

Chapter 10: Lake Okeechobee Protection Program – State of the Lake and Watershed

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SUMMARY

Given the central role of Lake Okeechobee in the regional aquatic ecosystem, and as the central water storage component in the Central and South Florida Flood Control Project, the *2005 South Florida Environment Report* (SFER) includes this chapter focusing on Lake Okeechobee. This chapter provides a general overview of the lake and its surrounding watershed, background material regarding the major issues impacting the lake's flora and fauna, and a summary of ongoing programs to address those issues with projects carried out under the Lake Okeechobee Protection Program.

Lake Okeechobee provides water supply for urban area, agriculture, and downstream ecosystems. It provides habitat for migratory water fowl, wading birds, a multi-million dollar recreational and commercial fishery, and the federally endangered Everglades snail kite. The lake currently faces three major environmental problems: (1) excessive phosphorus loads; (2) unnaturally high and low water levels; and (3) rapid spread of exotic and nuisance plants in the littoral zone. The South Florida Water Management District (District or SFWMD), Florida Department of Environmental Protection (FDEP), Florida Department of Agriculture and Consumer Services (FDACS), U.S. Army Corps of Engineers (USACE), and Florida Fish and Wildlife Conservation Commission (FWC) are working cooperatively to address these interconnected issues, in order to rehabilitate the lake and enhance the ecosystem services that it provides.

The excessive loads of phosphorus originate from agricultural and urban activities, which now dominate land use in the watershed. Phosphorus loading now averages 528 metric tons per year (five-year rolling average, 2000–2004), which is almost four times higher than a recently established Total Maximum Daily Load (TMDL) of the 140 metric tons per year considered necessary to achieve the target in-lake phosphorus concentration of 40 parts per billion (ppb). Although there is a long history of regulatory and other programs to control phosphorus inputs to the lake, there has not been any substantial reduction in loading in the last decade, and the lake displays signs of hyper-eutrophication, including blooms of noxious blue-green algae (cyanobacteria), loss of benthic invertebrate diversity, and spread of cattail in shoreline areas. As a result, the Florida Legislature passed the Lake Okeechobee Protection Act (LOPA) in 2000, mandating that the TMDL be met by 2015, and that the SFWMD, FDEP, and FDACS work together to implement an aggressive program to address the issues of excessive phosphorus loads and exotic species expansion. In concert, the SFWMD and USACE are implementing

components of the Comprehensive Everglades Restoration Program (CERP) that will address, in part, the phosphorus issue, and provide alternative storage locations so that water levels in the lake can be regulated in a manner that has greater environmental benefits, while still supporting water supply and other water resource functions.

The SFWMD, FDEP, and FDACS developed the Lake Okeechobee Protection Plan (LOPP), which lays out the major projects that will address the issues identified in the LOPA, and submitted it to the Florida Legislature in January 2004. These coordinating agencies are aggressively implementing the components of the plan, which include optimization of existing regulatory and best management programs, development and implementation of new Best Management Practices, improvement and restoration of hydrologic functions in natural and managed systems in the watershed, and use of alternative technologies for nutrient reduction. The Lake Okeechobee Watershed Project of CERP, which will provide substantial amounts of water storage and approximately 38.5 percent of the phosphorus load reduction needed to meet the TMDL, is moving forward on schedule. The SFWMD and FDACS have implemented a comprehensive program to monitor water quality in the watershed, which extends beyond the historical network of flow/load monitoring stations at basin outlet structures. Because the legislature has provided substantial funding for the implementation of the LOPA since 2000, the cooperating agencies have been able to implement a large number of phosphorus reduction projects, including source control grant programs for agricultural land owners, dairy best available technology pilot projects, soil amendment projects, isolated wetland restoration, remediation of former dairies, and regional public/private partnerships.

Conditions in Lake Okeechobee related to phosphorus inputs have not changed noticeably in the last decade because (1) external loads have remained high and (2) the lake sediments contain thousands of tons of phosphorus that buffer changes in water column total phosphorus (TP). The response of the lake to load reductions, when they occur, is expected to take 20 to 30 years because of this internal recycling. Water column TP now averages approximately 120 micrograms per liter ($\mu\text{g L}^{-1}$), or three times higher than the goal of $40 \mu\text{g L}^{-1}$ that was used to establish the TMDL. The ratio of total nitrogen to total phosphorus (TN:TP) averages 13:1, and the ratio of dissolved inorganic nitrogen to soluble reactive phosphorus (DIN:SRP) averages 5:1. These values favor dominance of blue-green algae, which presently account for most of the algal biomass in the lake. Water clarity goals in shoreline areas are attained approximately 30 percent of the time, and the targeted frequency for algal blooms is exceeded approximately threefold. Despite these problems and the knowledge that the lake response to load reductions will be slow, a multi-year sediment management feasibility study concluded that large-scale sediment management is not a feasible option for accelerating changes in water quality in this lake. This reflects the large size of the lake and the widespread distribution of a relatively thin layer of phosphorus rich mud on the bottom, along with associated engineering, economic, and ecological constraints.

During 2002–2004, water levels in the lake generally have been favorable for development of a diverse community of submerged aquatic vegetation (SAV) in the lake's shoreline areas, where plants were almost completely eliminated by high water in the late 1990s. Along with a resurgence of plants, key species of fish (e.g., largemouth bass) now are displaying successful recruitment. The SFWMD and USACE are in the process of refining the operating schedule for the lake in order to develop release rules that will be more favorable to sustaining these communities in the long term, while also not impacting downstream ecosystems with large discharges from the lake or impacting water supply. Until there are large alternative storage projects (completed by CERP sometime near 2010–2015), this is a difficult balancing act because the lake receives water from a large watershed, it provides the main source of irrigation water in

drought, and its major outlets are to estuarine systems that are impacted by large releases of fresh water. The SFWMD and USACE demonstrated success in 2003–2004 by using a flexible operating approach and intend to build on this in upcoming years.

In addition to the long-term programs, projects are occurring in the lake to restore natural habitats. The current focus is on three large islands at the south end of the lake, where former agricultural ditches and levees are being degraded to reestablish a more natural hydrologic connection with the lake. Work also has been done to remove organic tussocks that accumulated along the western shoreline during years of high water.

A critical component of the Lake Okeechobee Protection Program is a comprehensive program of water quality monitoring in the lake and watershed and ecological monitoring in the lake. There also is ongoing research and model development aimed at providing the predictive understanding necessary to effectively manage this water resource. Like CERP, the Lake Okeechobee Protection Program is an adaptive program, meaning that if responses are not occurring as expected, or if research and demonstration elucidates important new information, restoration programs can be modified accordingly to optimize their effectiveness.

