Technical Memorandum 56

WATER QUALITY CHANGES IN LAKE APOPKA, FLORIDA, AND THE ST. JOHNS RIVER WATER MANAGEMENT DISTRICT'S RESTORATION PROGRAM

by

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SUMMARY

The primary step in the St. Johns River Water Management District's comprehensive restoration program for Lake Apopka is a substantial reduction in external phosphorus (P) loading. This step largely has been achieved through progressive restoration of former farms on the Lake Apopka North Shore (LANS) to wetlands after remediation of residual pesticides in soils to ecologically safe levels. Drainage infrastructure in the LANS was modified to impound rainwater and to treat any necessary discharges to the lake with alum.

To date, P loading to Lake Apopka has met the total maximum daily load (TMDL) target P loading (15.9 metric tons per year) in years during or following droughts when little rainwater was discharged from the LANS. Further improvements to water management and P treatment infrastructure will be needed to ensure that the current loading limit can be met in normal to wet years and that lower loading limits can be met, if necessary, during low water periods to prevent hypereutrophic water quality conditions. Achieving the target P loading for Lake Apopka should result in meeting the target total phosphorus (TP) concentration (0.055 mg P/L) as well if lake levels remain within a normal fluctuation range.

Long-term (1987 to present) changes in water quality in Lake Apopka largely are explained by three factors, which are 1) improving trends due to reduced P loading and P removal, 2) cyclical oscillations since 2000 due to alternating periods of extremely low and normal lake levels, and 3) seasonal cycles.

The restoration program has reduced annual P loading to Lake Apopka from about 62 metric tons to an average of 11 metric tons during 2010 – 2014. Reduction in external P loading and removal of P from lake water resulted in improvements in key water quality indicators TP, chlorophyll-*a* (Chl-*a*), and Secchi transparency. Despite worsened conditions at low lake levels during recent droughts, water quality improved since the late 1980s in Lake Apopka in response to restoration efforts.

Calculated using total water column mass to reduce the confounding effects of smaller lake volume during droughts, TP averaged over the past five years was 50% lower than pre-restoration (1987 – 1992) values. Algal chlorophyll-*a* declined 43%, and Secchi transparency increased 24% over this same period. Long-term improvements persisted despite short-term wind effects caused by multiple hurricanes in 2004, which is evidence for a controlling role of external loading rather than wind resuspension or P recycling for long-term lake water TP concentration.

Since 2000, recurring low lake stage during droughts at 5 to 6-yr intervals resulted in periodic degradation of all water quality indicators. TP, total suspended solids (TSS), total nitrogen (TN), and Chl-*a* concentrations increased greatly at low lake levels because their lake water masses were concentrated in a smaller volume and because the normal net sedimentation of TP to sediments was interrupted.

Secchi transparency worsened until 1993 but then followed the same general pattern as TP, TSS, and TN – long-term improvements from 1993 through 2000 followed by temporarily worsened conditions during subsequent periods of low lake level.

Mass of TP in Lake Apopka declined in parallel with concentration from 1987 until 2000 and subsequently maintained a low and quasi-stable level. In contrast, lake water masses of TSS and TN declined initially but then trended upwards from 2000 through 2015. Mass of particulate N increased proportionally to TSS, but particulate P did not. Therefore, suspended matter in Lake Apopka, increasing since 2000, maintained a similar N content but a lower P content than in prior years.

Annual mean Chl-*a* concentration in Lake Apopka showed a strong linear relationship with TP concentration. Continued reduction in TP concentrations should translate to continued reduction in phytoplankton biomass. Annual mean concentration of Chl-*a* also varied linearly with TSS concentration. Most of the TSS was not living algal biomass but may consist of algal detritus.

We predicted that the restoration program in Lake Apopka would produce a cascade of ecological changes. Reduced external P loading would lead to reduced TP concentrations in lake water and lower algal levels. Lower algal biomass would lead to improved water transparency that would allow submersed aquatic vegetation (SAV) to recolonize the bottom. Re-growth of submersed plants would provide improved habitat, and game fish populations would increase to levels that allow successful recreational fishing.

External P loading to Lake Apopka has been reduced, although the only years to date that P loading met the restoration (TMDL) target were years during or immediately following droughts. All steps in the cascade of restoration effects, down to colonization by submersed plants, currently are operating in Lake Apopka. Native submersed aquatic vegetation (SAV) began to grow in the littoral zone of Lake Apopka in 1995 but almost was eliminated in subsequent droughts. By 2012, SAV had expanded to about 23 ha (57 acres). SAV declined during the most recent (2012 – 2014) drought as well, but losses were much less than previously, which showed greater resilience by the SAV community. As littoral plants continue to expand, other monitoring will be necessary to determine whether game fish populations also respond.

During extreme low-water periods, TP concentrations in lake water were decoupled from external loading and increased despite low loading. Chl-*a* increased proportionally, and Secchi transparency decreased. SAV either disappeared or decreased in total area. It is clear that under current conditions, sustained improvements in TP, algal Chl-*a* transparency, and SAV will require sustained periods without the extreme low lake levels typical of the past fifteen years.

Contents

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) developed and is implementing a restoration program for Lake Apopka, a shallow, 125 km^2 (31,000 acre), eutrophic lake in the Upper Ocklawaha River Basin 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 of mostly floodplain marshes at the north end of Lake Apopka began in the 1940s. Drainage and farming of the peat (“muck”) soils increased nutrient loading, water color, and lake stage, and precipitated a shift in the primary producer community from submersed macrophytes to phytoplankton (Schelske et al. 2010). Submersed macrophytes declined rapidly and almost disappeared by 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 elevations in the 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. The District began diagnostic and feasibility studies for the lake 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 P 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 P concentration target by rule in 1996 and completed buyout of most of the farms by 1999 using both state and federal funds.

The District established a restoration P loading target for Lake Apopka of 15.9 metric tons P per year (0.13 g P m^{-2} yr^{-1}) (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 this concentration goal through a weight-of-evidence approach that estimated TP levels prior to large-scale farming (Lowe et al. 1999).

The 15.9 metric tons P annual loading target represented a 74% reduction from baseline loadings measured in a six-year P budget (Fig. 1). Pumped discharges from the farms made up about 86% of baseline P loading (Fig. 1). Because we do not have direct control over many sources of P (e.g. atmospheric deposition and spring input), loading from the farm/former farm areas needed to be decreased by almost 90%. At the target P loadings for restoration, the former farm area

(Lake Apopka North Shore – LANS), the atmosphere, and other sources would contribute approximately equal shares (Fig. 1).

The Florida Department of Environmental Protection (FDEP) and the United States Environmental Protection Agency (EPA) 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 2014). Through the Basin Working Group, local stakeholders are involved with the District and FDEP in the efforts to improve Lake Apopka and downstream lakes.

This report summarizes the changes in important water quality indicators in Lake Apopka during 29 years of District restoration activities from 1987 through 2015. P loading calculations are included from 1989 through 2014.

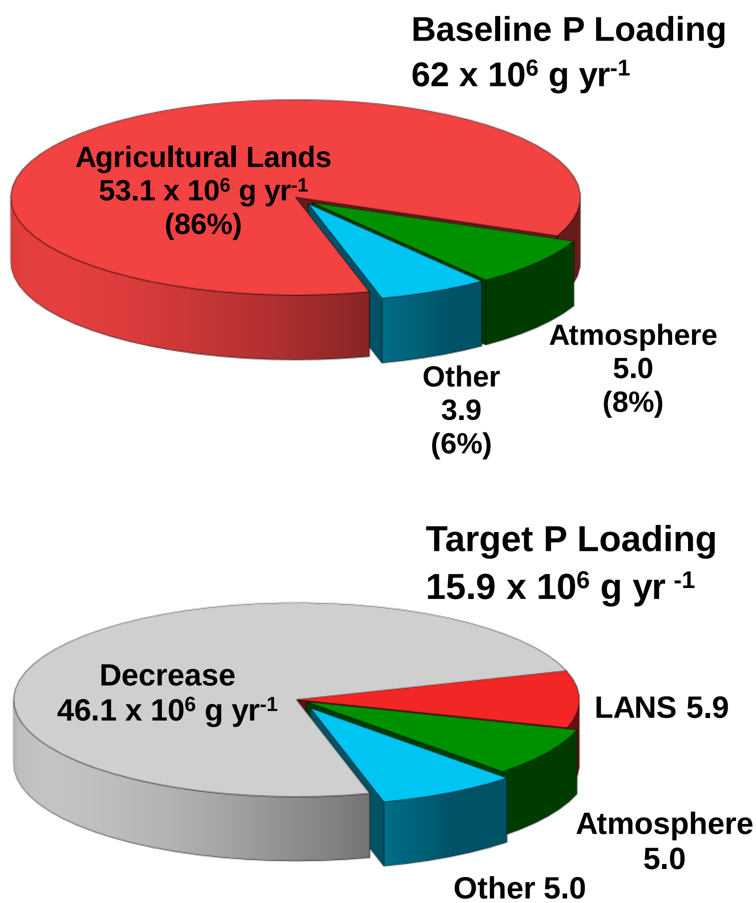

Figure 1. Top: Distribution of P loading from all sources to Lake Apopka measured for a baseline period (1989-94). Bottom: Projected P loading to meet the restoration (TMDL) target. The necessary reduction in P loading (46.1×10^6 g yr^{-1}) must come from discharges from the LANS (former agricultural lands) because other sources either are not subject to regulation (e.g. atmospheric loading) or are expected to remain level (e.g. watershed runoff). Derivation of target P loading found in Coveney (2000).

