). Linear trends for District data were evaluated with a non-parametric regression technique and were significant ($p < 0.05$).

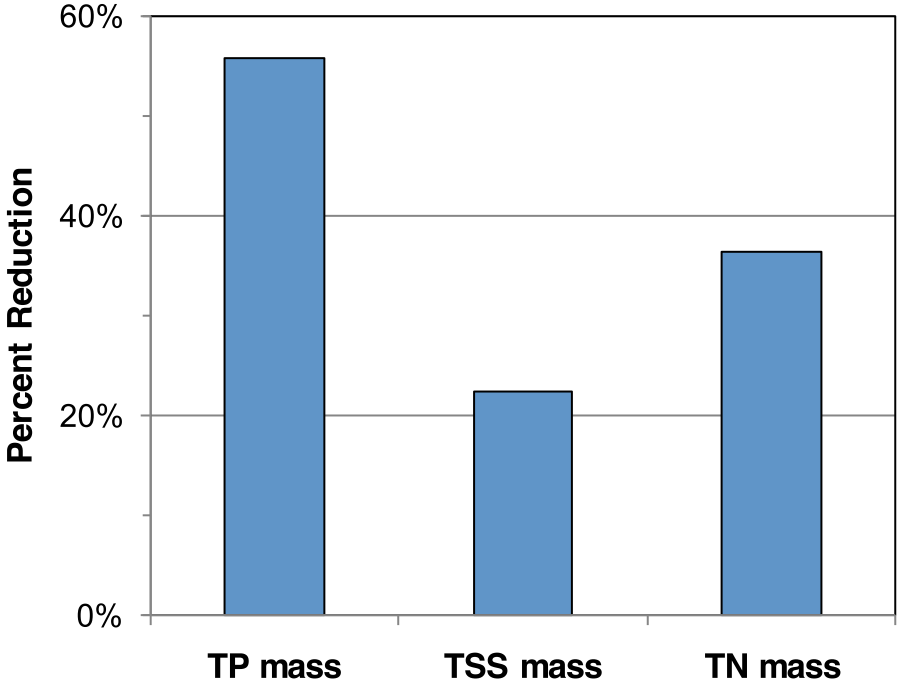
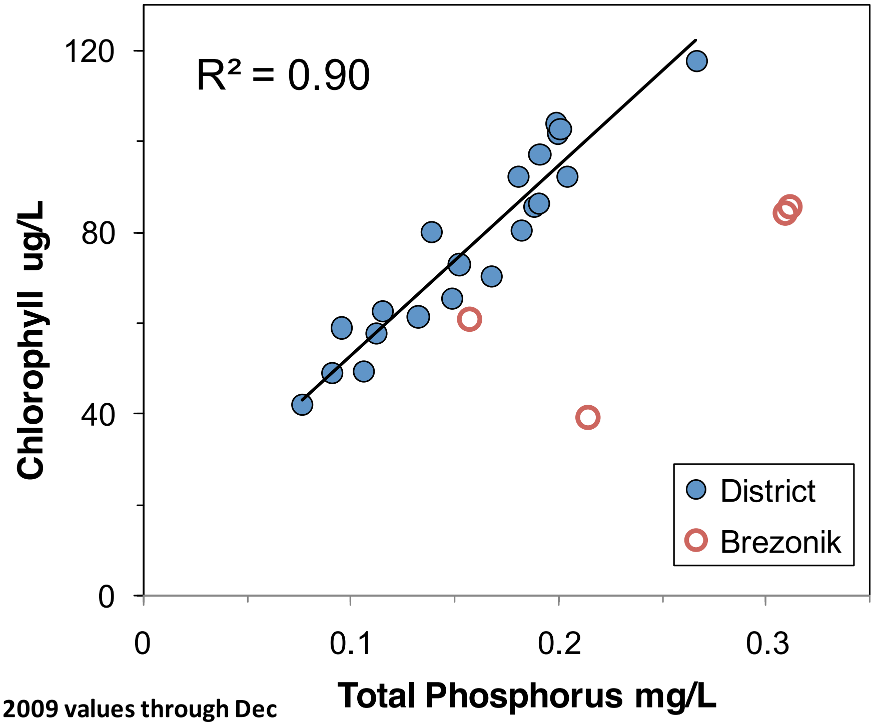


Figure 5. Percent reductions in water column masses of TP, TSS, and TN in Lake Apopka during the restoration program. Values compare the most recent five years (2005-2009) with the restoration baseline (1987 – 1992) prior to the start of watershed restoration activities. Comparison on a mass basis avoided the concentrating effects of low lake volume in 2007-2008.