INTRODUCTION

Lake Okeechobee (located at 27° N Latitude and 81° W Longitude) is a central feature of the interconnected South Florida aquatic ecosystem and the U.S. Army Corps of Engineer's (USACE's) regional flood control project. The lake receives water from the Kissimmee River, Lake Istokpoga, Fisheating Creek, and other sub-basins, and water from the lake flows into the Everglades Protection Area, the St. Lucie River, and the Caloosahatchee River. Although Lake Okeechobee has a surface area in excess of 1,730 km², it is extremely shallow, with mean and maximal depths of 2.7 m and 5.5 m, respectively (James et al., 1995a). The lake originated approximately 6,000 years ago during oceanic recession (Gleason and Stone, 1975), and under natural conditions (**Figure 10-1**) is considered to have been moderately eutrophic (Brezonik and Engstrom, 1998) and considerably larger in spatial extent, with vast littoral wetlands to the west and south (Havens et al., 1996a). The southern littoral region was contiguous with the Florida Everglades and during periods of high rainfall, water may have flowed from the lake to the Everglades as broad sheet flow (Steinman et al., 2001). Modern-day Lake Okeechobee differs in size, range of water depths, connections with other parts of the regional system, and water quality (Havens et al., 1996a; Steinman et al., 2001). The lake presently receives water from a 10,400-km² watershed (**Figure 10-2**), with headwaters in a chain of lakes located to the north, near the City of Orlando, FL.

Although all lakes provide services to nature and society (Postel and Carpenter, 2001), Lake Okeechobee is probably at the extreme end of the continuum in terms of the number of services that it provides, the diversity of users, and the tremendous economic interest in its health and fate. The lake provides water supply to urban areas, agriculture, and downstream ecosystems, it supports a multi-million dollar sport fishery (Furse and Fox, 1994), a commercial fishery, various recreational activities, and it provides habitat for migratory waterfowl, wading birds, alligators, and the Everglades snail kite (Aumen, 1995). The lake currently faces three major environmental problems: (1) excessive phosphorus loads; (2) unnaturally high and low water levels; and (3) rapid spread of exotic and nuisance plants.

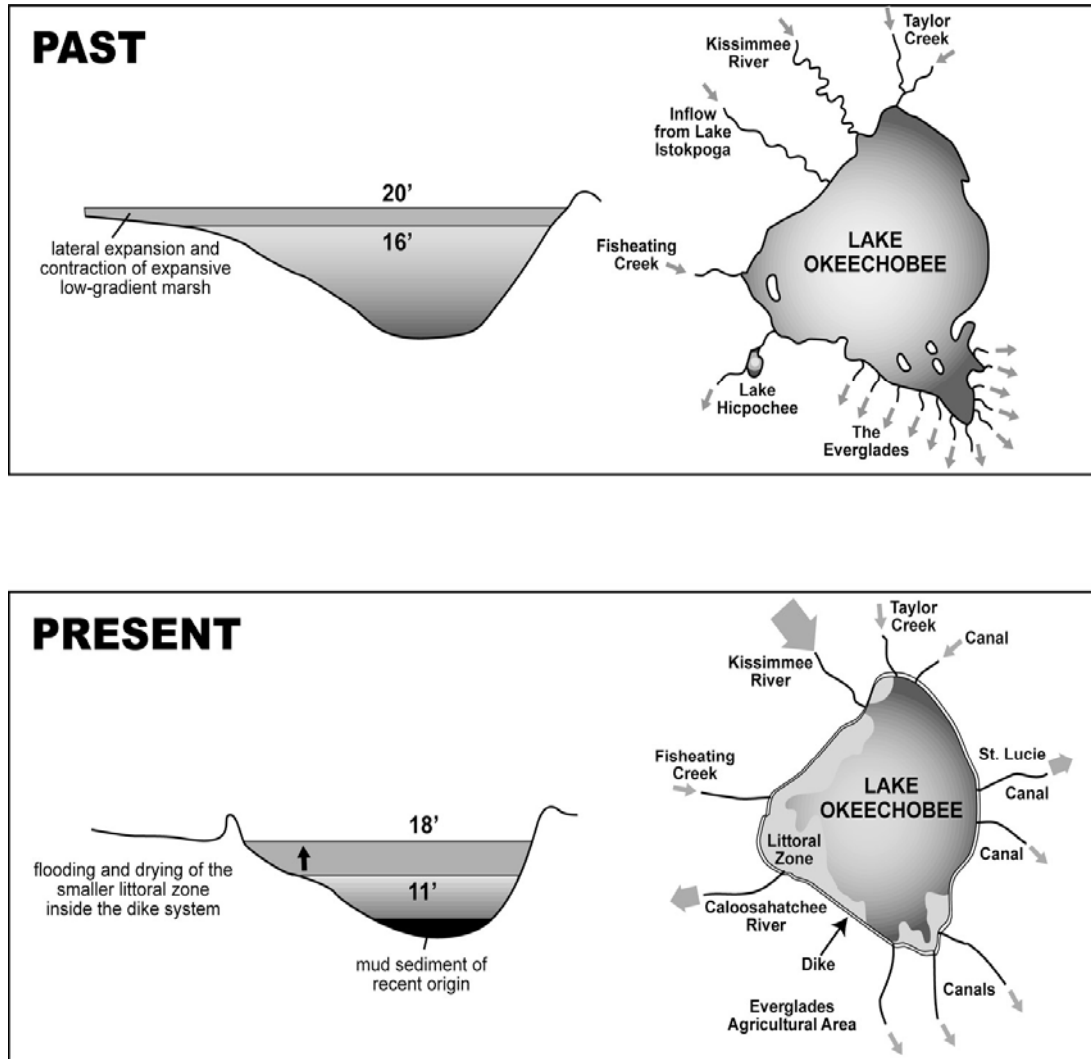


Figure 10-1. Schematic diagrams of Lake Okeechobee showing past versus present morphometric and hydrologic conditions of the lake and surrounding lands. Depth is highly exaggerated in the side view of the ecosystem.