RESTORATION PROGRAM

Background information on Lake Apopka and details about the restoration plan, the early diagnostic and feasibility studies, and the land acquisition program are found in the Lake Apopka SWIM Plan (Hoge et al. 2003).

The primary step in the comprehensive restoration of Lake Apopka was a large reduction in external P loading through gradual restoration of wetlands on about 60 km^2 (14,800 acres) of the former agricultural lands. Wetland restoration was done of necessity behind intact lake-shore levees because soil subsidence left much of the former farm lands well below lake level. High mortality of fish-eating birds occurred during the initial phases of reflooding in winter 1998 – 1999. These deaths were attributed to organochlorine pesticide (OCP) residues bound to the organic, peat soils (USFWS 2004). 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 these contaminants to ecologically safe levels before re-initiating large-scale reflooding (Conrow et al. 2011, Coveney et al. 2008).

Approximately 1,610 ha (3,970 acres) of contaminated soil were remediated by inverting soil layers to bury the top 30 cm (12 inches) under about 60 cm (24 inches) of deeper, cleaner soil (Bartol and Brown 2012). Remediation was completed in 2009. Controlled reflooding began in 2002 on the former Duda property where no remediation was needed. Reflooding progressed in stages to other areas. We monitored OCP levels in fish at each step to confirm our predictions and to ensure safe conditions. Concurrently, drainage works over this 80 km^2 wetlands and uplands area were reconfigured to impound rainwater in the restored marshes and route any necessary discharge water through alum treatment and settling systems. Treated water now is discharged by pumps both to the Apopka-Beauclair Canal (primary) and to Lake Apopka (secondary). Rebuilding the drainage and treatment structures and shallow reflooding of the last parts of the entire 60 km^2 wetland restoration area were completed in 2014. Management of the reflooded marshes as well as the surrounding upland areas (the LANS) is described in the current Lake Apopka North Shore Land Management Plan (SJRWMD 2013).

In addition to projects to reduce P loading, the District's restoration program for Lake Apopka includes wetland treatment and rough-fish harvest projects that remove P from the nutrient-rich lake water.

The Lake Apopka Marsh Flow-Way is a 310-ha (766 acre) treatment wetland with four wetland cells. The project was constructed on a part of the former farmlands and has operated in phases beginning in 1990 to remove suspended particles and nutrients from recirculating lake water (Coveney et al. 2002; Dunne et al. 2012). Median P removal efficiency from lake water was about 30%, and median removal of P has been 2.5 metric tons (5,500 lb) annually. In addition to

P, the Marsh Flow-Way removes nitrogen and is an effective filter for suspended particles. The wetland treats about 40% of the lake volume per year.

A second long-term District project is the large-scale removal of rough fish, primarily gizzard shad (*Dorosoma cepedianum*) from Lake Apopka. This project started in 1993 and has removed from 125 to 880 metric tons (0.28 to 2.0 million lb) of fish per year. The project removes P in the fish biomass and reduces P recycling caused by gizzard shad feeding in bottom sediments (Schaus et al. 2010). Rough-fish removal relies upon a cooperative agreement between governmental agencies (Florida Fish and Wildlife Conservation Commission and the District) and is a public-private partnership funded partly through private profits. The direct removal of P in fish biomass varies with catch and has ranged from 1 to 7 metric tons P with median 3.8 metric tons P (8,360 lb) removed annually.

The Florida Fish and Wildlife Conservation Commission (FWC) has worked to accelerate development of shallow-water habitat by planting more than 500,000 emergent and floating-leaved plants (giant bulrush, *Schoenoplectus californicus* and spatterdock, *Nuphar luteum*) over 182 ha (450 acres) of the littoral zone of Lake Apopka in 2012 – 2014.

Additional projects are planned or underway in Lake Apopka funded by the Florida Legislature and conducted by FDEP, FWC, and the District. These projects include removal of flocculent sediment for near-shore habitat improvement, excavation of sumps to trap sediments, and improvements to navigation. Further, several pilot projects are testing innovative advanced technologies to remove nutrients from lake water and sediments.

PHOSPHORUS LOADING

External P loading to Lake Apopka from the watershed has been reduced significantly (Fig. 2). Beginning with the initial purchases of some farmlands by the District in the late 1980s and continuing with regulatory efforts and then complete acquisition of the farms by 1999, the restoration program has reduced annual P loading to Lake Apopka from about 62 metric tons to an average of 11 metric tons during the last five years with complete data (2010 – 2014) (Fig. 2). Watershed modifications to reduce loading began in 1993 during the farming period with construction of retention ponds and are ongoing as rainwater is impounded in restored marshes on the LANS, and any water discharges are treated with alum.

However, P loading from the watershed is controlled in part by rainfall, and the decline in loading has not been monotonic. The increase in P loading to Lake 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. To date, P loading has met the TMDL target (15.9 metric tons P per yr) only for years during or following droughts (2000 – 2001, 2006 – 2007, 2011 – 2014) when very little rainwater was discharged from the LANS (Fig. 2). Further improvements to water management and P treatment infrastructure on the LANS will be needed to ensure that current loading limits for Lake Apopka will be met in normal to wet years and that lower loading limits can be met, if necessary, during low water periods to prevent hypereutrophic water quality conditions.

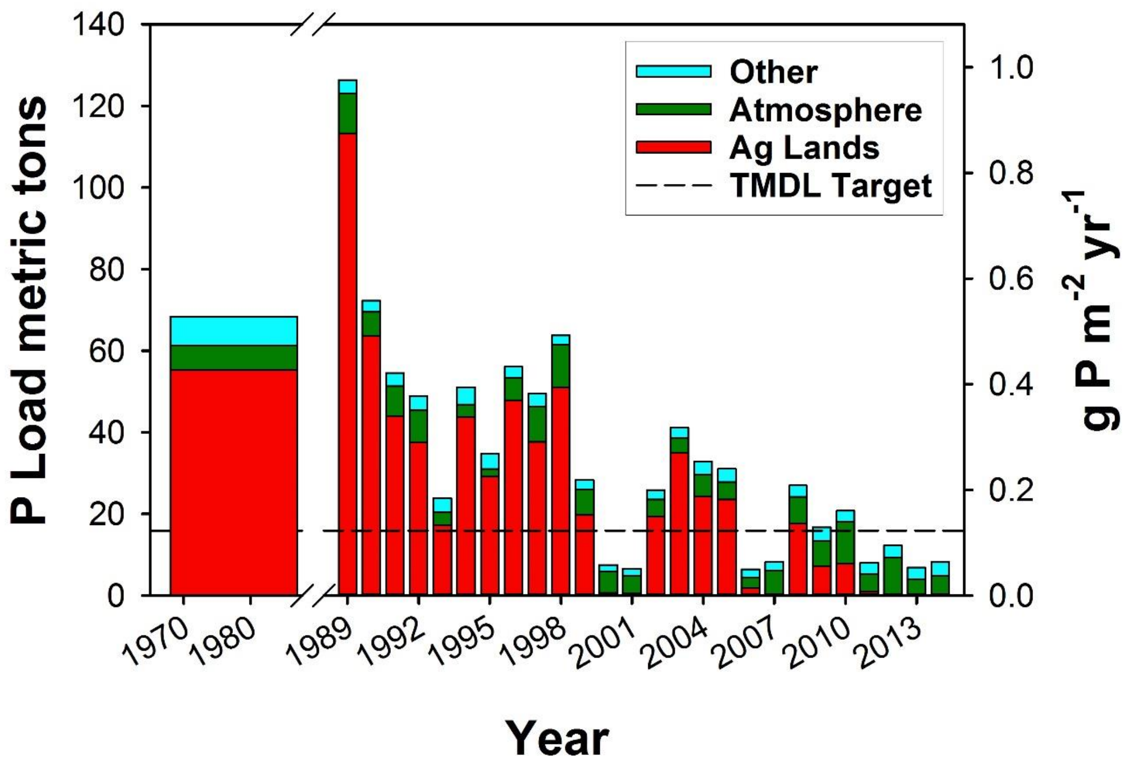

Figure 2. Annual phosphorus loading from all sources to Lake Apopka. "Agricultural Lands" are the Lake Apopka North Shore. Land use in that area shifted from mostly agriculture prior to 1996 to mostly reflooded wetlands by 2013. The TMDL target for P loading is 15.9 metric tons P per yr. Mean loading for 1968-87 was derived through analyses of sediment stratigraphy (Coveney 2000). P loading was measured directly beginning in 1989. Loading sources included discharges from agricultural lands, wet and dry atmospheric deposition, basin runoff, Apopka Spring, Winter Garden wastewater treatment, and groundwater exchange through the lake bottom.