Ecological Changes in Lake Apopka

We predicted a cascade of ecological changes in Lake Apopka, where reduced P loading leads to reduced TP concentrations in lake water and lower algal levels. Lower algal biomass leads to improved water transparency that allows submersed plants to colonize the bottom. Re-growth of submersed plants provides improved habitat, and sport fish populations increase to levels needed for successful recreational fishing. Although reduction in P loading still is a work in progress, all steps in this cascade of restoration effects, down to initial colonization by submersed plants, currently are operating in L. Apopka. As littoral plants continue to expand over the next several years, further monitoring will be necessary to determine whether sport fish populations also respond.

We found a strong linear relationship between TP concentration and chlorophyll-*a* concentration in L. Apopka (Fig. 6). Declines (and increases) in TP over the past 21 yr have without exception been accompanied by similar changes in chlorophyll-*a*. This relationship supports our conclusion that continued reduction in TP concentrations will translate to continued reduction in phytoplankton biomass.



2009 values through Dec

Figure 6. Relationship between mean annual chlorophyll-*a* and mean annual TP in L. Apopka for the 21-yr period (1989-2009) with District data for chlorophyll. Regression line fit to District data by ordinary least squares. Data for 1977-1980 from Brezonik et al. (1981) are shown for comparison. Brezonik et al. and the District used different methods for analysis of chlorophyll-*a*.

Much speculation has occurred about resuspension of sediments in L. Apopka as a primary source of turbidity that is separate from phytoplankton biomass and that will not decline even as phytoplankton biomass declines. However, the data supported the opposite conclusion. For the District's 21-yr chlorophyll-*a* data set, the concentration of total suspended solids was proportional to the concentration of chlorophyll-*a*. There was a linear relationship over a three-fold range in chlorophyll with Y-intercept not significantly different from zero ($p = 0.927$) (Fig. 7). This relationship suggested that the majority of TSS in L. Apopka was algae or algal detritus. As nutrient control limits algal biomass (Fig. 6), TSS should decline as well. Declines in algal biomass and TSS will be important to produce improved light conditions for submersed vegetation.

All data were included in the regression of TSS on chlorophyll-*a* (Fig. 7), but 2008 stands out from remaining years. TSS increased more during drought in 2007 – 2008 than did chlorophyll-*a* or other water quality variables. This effect was not present during drought in 2001 – 2002 (Fig. 3).

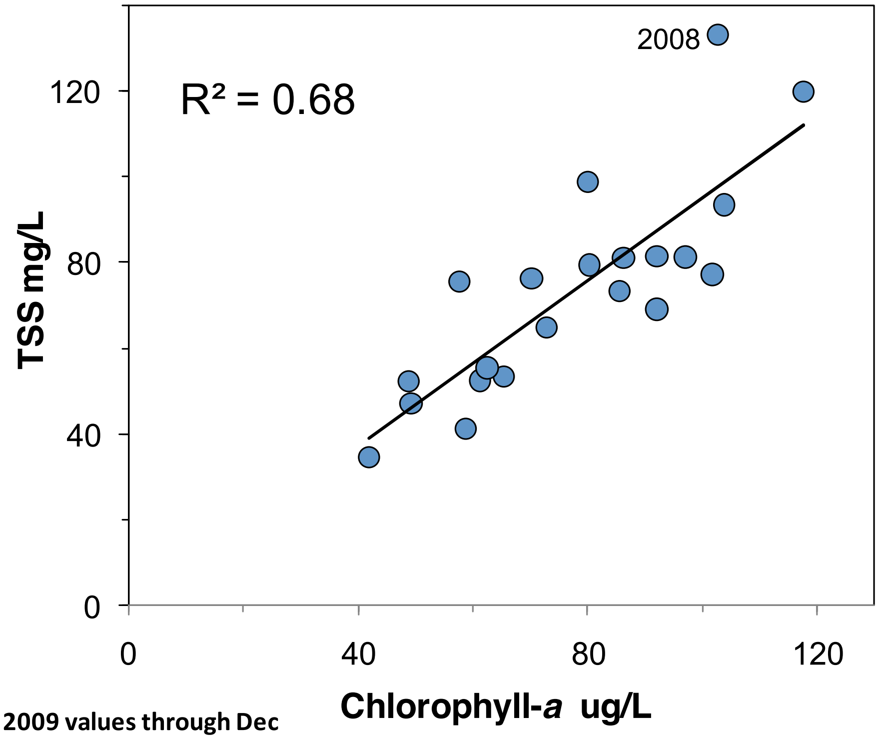


Figure 7. Relationship between mean annual TSS and mean annual chlorophyll-*a* in L. Apopka for the 21-yr period (1989-2009) with District data for chlorophyll. Ordinary least squares regression line was fit to all points. The point for 2008 is indicated (see text).