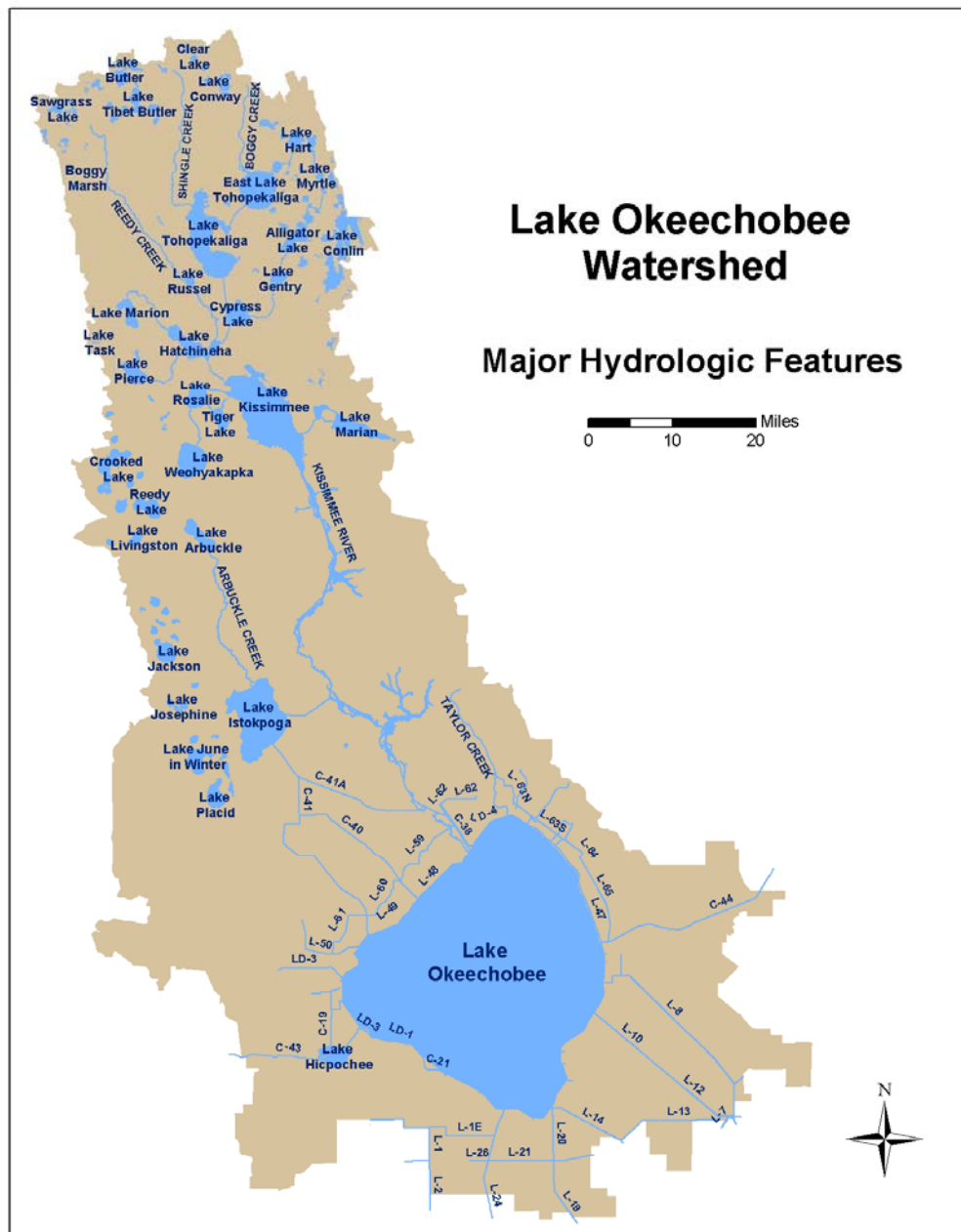


Figure 10-2. Major hydrologic features of the Lake Okeechobee watershed.

In regard to the water quality issue, the focus on phosphorus as the main chemical stressor is supported by a wealth of information in the peer-reviewed literature. However, it should be noted that the SFWMD does sample more than 20 other chemical constituents, including total and dissolved nitrogen, alkalinity, cations and anions, and certain metals. Much of this sampling is mandated under the Clean Water Act because the lake is classified as a drinking water reservoir, and changes in concentrations of certain elements (such as calcium) have been helpful in understanding observed trends in the lake's phosphorus cycle.

Excessive inputs of phosphorus originate from agricultural and urban activities, which now dominate the land use in the watershed. Phosphorus loading rates are approximately four times higher than has been determined necessary to protect the ecosystem (FDEP, 2000). The main symptoms of excessive phosphorus loading include: increased frequency and intensity of nitrogen-fixing cyanobacteria (blue-green algae) blooms (Havens et al., 1995; 2003), loss of taxonomic diversity and extreme dominance by pollution-tolerant benthic invertebrates (Warren et al., 1995), reduced water column transparency, which contributes to a reduced spatial extent of SAV in shoreline areas (Havens, 2003), and spread of cattail (*Typha* spp.) in the lake's littoral zone (Havens and Schelske, 2001). It is well-established from observational and controlled experimental research that the lake's phytoplankton now is limited by nitrogen, rather than phosphorus, due to the long history of high phosphorus loading (Aldridge et al., 1995; Havens, 1994 and 1995a; Havens and Schelske, 2001). A large number of past and present phosphorus control programs have been implemented in the lake's watershed in order to reduce the excessive loads (these programs are described in detail in Flaig and Havens [1995] and SFWMD [2002]). They included the Lake Okeechobee Works of the District (LOWOD), a permitting program applied to all non-dairy land uses by the South Florida Water Management District (District or SFWMD), with numeric standards for phosphorus discharge, and the Dairy Rule, a technology-based program administered by the Florida Department of Environmental Protection (FDEP).

Recognizing that existing programs were not sufficiently reducing phosphorus loads to the lake, and that the lake was displaying increasing symptoms of cultural eutrophication, the Florida Legislature passed the Lake Okeechobee Protection Act [LOPA; Section 373.4595(3), Florida Statutes (F.S.)] during the 2000 session. The law established a comprehensive long-term program to rehabilitate and protect Lake Okeechobee and its downstream receiving waters. The legislature initially appropriated \$38.5 million for the program, and has continued to provide substantial funding. The program now is also funded as a high priority item by the SFWMD from its *ad valorem* budget. The LOPA requires significant involvement and cooperation among the SFWMD, FDEP, Florida Department of Agriculture and Consumer Services (FDACS), U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS), and University of Florida Institute for Food and Agricultural Sciences (UF-IFAS) to implement the program. The LOPA is similar in scope and approach to the Everglades Forever Act (EFA), involving major new programs in planning, construction of major public treatment projects, new Best Management Practice (BMP) and permitting requirements, and specific research and modeling mandates.

The LOPA also mandates that the rate of phosphorus loading to Lake Okeechobee be reduced to a long-term (five-year) rolling average of 140 metric tons per year (mt y^{-1}) by 2015. This is a loading rate identified in the Total Maximum Daily Load (TMDL) rule for Lake Okeechobee (FDEP, 2001); it includes 105 mt y^{-1} from the watershed, and an estimated 35 mt y^{-1} from atmospheric deposition on the lake. The LOPA also requires aggressive programs to control exotic plants and a long-term program of water quality and ecological assessment, research, and predictive model development. A more detailed overview of the LOPA and its associated planning document, the LOPP, is provided below, and an annual update on projects being conducted under that program is provided in Chapter 3 of the *2005 South Florida Environmental Report – Volume II* (2005 SFER).

The second major issue for Lake Okeechobee is its water level. The lake is encircled by a 10.4 m high earthen levee that was built in the first half of the twentieth century in response to catastrophic hurricanes that caused thousands of human deaths in the late 1920s (Steinman et al., 2001). Today all inflows but one (Fisheating Creek, on the western shore) and all outflows are controlled by gates and locks, and lake stage is controlled in part by a USACE 1999 regulation schedule. The schedule determines the timing and quantity of water to be released from the lake when the stage exceeds a defined level that varies by season, antecedent hydrologic conditions, and long-range climate forecast. The schedule has been changed over time to reflect changing philosophies. The current schedule was adopted in 2000 and was designed to be more responsible to environmental needs of the lake and downstream ecosystems. However, the schedule is under constant scrutiny and was modified in 2003–2004 by a temporary deviation designed to increase discharge amounts to achieve a lowered lake stage. This issue is further elaborated below.

The third stressor impacting the ecosystem is rapid expansion of exotic and nuisance plants in the lake's 430-km² littoral zone. Approximately 20 percent of this habitat has been overtaken by melaleuca (*Melaleuca quinquenervia*), torpedograss (*Panicum repens*), and Brazilian pepper (*Schinus terebinthifolius*). Melaleuca is a native tree of Australia, and torpedograss is a pasture grass native to Europe. Both were intentionally planted in the vicinity of the lake, and both rapidly colonized the littoral zone. The SFWMD and other agencies are actively engaged in programs to eradicate melaleuca, torpedograss, and Brazilian pepper from the littoral zone. One issue regarding torpedograss is that both its rate of expansion and the effectiveness of control measures (fire and herbicide) are linked to water level – both are enhanced when lake stage is low, drying out areas of the marsh – exposing new areas to expansion but also allowing for effective treatment of dense monocultures.