Although TP in lake water declined in response to reduced loading (Fig. 3), annual TP concentration was not closely related to annual P loading (Coveney et al. 2005). Because of relatively long residence times for water and for P in Lake Apopka, loading and TP concentrations must be averaged over multiple years to establish even an approximate relationship. Furthermore, hydrologic characteristics (e.g. lake volume and hydraulic residence time) change through time and especially during drought years. These changes must be considered to compare properly the effects of various P loading rates.

In the long run, steady state models predict that Lake Apopka will meet the target TP concentration (0.055 mg/L) when loading meets the TMDL target (Coveney 2000). In the short run, many other variables affect the relationship between P loading and TP concentration. For example, low loading during drought years coincided with high rather than low TP concentrations because of reduced lake volume, evaporative concentration, and reduced net P sedimentation.

Nitrogen (N) loading to Lake Apopka was not calculated for most of the 26-yr reporting period. However, reductions in water discharges from the farms to target P loading likely reduced N loading as well.

WATER QUALITY INDICATORS

Long-term changes in water quality in Lake Apopka largely can be attributed to three drivers:

1. An improving trend due to reduced P loading and P removal achieved by the restoration program
2. Cyclical oscillations in water quality since 2000 due to alternating periods of extremely low and normal lake levels
3. Seasonal cycles in water quality

To summarize overall changes in water quality, we compared "Pre", the period prior to start of watershed restoration, 1987 – 1992; and "Post", the most recent five-year period, January 2011 – December 2015 (Fig. 3). For water constituents, we based the comparison on total water column masses to minimize the confounding effects of changes in lake volume during droughts.

Reduction in external P loading to Lake Apopka and P removal projects resulted in long-term improvements in the key water quality indicators TP, chlorophyll-*a* (Chl-*a*), and Secchi transparency compared with pre-restoration conditions. TP showed the greatest (50%), and TSS showed the least (11%), improvement. TN, Secchi transparency, and Chl-*a* were intermediate with improvements from 24% to 43% (Fig. 3). Neither internal recycling of sediment P nor wind-driven resuspension of sediments prevented improvements in these water quality measures in this shallow, eutrophic lake (Coveney et al. 2005).

However, it is important to note that since 2000, recurring low lake stage during droughts resulted in degradation of all water quality indicators but especially total nitrogen (TN) and total suspended solids (TSS). Droughts and low lake stages recurred at 5 to 6-yr intervals (e.g. Fig. 4). The low lake stages reached at the end of each of these droughts were the lowest lake levels in the entire data record (start 1936) for Lake Apopka. At the lowest point in 2002, the lake had lost 72% of its mean volume. Maximal loss of volume was about 50% in 2008 and in 2012. These low lake stages and long durations exceeded the low end of the range of fluctuation in lake level that is beneficial to develop and sustain healthy littoral plant communities.

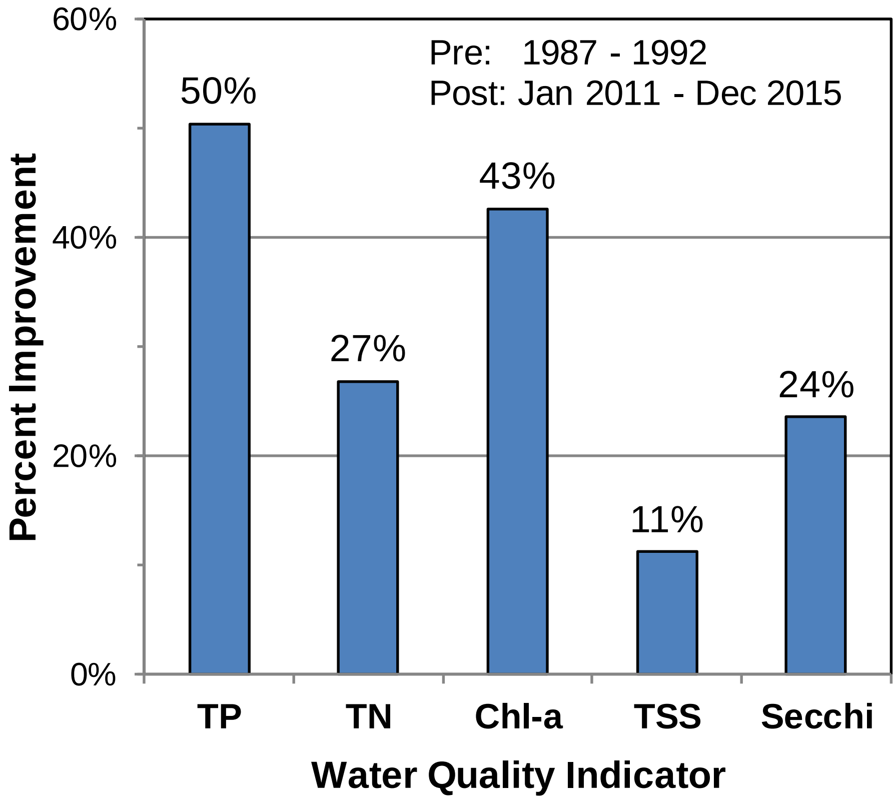

Figure 3. Percent improvements to date in mass of TP, TN, Chl-*a*, and TSS, and in Secchi transparency in Lake Apopka during the restoration program. Improvements were decreases in TP, TN, Chl-*a*, and TSS and an increase in Secchi transparency. Because water quality conditions are variable, we calculated improvements by comparison of the most recent five years with the period 1987 – 1992, prior to the start of watershed restoration. Except for Secchi transparency, we based percentages on water column masses to reduce the confounding effects of changing lake volume.

A seasonal pattern in water quality was evident in Lake Apopka in most but not all years. This pattern consisted of worsening water quality in the winter/spring and improvements in the summer/fall. This seasonality appeared to be due, in part, to slower P sedimentation and possible sediment resuspension during winter because of wind mixing from frontal events (Coveney et al. 2005). The analyses in this report were based on mean annual constituent values so seasonal patterns will not be discussed. These patterns are illustrated, however, in the six-year monthly data set for TP presented in Appendix A.

TOTAL PHOSPHORUS

A detailed examination of changes in TP through time will serve as an example for other water quality constituents. The time series of TP masses, as well as concentrations, reveals important dynamics of the changes in nutrient levels during drought conditions.

The average composition of TP in Lake Apopka for 1987 – 2015 was 91% particulate P (PP), 5% dissolved organic P, and 4% dissolved inorganic P (soluble reactive P, SRP). Accordingly, virtually all dynamics in TP reflected changes in concentration or mass of the particulate fraction.

TP concentrations in lake water (Fig. 4, top) declined along with reductions in P loading (Fig. 2) until 2000. A marked exception to this trend was 1993, where TP concentrations were elevated considerably despite relatively low loading. This increase in TP corresponded with the "Storm of the Century" in March 1993 with high winds and numerous tornados in central Florida. Lake water ammonium (NH_4) increased greatly in Lake Apopka at the same time (data not shown). We interpret this sudden increase in NH_4 as a marker for strong disturbance of the sediments that also recycled dissolved and particulate P to the water column. Elevated TP concentrations in 1993 occurred at normal water levels and reflected increased TP mass in the water column (Fig. 4, bottom). Annual P budget calculations for 1993 showed a net flux of P from the sediments to the water (data not shown).

From 2000 until 2015, TP concentrations oscillated greatly, associated with multi-year cycles of dry and wet conditions. TP concentrations increased during each period of low lake stage only to decrease again as lake stage recovered to a normal range (Fig. 4, top).

Mass of TP in Lake Apopka declined in parallel with lake water concentration until TP mass reached a low and quasi-stable level about 2000 (Fig. 4, bottom). Both the period of decline in TP mass (1987-2000) and the subsequent fluctuations around the new reduced mass level were similar to patterns of TP loading (Fig. 2). In addition to changes in external loading, other mechanisms might have contributed to increases in water column TP mass during droughts. These factors included increased sediment-water exchange, release of P through oxidation or erosion of exposed sediments, and low net sedimentation of P during low water periods (Coveney et al. 2005).

Whereas TP concentration increased sharply at low lake stage in 2001 – 2002, TP mass increased only slightly (Fig. 4). This increase in TP concentration at a constant TP mass is consistent with a concentrating effect of declining lake volume. Similar increases were evident during low lake levels in 2007-2008 and again in 2012-2014, where TP concentration increased greatly, while TP mass increased only modestly (Fig. 4). Pumping from LANS needed to keep large portions of the former farms dry for mechanical remediation of soil pesticides was responsible for most of the increase in TP mass in 2008.

This apparently conservative behavior of TP mass in Lake Apopka during drought, where concentrations varied inversely with lake stage, was unexpected. A concentration of TP through evaporation of water from the lake followed by dilution upon refill of the lake appeared to explain in part both the rapid increase in TP concentration at low lake stage and the decrease in TP concentration as the lake refilled to normal level in 2003 (Fig. 4).