Beginning in 1995, small patches of native submersed aquatic vegetation (SAV), primarily eelgrass (*Vallisneria americana*) and muskgrass (*Chara* sp.), began to grow in the littoral zone of Lake Apopka after an absence of several decades. Recovery was slowed by drought in 2001 – 2002, when many of these patches were exposed and damaged by low water levels. Submersed vegetation was again limited by low water and worsening water quality during drought in 2007 – 2008. However, as water transparency continues to improve, we expect these initial volunteer patches to expand and provide improved habitat for fish and wildlife. District staff counted almost 400 small native SAV beds in 2009.

References

Battoe L.E., Coveney M.F., Lowe E.F. & Stites D.L. 1999. The role of phosphorus reduction and export in the restoration of Lake Apopka, Florida. In: Phosphorus Biogeochemistry of Subtropical Ecosystems (Eds K.R. Reddy, G.A. O'Connor & C.L. Schelske), pp. 511–526. Lewis Publishers, Boca Raton.

Brezonik, P. L., Preston, S.D., and Crisman, T. L. 1981. Limnological studies on Lake Apopka and the Ocklawaha Chain of Lakes. 4. Water quality in 1980 and a summary of the four-year data base. Report No. ENV-07-81-02. Dept. of Env. Engineering, University of Florida, Gainesville, FL.

Clugston J. P. 1963. Lake Apopka, Florida, A changing lake and its vegetation. Florida Academy of Sciences 26: 168–174.

Coveney M.F. 2000. Sedimentary Phosphorus Stores, Accumulation Rates, and Sedimentation Coefficients in Lake Apopka: Prediction of the Allowable Phosphorus Loading Rate. Technical Memorandum. St. Johns River Water Management District, Palatka, FL, U.S.A.

Coveney M.F., Lowe E.F., Battoe L.E., Marzolf E. R. & Conrow R. 2005. Response of a eutrophic, shallow subtropical lake to reduced nutrient loading. Freshwater Biology 50: 1718–1730 (and Erratum Freshwater Biology 50: 2167).

Florida Department of Environmental Protection. 2007. Basin Management Action Plan for the Implementation of Total Maximum Daily Loads Adopted by the Florida Department of Environmental Protection in the Upper Ocklawaha River Basin. Developed by the Upper Ocklawaha Basin Working Group in Cooperation with the Florida Department of Environmental Protection. Tallahassee. 46 p.

Hoge V.R., Conrow R., Stites D.L., Coveney M.F., Marzolf E.R., Lowe E.F. & Battoe L.E. 2003. SWIM (Surface Water Improvement and Management) Plan for Lake Apopka, Florida. St Johns River Water Management District, Palatka, FL.

Jeppesen E., Søndergaard M., Jensen J. P., Havens, K. E., Anneville, O., Carvalho, L., Coveney M. F., Deneke R., Dokulil M T., Foy B., Gerdeaux D., Hampton S. E., Hilt S., Kangur K., Köhler J., Lammens E. H. H. R., Lauridsen T. L., Manca M., Miracle M. R., Moss B., Nõges P., Persson G., Phillips G., Portielje R., Romo S., Schelske C. L., Straile D., Tatrai I., Willén E. & Winder M. 2005. Lake responses to reduced nutrient loading – an analysis of contemporary long-term data from 35 case studies. Freshwater Biology 50: 1747–1771.

Lowe E.F., Battoe L.E., Coveney M.F. & Stites D.L. 1999. Setting water quality goals for restoration of Lake Apopka: Inferring past conditions. Lake and Reservoir Management 15: 103–120.

Magley W. 2003. Total Maximum Daily Load for Total Phosphorus for Lake Apopka, Lake and Orange Counties, Florida. Florida Department of Environmental Protection Watershed Assessment Section, Tallahassee, FL. 96 p.

Schelske, C.L., E. F. Lowe, W. F. Kenney, L. E. Battoe, M. Brenner and M. F. Coveney. 2010. How anthropogenic darkening of Lake Apopka induced benthic light limitation and forced the shift from macrophyte to phytoplankton dominance. Limnology and Oceanography. In press.