This chapter briefly summarizes the LOPA and then provides a comprehensive update of watershed and lake conditions, focusing on two of the issues identified above, phosphorus and water levels. Results of recently completed research projects are presented, as well as status updates for ongoing watershed and in-lake management projects. Project timelines, information about funding sources, and other aspects of project planning are covered in Chapter 3 of the 2005 SFER – Volume II. Information regarding exotic plant control programs and associated research projects to optimize those programs are presented in Chapter 9 of the 2005 SFER – Volume I.

LAKE OKEECHOBEE PROTECTION PROGRAM OVERVIEW

The Lake Okeechobee Protection Program, which was authorized in the Lake Okeechobee Protection Plan in 2000, includes seven elements, as discussed below.

LAKE OKEECHOBEE PROTECTION PLAN

The SFWMD, in cooperation with the FDEP and FDACS, developed the Lake Okeechobee Protection Plan (LOPP), which was submitted to the Florida Legislature on January 1, 2004. The LOPP describes in detail how water quality standards, particularly for phosphorus, will be met in Lake Okeechobee and its downstream receiving waters by 2015. The LOPP includes a combination of source controls (e.g., BMPs), as well as subregional water treatment facilities that will be constructed by the SFWMD and its partners. An integral part of the plan is coordination with the Lake Okeechobee Watershed Project of the Comprehensive Everglades Restoration Plan (CERP). The anticipated trajectory of total phosphorus (TP) load reductions resulting from implementation of the LOPP is shown in **Figure 10-3**. Details of the plan are provided below and in Chapter 3 of the 2005 SFER – Volume II. The LOPP also addresses exotics control, sediment management options, alternative nutrient reduction technologies, long-term lake restoration assessment, and research and modeling needs.

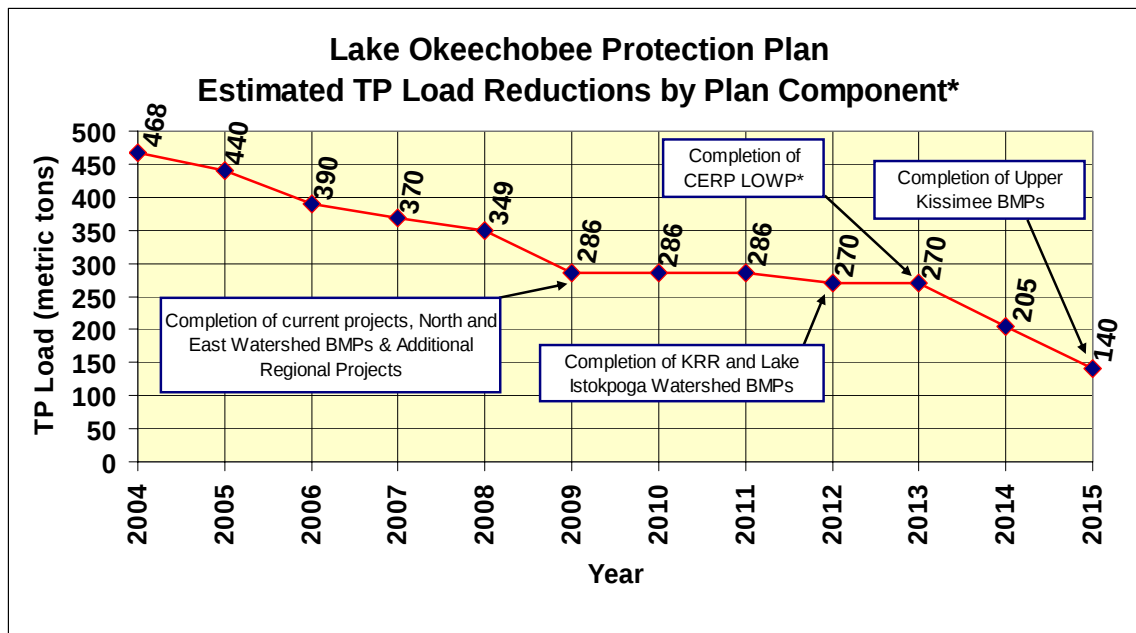


Figure 10-3. Anticipated trajectory of total phosphorus (TP) loads from 2004–2015, with timing of completion for major components of the Lake Okeechobee Protection Plan indicated. These anticipated reductions in loading are based on current watershed activities. The actual load reductions, as measured at the lake inflow structures, may be delayed due to historical phosphorus in soils and tributaries.

WATERSHED PHOSPHORUS CONTROL PROGRAM

The Lake Okeechobee Watershed Phosphorus Control Program is designed to be a multifaceted approach that includes continued implementation of existing regulations and voluntary agricultural and non-agricultural BMPs, development and implementation of improved BMPs, improvement and restoration of hydrologic function of natural and managed systems, and utilization of alternative technologies for nutrient reduction. In February 2001, the SFWMD, FDEP, and FDACS entered into an interagency agreement to address how to implement the programs and coordinate with existing regulatory programs [Lake Okeechobee Works of the District (LOWOD), Dairy Rule, and Everglades Forever Act (EFA) restoration programs]. Under the legislation, the FDACS is charged with implementing a voluntary BMP program on all agricultural lands within the Lake Okeechobee watershed, starting with four basins (S-191, S-65D, S-65E, and S-154) north of the lake that are considered a priority because of their intensive agricultural activities and high phosphorus loads (**Figure 10-4**). The FDACS implementation program for BMPs (**Figure 10-5**) has two phases. The first phase is implementation of interim BMPs based on assessments contained in existing cow-calf and citrus water quality BMP manuals. The second phase involves development of more detailed conservation and nutrient management plans. For agricultural land uses not addressed in a water quality BMP manual (e.g., dairy farms and row crop operations), such properties are immediately addressed under the process in the second phase. In both phases, property owners are required to (1) maintain BMPs as implemented, (2) keep appropriate records, and (3) submit to periodic verification inspections by the FDACS. If water quality problems persist where BMPs have been implemented, then the FDACS will reevaluate the agricultural BMPs and make appropriate changes to the rule to adopt additional BMPs.

Development of non-agricultural non-point source BMPs will be the responsibility of the FDEP. The FDEP will also implement a phased approach on non-agricultural lands. The first phase was to implement interim measures/BMPs such as University of Florida - Institute of Food and Agricultural Sciences (UF-IFAS) lawn fertilization rates, UF-IFAS turf grass BMPs, and other practices identified in the Florida Land Development Manual. The next phase is to develop more detailed stormwater and wastewater plans within the urbanized areas in the watershed. There are currently no urban areas in the four priority basins, so the focus has been on the cities surrounding the lake. Stormwater retrofits, such as detention/retention facilities, swales and sediment traps are components of the plans. Investigations conducted in support of the protection plan estimate that the implementation of typical suites of BMPs for agricultural and non-agricultural land uses can provide a 25-percent reduction in loading to the lake (Bottcher and Harper, 2003). Phosphorus reductions will also be seen by replacing septic tanks and failing package plants with central sewer systems. The FDEP has also required that the land application of wastewater residuals and septage be based on agronomic rates of phosphorus instead of nitrogen.