Loss of TP from lake water in Lake Apopka occurs mainly through sedimentation. Net sedimentation of TP can be described by the sedimentation coefficient, which is the proportion of mean annual TP mass that sediments each year (Coveney et al. 2005) and is calculated from TP mass budgets. Annual sedimentation coefficients declined almost to zero during each period of low lake level (data not shown). In other words, lake water TP concentrations increased greatly at low lake levels both because lake water TP mass was concentrated in a smaller volume and because the normal net sedimentation of TP from lake water to sediments was interrupted. Net sedimentation is the difference between sedimentation (downward flux) and recycling from sediments due to diffusion and resuspension (upward flux). Whether low net sedimentation was due to decreased sedimentation or increased recycling cannot be determined from TP mass balance data.

Annual TP concentrations in 2004 – 2006 and again in 2010 – 2011 were under 0.1 mg P/L, and some monthly values approached the TMDL target of 0.055 mg/L (Fig. 4; Appendix A). These long-term improvements persisted despite short-term wind effects caused by multiple hurricanes affecting central Florida in 2004. This pattern was evidence for a primary controlling role of external loading rather than wind resuspension on long-term lake water TP concentration at normal water levels.

TOTAL SUSPENDED SOLIDS, TOTAL NITROGEN, CHLOROPHYLL-*A*, SECCHI TRANSPARENCY

Lake water concentrations and masses of TSS and TN in Lake Apopka showed changes since 1987 similar to those described above for TP, including elevated values during periods with low lake stage caused by drought. However, the behavior of these constituents showed important differences as well.

Temporary increases in TSS and TN concentrations and masses were evident in 1993 and likely were initiated by storm disturbance as described above for TP (Figs. 5 & 6). Concentrations, and particularly masses, declined from 1993 through 2000. Lake water concentrations of both TSS and TN increased during the subsequent three periods of low lake levels (2001 – 2002, 2007 – 2008 and 2012 – 2014) (Figs. 5 & 6). As discussed above for TP, these increases appeared to be due in part to the concentrating effects of declining lake volume. However, an important difference was that lake water masses of TN and, in particular, TSS increased during periods of low water (Figs. 5 & 6, bottom). Increases in mass contributed to the sharp increases in concentration. Further, lake water masses of TSS and TN trended upwards from 2000 through 2015, but mass of TP did not (ordinary least squares linear regression, significance criterion $p < 0.05$) (Figs. 4 - 6).

The average composition of TN in Lake Apopka for 1987 – 2015 was 60% particulate N (PN), 38% dissolved organic N (DON), and 2% dissolved inorganic N (DIN). Changes in mass of the PN fraction accounted for virtually all of the dynamics in TN, including the increase in lake water mass since 2000 (Fig. 7). The DON fraction declined slowly over most of the period, and DIN was a small part of the whole. The increase in mass of PN from 2000 to 2015 was proportional to the increase in mass of TSS. Mean mass ratios of PN:TSS during 2000/01 and 2014/15 were practically identical at 0.038 and 0.036, respectively.

In summary, concentration and mass of TSS in Lake Apopka mostly decreased from 1987 to 2000 and then increased significantly during periods of low lake levels in 2007 – 2008 and 2012 – 2014. Additionally, TSS mass showed a general increase from 2000 through 2015. This increase in TSS was accompanied by proportional increases in particulate N but not particulate P. Therefore, suspended matter in Lake Apopka, increasing since 2000, had similar N content but a lower P content than in prior years.

Changes in lake water concentrations of Chl-*a* in Lake Apopka (Fig. 8) were almost identical to changes in TP (Fig. 4) – long-term improvements from 1987 through 2000 followed by worsened conditions during subsequent periods of low lake level.

Secchi transparency worsened somewhat from 1987 to 1993 but then followed the same general pattern as TP, TSS, and TN – improvements through 2000 and temporarily, but significantly, worsened conditions during subsequent periods of low lake level (Fig. 8). It is notable that, whereas TSS showed an increasing trend post 2000 (Fig. 5), Secchi transparency showed no significant trend but fluctuated about a median of 0.30 m (ordinary least squares linear regression, significance criterion $p < 0.05$) (Fig. 8).

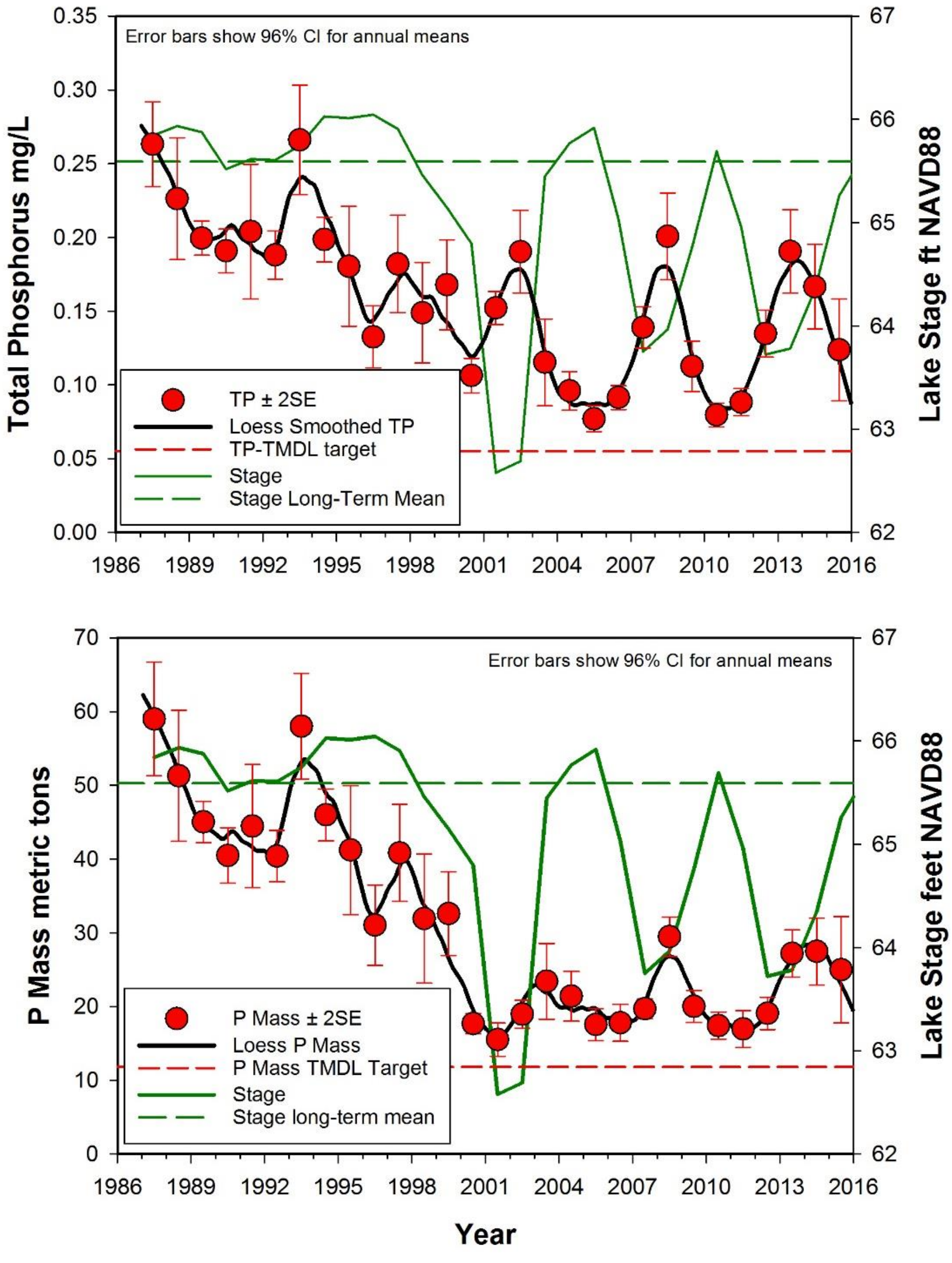

Figure 4. Mean annual values for total phosphorus (TP) concentration (top) and TP mass (bottom) in Lake Apopka for the period (1987-2015) of District monitoring. Local polynomial regression (LOESS) smooth curves were fit to mean monthly values. Mean annual lake stage, long-term mean stage (1960 – 1990), and the TMDL target concentration for P are included. Error bars are 96% confidence limits around means (±2SE).