Investigations conducted in support of the LOPP estimate that the implementation of a typical suite of agricultural and non-agricultural BMPs can provide a 25-percent reduction in loading to the lake (Bottcher and Harper, 2003). Under the LOPP, the SFWMD and FDEP need to monitor the effectiveness of BMPs and develop alternative nutrient reduction technologies if the anticipated reductions in loading are not achieved.

The SFWMD, in coordination with the FDACS and FDEP, has developed and implemented 22 phosphorus reduction projects and has more than 40 projects under construction or in the planning/design phase (**Figure 10-6**). These projects were implemented under programs such as the Phosphorus Source Control Grants, Isolated Wetland Restoration, Dairy Best Available

Technologies, Public/private partnerships, Former Dairy Remediation, and Structure Retrofit and Tributary Dredging. Additional information regarding these projects can be found in Chapter 3 of the 2005 SFER – Volume II. Load reduction from these other phosphorus reduction projects is estimated at 18 percent of the load reductions necessary to meet the lake's TMDL.

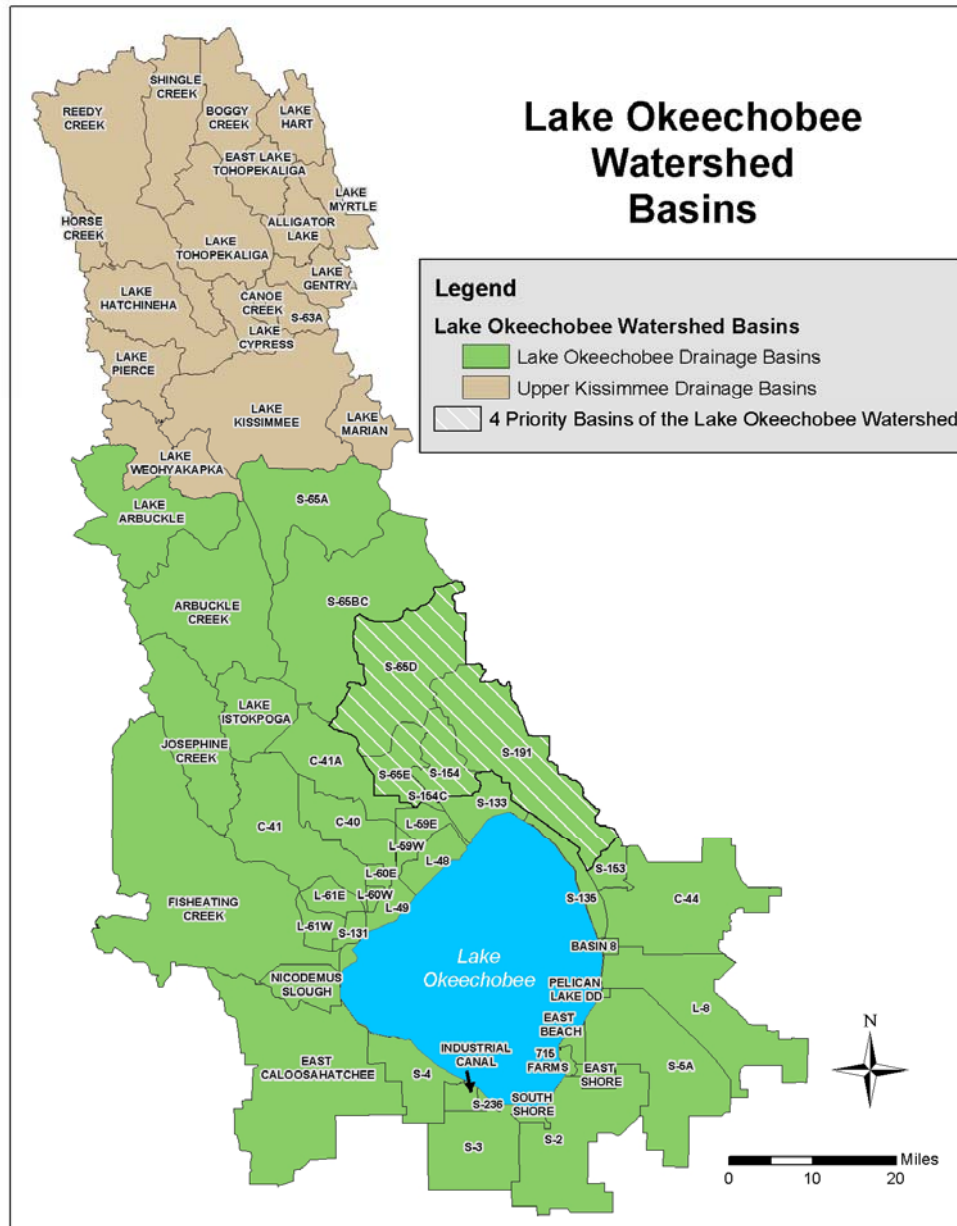


Figure 10-4. Tributary drainage basins in the Lake Okeechobee watershed.

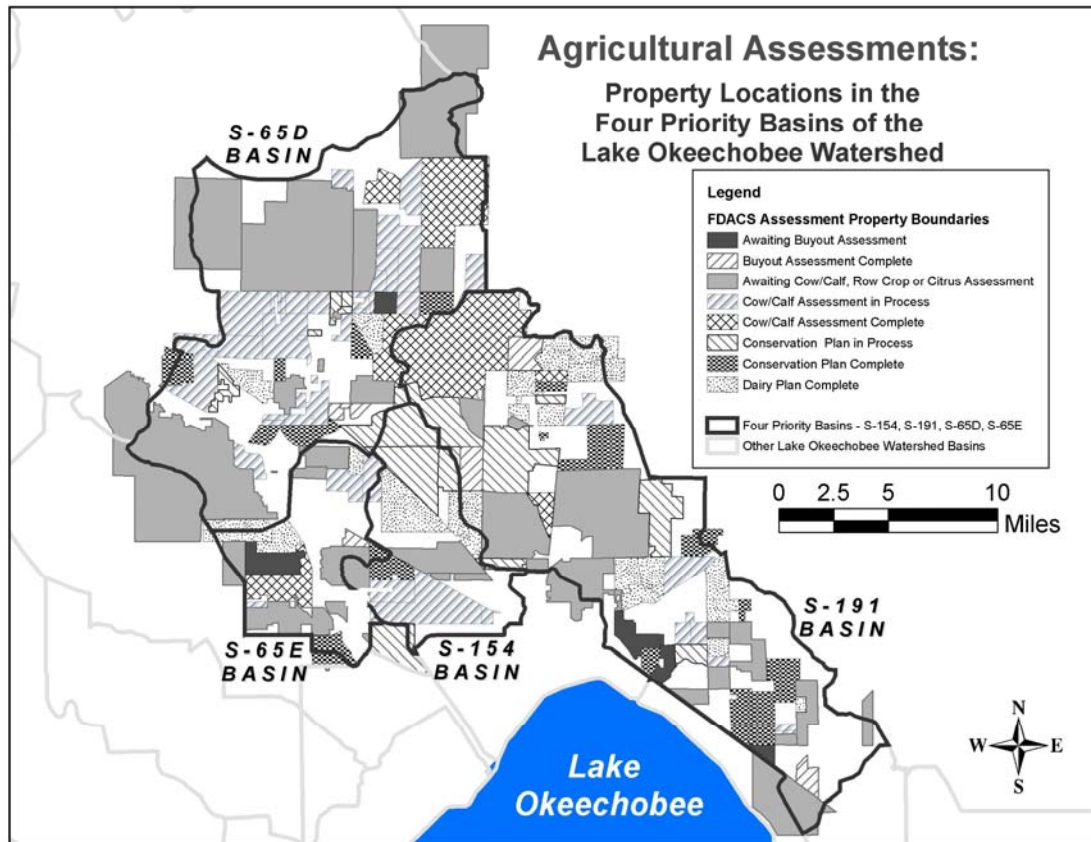


Figure 10-5. Florida Department of Agriculture and Consumer Services (FSACS) assessment program property boundaries.

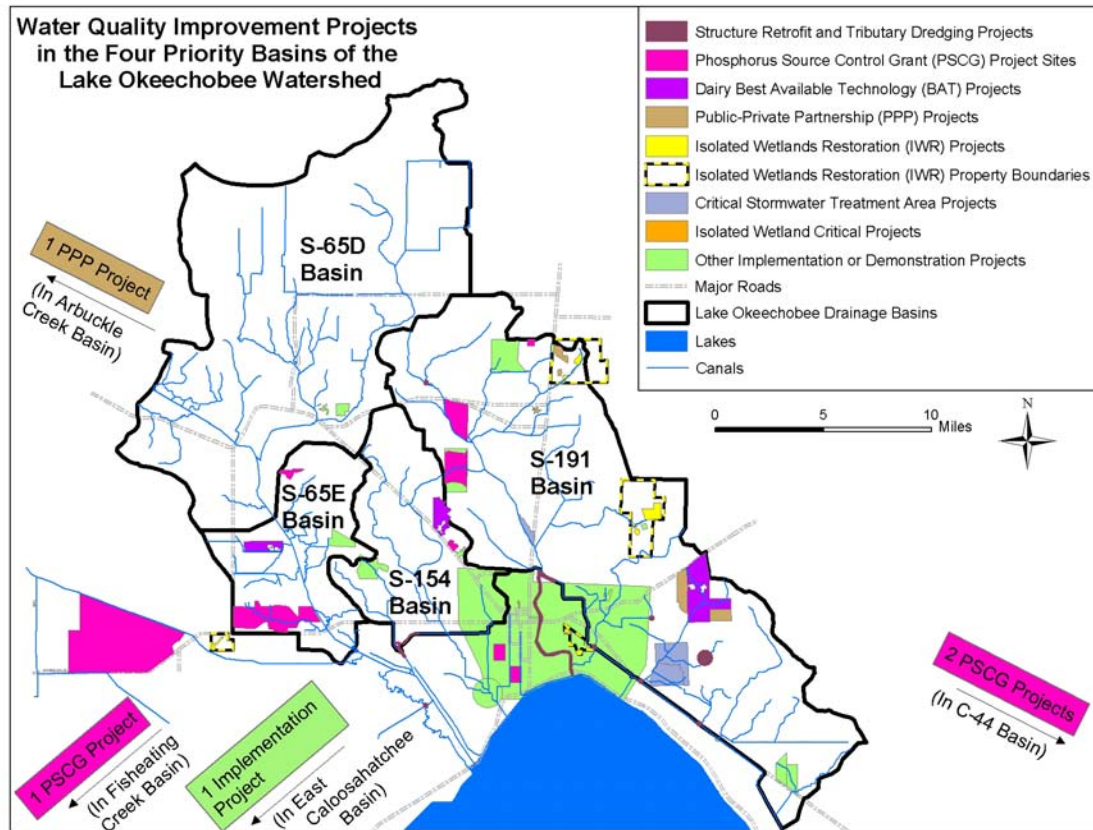


Figure 10-6. Water quality improvement projects in the Lake Okeechobee watershed, with color codes corresponding to project type. Note that five projects are located outside of the priority basins.

LAKE OKEECHOBEE CONSTRUCTION PROJECT

The Lake Okeechobee Construction Project is being implemented in two phases. In Phase I, projects are being constructed in the four priority basins, including two pilot stormwater treatment areas, the construction of a stormwater detention pond as part of the Lake Okeechobee Critical Projects (a joint program between the SFWMD and USACE), a sediment removal pilot project, and design work on a large-scale Stormwater Treatment Area (STA) in the S-191 basin.

In the plan, Phase II is identified as the Lake Okeechobee Watershed Project (LOWP) of CERP, which includes a variety of projects that account for 38.5 percent of the phosphorus load reduction needed to meet the TMDL target of 140 metric ton y^{-1} . The major features of the initial conceptual plan for the LOWP include the following:

- **Taylor Creek/Nubbin Slough (S-191 Basin) Reservoir-assisted Stormwater Treatment Area:** Estimated to be a 5,000-acre storage reservoir and a 5,000-acre wetland treatment area

- **North of Lake Storage Area:** An estimated 17,500-acre storage reservoir and 2,500-acre wetland treatment area
- **Lake Okeechobee Water Quality Treatment Facilities:** Additional 1,775-acre reservoir-assisted STA in the S-154 basin, 2,600-acre wetland treatment area in the S-65D basin, and plugged drainage ditches that will result in restoration of approximately 3,500-acres of wetlands in the watershed
- **Tributary Sediment Control:** Capture or removal of phosphorus-laden sediment in tributaries to prevent it from reaching the lake

At this time, the LOWP is in the plan formulation phase that will identify size, location, and operating strategies for project features that will meet the project goals in the most cost-effective manner. Information regarding the LOWP is updated on a regular basis on the District's Website at http://www.evergladesplan.org/pm/projects/proj_01_lake_o_watershed.cfm.

RESEARCH AND WATER QUALITY MONITORING PROGRAM

The SFWMD, in cooperation with the FDEP and FDACS, has implemented a comprehensive research and water quality monitoring program for the lake and watershed. Water quality and ecological baseline data are being collected, and long-term assessment will continue through the life of the program. Assessment focuses on quantifying trends in specific performance measures with quantitative targets, which are described in detail in later in this chapter. Other components of this program include (1) development of a Lake Okeechobee water quality model; (2) identification of phosphorus sources within the watershed; (3) assessment of phosphorus sources to the watershed from upstream, specifically from the Upper Kissimmee Chain of Lakes and Lake Istokpoga basins; (4) assessment of water management practices within the watershed; and (5) evaluation of feasibility of alternative nutrient removal technologies.

EXOTIC SPECIES CONTROL PLAN

The SFWMD, in cooperation with the FDEP and FDACS, has developed an exotic species control plan for the lake and watershed. This plan was developed to protect native flora and fauna in the region. Additional information on exotic species is described in Chapter 9 of the 2005 SFER – Volume I.

INTERNAL PHOSPHORUS MANAGEMENT PROGRAM

The LOPA required a study to examine the engineering, ecological, and economic feasibility of removing or treating Lake Okeechobee sediments to reduce internal phosphorus loading. If this was determined to be feasible, then the SFWMD is directed to develop an Internal Phosphorus Management Program. The feasibility study was completed in 2003, and it was determined that sediment removal would not be effective in reducing internal phosphorus loading. Results of this study are described in further detail later in this chapter.