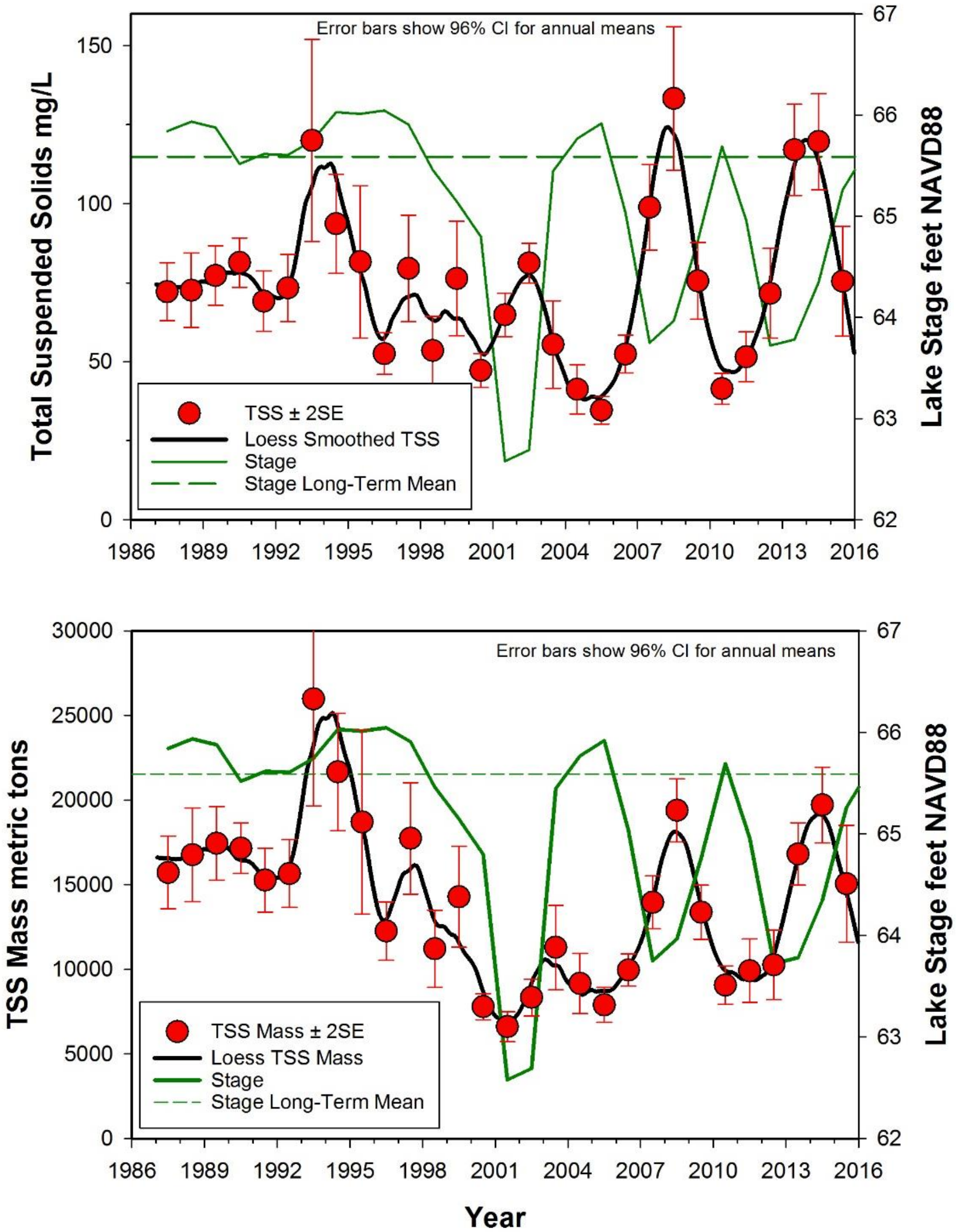

Figure 5. Mean annual values for total suspended solids (TSS) concentration (top) and TSS mass (bottom) in Lake Apopka for the period (1987-2015) of District monitoring. Local polynomial regression (LOESS) smooth curves were fit to mean monthly values. Mean annual lake stage and long-term mean stage (1960 – 1990) are included. Error bars are 96% confidence limits around means (±2SE).

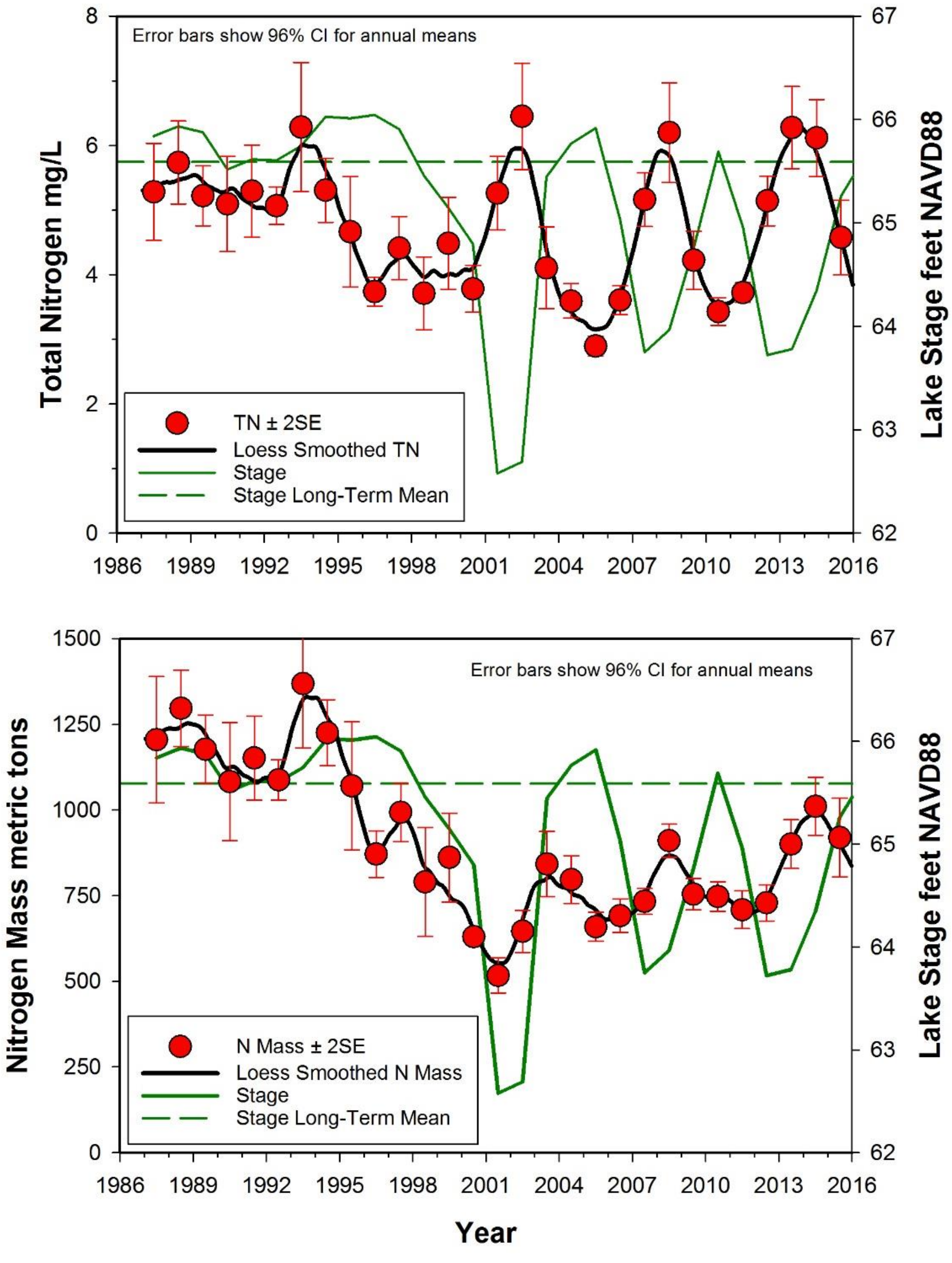

Figure 6. Mean annual values for total nitrogen (TN) concentration (top) and TN mass (bottom) in Lake Apopka for the period (1987-2015) of District monitoring. Local polynomial regression (LOESS) smooth curves were fit to mean monthly values. Mean annual lake stage and long-term mean stage (1960 – 1990) are included. Error bars are 96% confidence limits around means (±2SE).