ANNUAL PROGRESS REPORT

The SFWMD is required to submit an annual progress report on implementation of the LOPA and LOPP to the Governor of Florida and the Florida Legislature. Previous stand-alone reports were annual submitted on January 1 from 2001 through 2004. The 2005 Annual Progress Report is included in Chapter 3 of the 2005 SFER – Volume II.

WATERSHED STATUS, MANAGEMENT, AND RESEARCH

WATERSHED STATUS

The continuous population influx and agricultural development in South Florida are causing rapid changes in regional land use, including the Lake Okeechobee watershed. Therefore, periodic land use updates are required to support planning and management activities. The most recent land use maps were developed in 2000–2001 based on the U.S. Geological Survey (USGS) National High Altitude Photography and the National Aerial Photography Program (**Figure 10-7**). To the north of the lake, the major land use is for improved pasture for beef cattle grazing; to the south the major land use is for sugar cane. Citrus groves also represent a large land use to the northwest. Although they do not represent a large use of land, dairy farms that occur directly to the north of the lake represent a significant source of phosphorus to some tributaries and up to 8 percent of the total loading to the lake.

Surface water discharges and phosphorus loading rates from the major tributary basins were calculated for Water Year 2004 (WY2004) (May 1, 2003 through April 30, 2004) (**Table 10-1**). Data are based on continuous flow monitoring stations (**Figure 10-8**) and total phosphorus (TP) samples collected on a daily basis by auto-samplers at those same locations. Among the major tributary basins, the largest surface water inflow comes from the Kissimmee River, followed by Fisheating Creek and Taylor Creek/Nubbin Slough. Total amounts of surface inflow to the lake vary considerably from year to year (lake water budget presented below). However, the relative magnitude of inflow from the various tributary basins generally follows the indicated pattern. Taylor Creek/Nubbin Slough has the highest yearly input of TP loads to the lake, followed by Basins A through E along the Kissimmee River, Fisheating Creek, and C-41 and S-154 basins. There are large inputs of phosphorus to the watershed from Lake Istokpoga and the Upper Kissimmee Chain of Lakes, and some of this phosphorus travels downstream to Lake Okeechobee. Atmospheric deposition is considered to bring a constant 35 mt y^{-1} of phosphorus directly to the lake surface, with an approximately equal amount as wet and dry fallout (FDEP, 2001; Pollman et al., 2002). The TP load to the lake in WY2004 from all tributary basins and atmospheric deposition was 548 mt. The five-year rolling average TP load from 2000–2004 was 528 mt, which is almost four times higher than the 140 mt y^{-1} TMDL for phosphorus.

The SFWMD conducts a detailed inventory of imports and exports of phosphorus loads from the watershed. This inventory was updated most recently by Hiscock et al. (2003). They considered all imports, including fertilizer, feed and animals, and exports, including surface water runoff, milk, harvested crops, and animals for the northern watershed of Lake Okeechobee. The study area encompassed lands from Fisheating Creek north to Basin S-65A and east to Taylor Creek/Nubbin Slough. This large area accounts for a large percentage of the TP loading to Lake Okeechobee (**Table 10-1**). The net import of phosphorus (import minus export) was $1,717 \text{ mt y}^{-1}$, representing a 28-percent decline since the previous inventory in 1991 (Fonyo et al., 1991). The change was attributed to reduced net imports for dairy farms (decline from 1,170 to 458 mt y^{-1}) and improved pasture (decline from 1,010 to 559 mt y^{-1}). Dairy net imports declined because there were fewer dairy cows in 2003, and because of changes in dairy management practices. Improved pasture net imports declined due to lower fertilizer application rates. In contrast, there was an increase in net phosphorus import for row crops (from 72 to 545 mt y^{-1}), over the same time period, reflecting a fivefold increase in that particular land use. Overall, 83 percent of the net phosphorus import was stored in the watershed, with only 17 percent entering the lake. This relative storage is seven percent lower than what was reported in 1991. Hiscock et al. (2003) concluded that this was a result of reduced assimilative capacity of soils and wetlands for phosphorus in the Lake Okeechobee watershed. The authors also concluded that phosphorus loads to the lake could be appreciably reduced by a reduction in net phosphorus imports to the

tributary basins. A multiple regression model that considered net phosphorus import, plus the total length of streams, canals, and wetlands between the basin and the lake accounted for 80 percent of the variation in phosphorus loading rates among the basins included in this survey ($n = 25$).

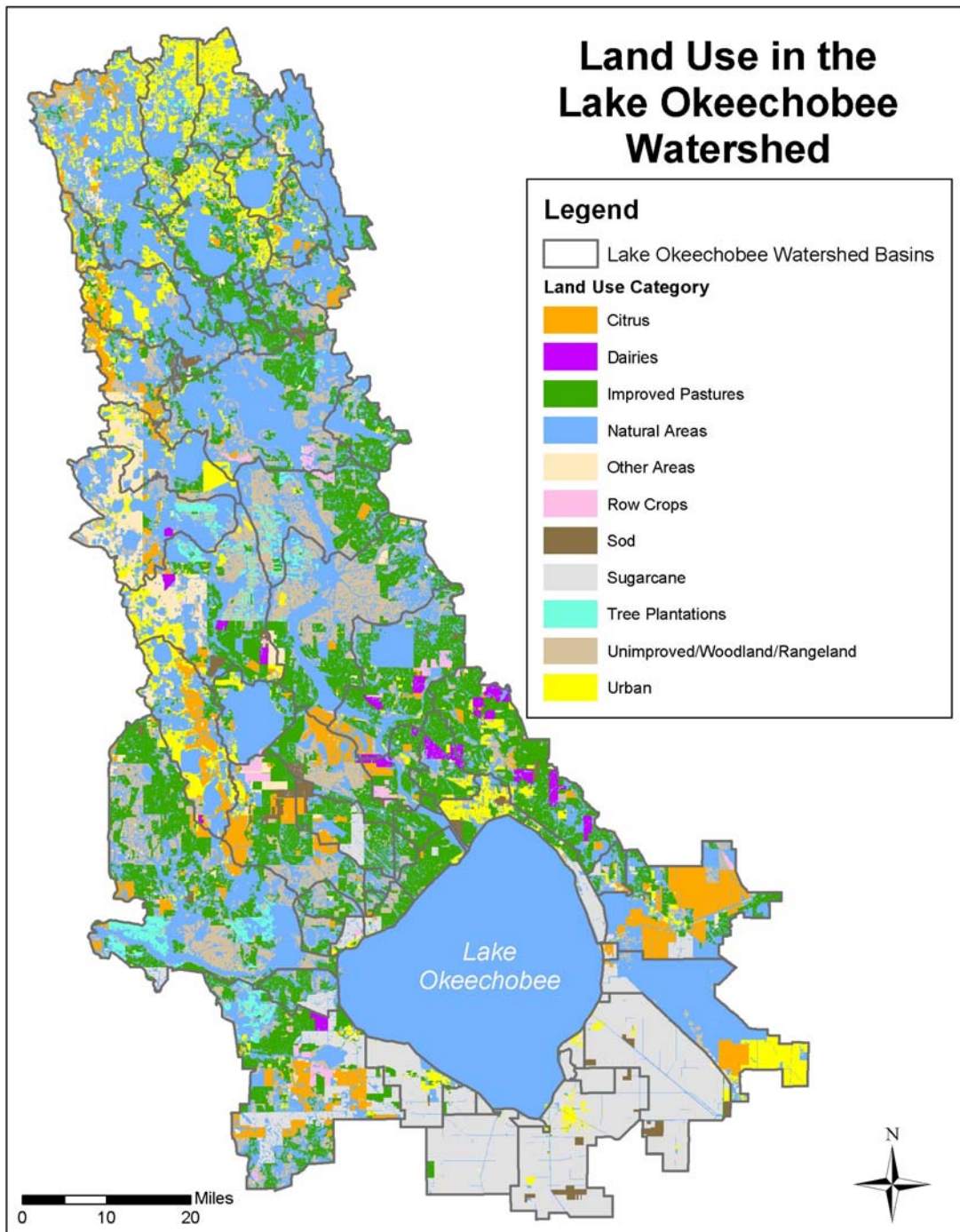


Figure 10-7. Land use map for the Lake Okeechobee watershed (2000–2001).