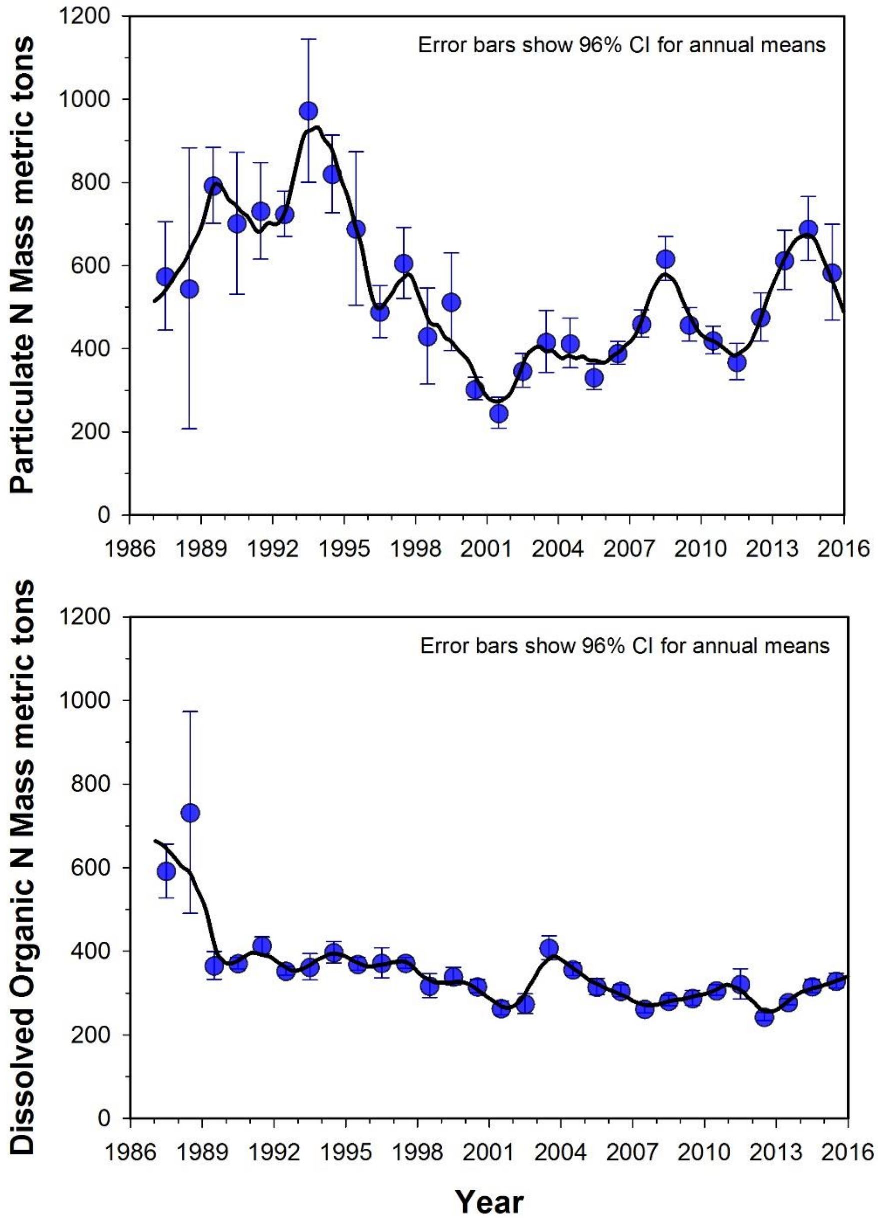

Figure 7. Mean annual values for particulate N mass (top) and dissolved organic N mass (bottom) in Lake Apopka for the period (1987-2015) of District monitoring. Local polynomial regression (LOESS) smooth curves were fit to mean monthly values. Error bars are 96% confidence limits around means (±2SE).

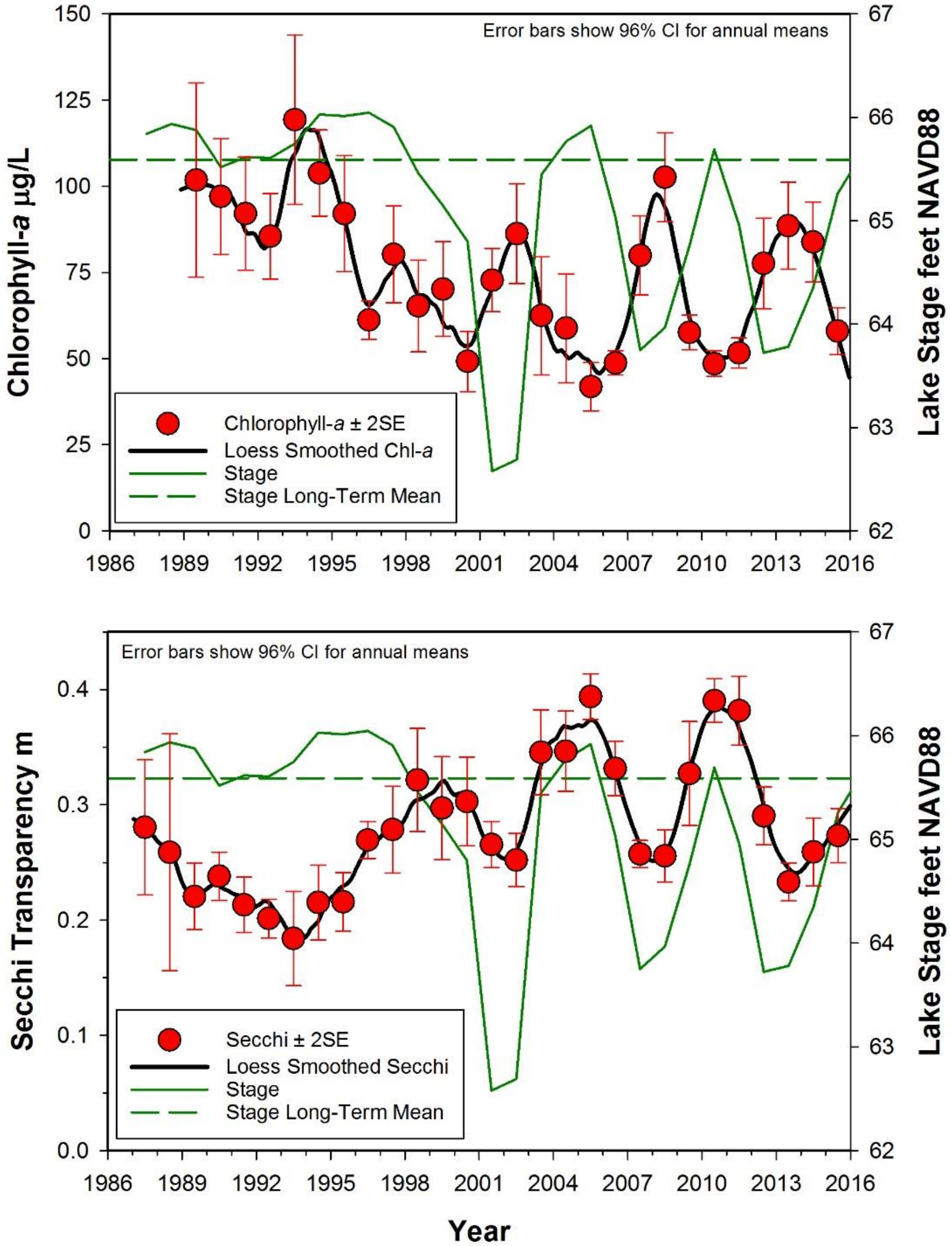

Figure 8. Mean annual values for chlorophyll-*a* concentration (top) and Secchi transparency (bottom) in Lake Apopka for the period (1987-2015) of District monitoring. Local polynomial regression (LOESS) smooth curves were fit to mean monthly values. Mean annual lake stage and long-term mean stage (1960 – 1990) are included. Error bars are 96% confidence limits around means (±2SE).

ECOLOGICAL CHANGES IN LAKE APOPKA

We predicted that the restoration program in Lake Apopka would produce a cascade of ecological changes (Fig. 9). Reduced external P loading would lead to reduced TP concentrations in lake water and lower algal levels. Lower algal biomass would lead to improved water transparency that would allow submersed aquatic vegetation (SAV) to recolonize the bottom. Re-growth of submersed plants would provide improved habitat, and game fish populations would increase to levels needed for successful recreational fishing (Battoe et al. 1999).

External P loading to Lake Apopka was reduced, although the only years to date when P loading met the restoration (TMDL) target were years during or immediately following droughts (Fig. 2). All steps in the cascade of restoration effects (Fig. 9), down to increased colonization by submersed plants, currently are operating in Lake Apopka. As littoral plant areas expand, monitoring will be necessary to determine whether game fish populations also respond.

However, the linear trophic cascade (Fig. 9) in Lake Apopka was severely impacted, and even reversed, during periods of extremely low lake levels due to drought. During these periods, TP concentrations in lake water were decoupled from external loading and increased despite low loading (Fig. 4). Chl-*a* increased proportionally, and Secchi transparency decreased (Fig. 8). Volunteer patches of SAV either disappeared or decreased in size (Fig. 11) due primarily to exposure and desiccation. It is clear that under current conditions, sustained improvements in TP, transparency, and SAV will require sustained periods without the extreme low lake levels typical of the past fifteen years.

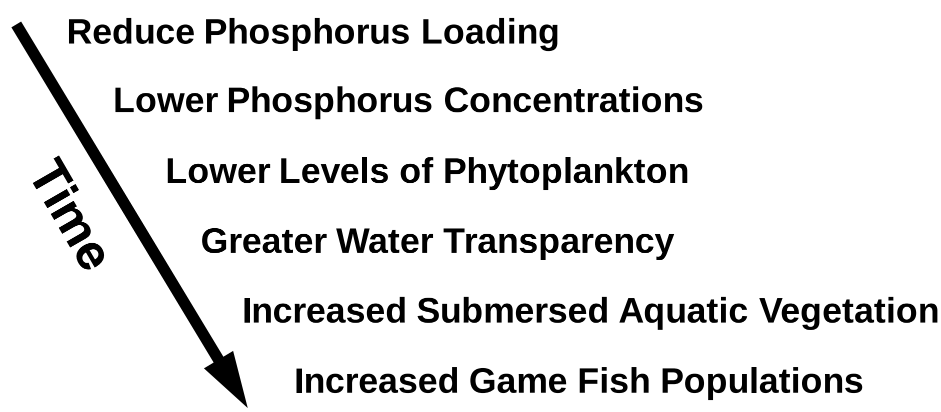

Figure 9. Conceptual cascade of events that we predicted to follow from reduction in P loading to Lake Apopka. These events describe both a reduction in trophic state (lower nutrients) and important ecological changes (e.g. shift in primary producer community structure from phytoplankton to aquatic macrophytes).

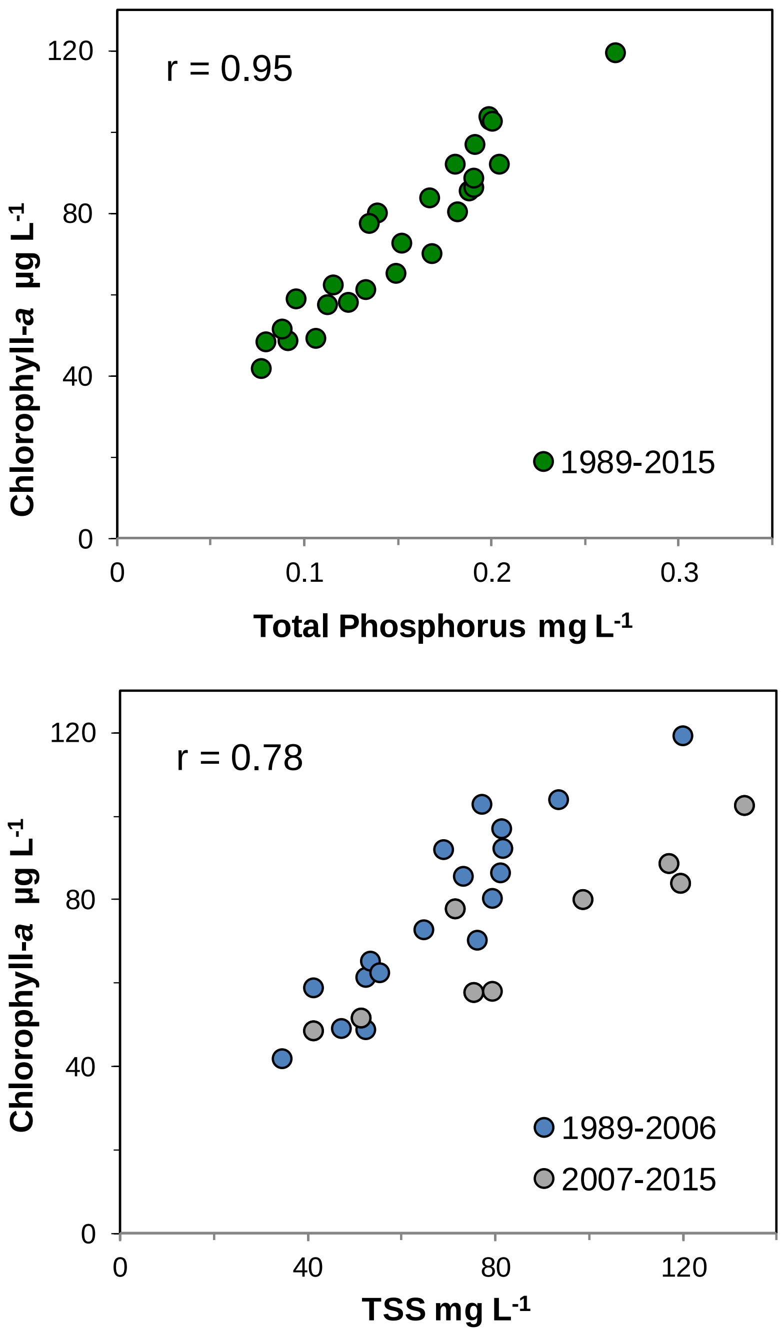

Figure 10. Top: Relationship between mean annual chlorophyll-*a* and mean annual TP in Lake Apopka. Bottom: Relationship between mean annual chlorophyll-*a* and mean annual TSS in Lake Apopka. For both data sets, Pearson's r indicates good linear correlation. Correlations are significant at $p < 0.001$.

We found a strong linear relationship between annual mean TP concentration and Chl-*a* concentration in Lake Apopka (Pearson's $r = 0.95$, $p < 0.001$) (Fig. 10, top). Declines and increases in TP over this 27-y data set were accompanied by similar changes in Chl-*a* without exception. This relationship supported our conclusion that continued reduction in TP concentrations will translate to continued reduction in phytoplankton biomass.

The Chl-*a*:TP ratio in Lake Apopka was lower and varied less with trophic state (e.g. TP concentration) than in downstream lakes in the Upper Ocklawaha River Basin (Table 1). For Lake Apopka, Chl-*a*:TP ranged from 0.47 to 0.58 for a range in TP concentrations. This same ratio ranged from 1.2 to 1.8 for a range in TP concentrations in downstream lakes (Table 1).

Much speculation has occurred about resuspension of sediments in Lake 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. The annual mean concentration of Chl-*a* varied more-or-less linearly with the concentration of TSS over a three-fold range in both variables (Pearson's $r = 0.78$, $p < 0.001$) (Fig. 10, bottom). Although the overall linear relationship is good, differences exist between earlier and later, drought years that show less Chl-*a* in relation to TSS (Fig. 10, bottom). This decline in the Chl-*a* content of TSS likely was related to the decline in TP content of TSS noted above, since Chl-*a* and TP covary closely (Fig. 10, top).

Cyanobacteria have dominated the phytoplankton in Lake Apopka based on biovolume since the start of District analyses in 1989, and *Planktolyngbya* has been the major genus (Fulton, unpublished). Phytoplankton vary in Chl-*a* content with a range for all taxa of about 0.5 – 2.0 % of dry weight (Reynolds 1984). For cyanobacteria, Reynolds (1984) included data for four taxa that averaged 1.2 %. Overall, Chl-*a* in Lake Apopka ranged from 0.07% to 0.14% of TSS. Even with the assumption that phytoplankton in Lake Apopka had low Chl-*a* content (0.5% of dry weight), phytoplankton would account for a minority (14% - 28%, median 22%) of TSS. Thus, Chl-*a* and TSS covary in Lake Apopka, but living algal biomass as represented by Chl-*a* does not appear to make up most of the TSS. One hypothesis that is consistent with these data is that much of the remaining TSS in Lake Apopka is algal detritus. In this scenario, TP reductions lower algal biomass (Fig. 10), and both the living algal biomass and algal detrital components of TSS decline, perhaps on different time scales. Declines in both algal biomass and other, possibly detrital, TSS will be important to produce improved light conditions for submersed vegetation. Here, the Marsh Flow-Way will play an important role due to its high efficiency for removal of TSS from inflowing lake water (Dunne et al. 2012).

TP*	Lake Apopka		Upper Ocklawaha lakes	
	Pred Chl-*a**	Chl-*a*:TP	Pred Chl-*a**	Chl-*a*:TP
50	NA	NA	61	1.2
75	43	0.58	116	1.6
100	54	0.54	183	1.8
200	95	0.47	NA	NA

* Concentration units µg/L

Table 1. Predicted Chl-*a* concentrations and Chl-*a*:TP ratios for a range of TP concentrations in Lake Apopka and downstream lakes. Linear (Lake Apopka, Fig. 10) and log-log (Upper Ocklawaha, Fulton & Smith 2008) equations fitted to annual mean Chl-*a* and TP values were used for predictions. NA: TP concentration outside range of prediction equation.

Beginning in 1995, small patches of native SAV, primarily eelgrass (*Vallisneria americana*) and muskgrass (*Chara* sp.), began to grow in the littoral zone of Lake Apopka after being almost absent for several decades (Fig. 11). Recovery was slowed by drought in 2001 – 2002, when many of these patches were exposed and damaged by low water levels. Submersed vegetation was limited again by low water and worsening water quality during drought in 2007 – 2008 but again recovered when water levels increased. By the time water levels declined in 2012, SAV had expanded to about 23 ha (57 acres) and was present in patches along much of the perimeter of the lake. SAV declined in area during this drought as well but showed greater resilience than previously. Declines were on the order of 40%, and SAV area expanded again with higher water levels in 2015 (Fig. 11).

District scientists have found SAV species colonizing all types of sediments in Lake Apopka including the soft, organic "muck" sediments that some have argued would preclude the establishment of rooted plants (Dobberfuhl et al. 2015). If lake levels remain within the typical fluctuation range, then we expect continued reduction in TP concentrations to approach the TMDL target of 0.055 mg P/L. Based on data to date, lower TP should result in lower phytoplankton Chl-*a* (Fig. 10), continued increases in Secchi transparency (Fig. 8), and further expansion of SAV.

Expanded SAV beds will provide improved habitat for fish and wildlife. At some point, expanded SAV will help to stabilize shallow sediments and reduce sediment-water nutrient recycling, which should increase net P sedimentation. SAV also will compete with phytoplankton for nutrients. All of these effects will provide positive feedback for further improvements in water quality and habitat conditions in Lake Apopka.

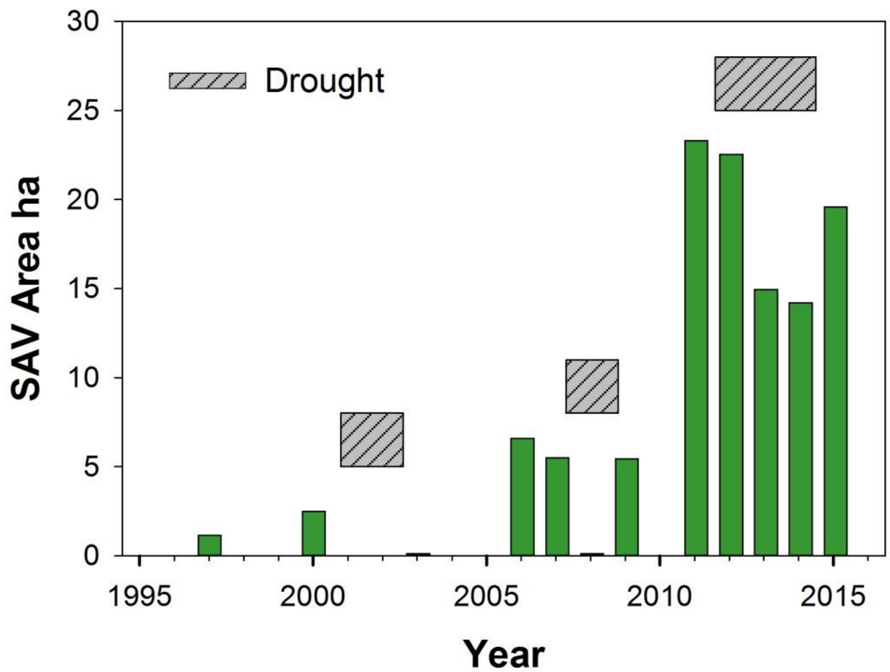

Figure 11. Colonization of littoral areas of Lake Apopka by native submersed aquatic vegetation (SAV). SAV in Lake Apopka consists mostly of eelgrass (*Vallisneria americana*) with some muskgrass (*Chara sp.*). Patches of Vallisneria were noticed first in 1995, and monitoring began in 1997. SAV area was negligible in 2003 and 2008 during or after droughts.

CONCLUSIONS

- The District's restoration program for Lake Apopka has reduced annual P loading to the lake from about 62 metric tons to an average of 11 metric tons for 2010 – 2014. P loading to Lake Apopka has met the total maximum daily load (TMDL) target (15.9 metric tons per year) in years during or following droughts. Further improvements to water management and P treatment on the Lake Apopka North Shore are needed to ensure that loading targets can be met in normal to wet years and that loading can be reduced further during low water periods to prevent hypereutrophic water quality. Steady-state models predict that Lake Apopka will meet the target TP concentration (0.055 mg P/L) when loading meets the TMDL target – if lake levels remain within normal ranges.
- Reduction in external P loading to Lake Apopka and removal of P from lake water resulted in improvements in key water quality indicators TP, Chl-*a*, and Secchi transparency. Neither internal recycling of sediment P nor wind-driven resuspension of sediments prevented improvements in these water quality metrics.
- Long-term changes in water quality in Lake Apopka largely are explained by three drivers: 1) improving trends due to reduced P loading and P removal, 2) cyclical oscillations since 2000 due to alternate periods of low and normal lake levels (and volumes), and 3) seasonal cycles.
- Calculation of water column masses of chemical constituents in addition to concentrations helped to minimize the confounding effects in analyses of changes in lake volume during droughts.
- TP and Chl-*a* concentrations in lake water declined along with reductions in P loading until 2000. Mass of TP in Lake Apopka declined in parallel with concentration until TP mass reached a low and quasi-stable level about 2000.
- Since 2000, extremely low lake stage during three droughts at 5 to 6-yr intervals resulted in periodic degradation of all water quality indicators. TP, TSS, TN, and Chl-*a* concentrations increased greatly at low lake levels both because their lake water masses were concentrated in a smaller volume and because the normal net sedimentation of TP to sediments was interrupted.
- Lake water masses of TSS and TN declined initially but then trended upwards from 2000 through 2015. Mass of particulate N increased proportionally to TSS, but particulate P did not. Therefore, suspended matter in Lake Apopka, increasing since 2000, maintained a similar N content but a lower P content than in prior years.
- Secchi transparency followed the same general pattern as TP, TSS, and TN – long-term improvements through 2000 and temporarily worsened conditions during subsequent periods of low lake level.

- Chl-*a* concentration in Lake Apopka showed a strong linear relationship with TP concentration. Continued reduction in TP concentrations should translate to continued reduction in phytoplankton biomass.
- Chl-*a* varied linearly with TSS concentration, although this relationship differed between earlier and later years. Most of the TSS was not living algal biomass, which suggests that algal detritus may be an important component.
- Native SAV began to recolonize the littoral zone of Lake Apopka in 1995 but almost was eliminated in subsequent droughts. By 2012, SAV had expanded to about 23 ha (57 acres). SAV declined during the most recent drought as well, but showed greater resilience than previously.
- Under current conditions, sustained improvements in TP, algal Chl-*a* transparency, and SAV will require sustained periods without the extreme low lake levels typical of the past fifteen years.

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APPENDIX A. SEASONAL TP PATTERNS IN LAKE APOPKA

A seasonal pattern in water quality has been evident in Lake Apopka in most but not all years of District monitoring. This pattern is illustrated with six years of TP data through one drought cycle (Fig. A-1). Generally, water quality tended to worsen in the winter/spring and improve in the summer/fall. This seasonality appeared to be due, in part, to lower net P sedimentation and possible sediment resuspension during winter/spring because of wind mixing from frontal events. However, the negative relationship between wind velocity and net P sedimentation was stronger in early years (1987 – 1995) than in later years (1996 – 2002) (Coveney et al. 2005).

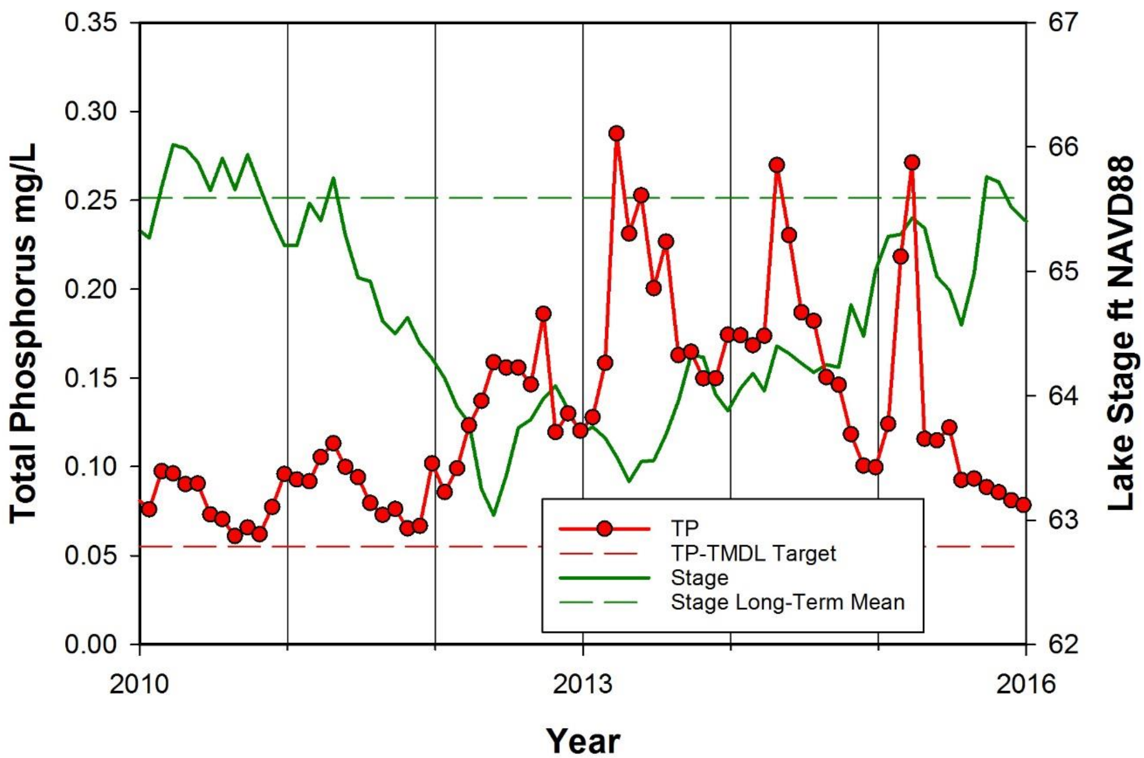

Figure A-1. Mean monthly values for total phosphorus (TP) concentration in Lake Apopka for the period 2010 – 2015. Mean monthly lake stage, long-term mean stage (1960 – 1990), and the TMDL target concentration for P are included.