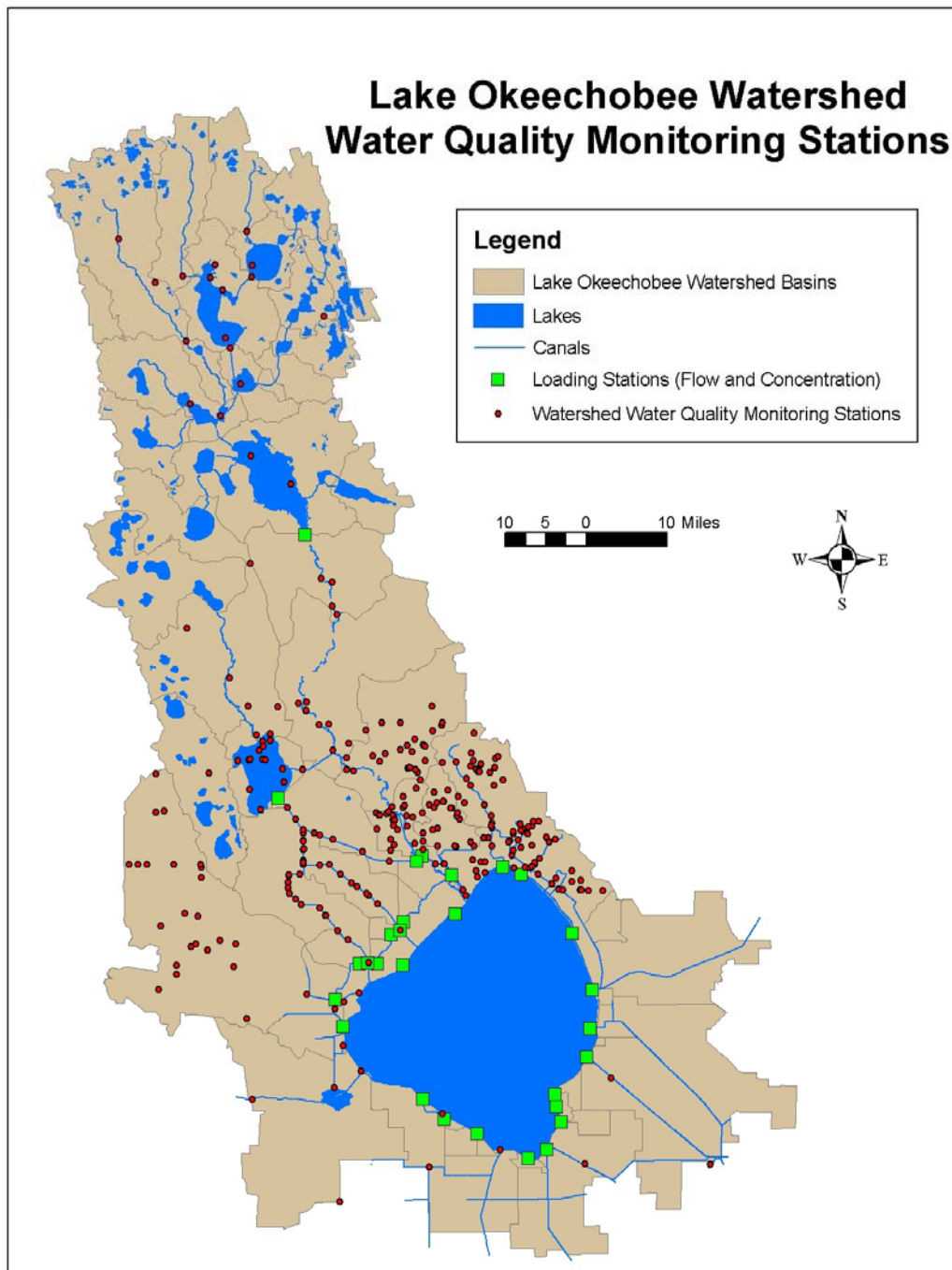


Figure 10-8. Location of sampling stations where TP loads are determined from tributary basins that drain into Lake Okeechobee (green squares). The program also includes stations to measure loads exiting Lakes Kissimmee and Istokpoga. Knowing these loads is essential to calculating phosphorus inputs occurring in the downstream basins. Other watershed water quality sampling stations also are shown (red dots).

Table 10-1. Surface water inflows and TP concentrations and loading rates for the major tributary basins in the Lake Okeechobee watershed for Water Year 2004 (WY2004) (May 1, 2003 to April 30, 2004). The acronym 'na' is used where data are not currently available. The acronym 'nc' indicates that samples were not collected due to lack of flow.

Source	Discharge ac-ft	Discharge million m ³	Area (km ²)	TP Concentration µg/L	TP Load Metric tons
715 Farms (Culv 12A)	0	0	2	nc	0
C-40 Basin (S-72) - S68	19,788	24	34	242	14
C-41 Basin (S-71) - S68	55,174	68	68	249	40
S-84 Basin (C41A) - S68	69,663	86	69	81	16
S-308C (St. Lucie-C-44)	0	0	73	nc	0
East Beach DD (Culv 10)	265	< 1	4	150	0
East Shore DD (Culv 12)	470	1	5	61	0
Fisheating Creek	246,117	304	178	163	50
Industrial Canal	13,903	17	9	202	3
L-48 Basin (S-127 total)	0	0	12	nc	0
L-49 Basin (S-129 total)	18,850	23	7	82	2
L-59E	62,773	77	6	149	12
L-59W	40,636	50	6	447	22
L-60E	7,353	9	2	199	2
L-60W	1,731	2	2	233	0
L-61E	7011	8.6	9	na	na
L-61W	10669	13.2	9	na	na

Table 10-1. Continued.

Taylor Creek/Nubbin Slough (S-191)	89,663	111	73	644	71
S-131 Basin	9,834	12	4	106	1
S-133 Basin	4,116	5	15	187	1
S-135 Basin (S-135 total)	32,077	40	11	66	3
S-154 Basin	27,032	33	14	534	18
S-2	211	< 1	64	199	0
S-3	261	< 1	39	217	0
S-4	19,455	24	26	183	4
S65E - S65	585,265	722	289	23	102
South FL Conservancy DD (S-236)	15,304	19	6	115	2
South Shore/South Bay DD (Culv 4A)	5,534	7	3	85	1
Nicodemus Slough (Culv 5)	3,344	4.1	11	na	na
Rainfall	--	--	--	--	35
S65 (Lake Kissimmee)	1,193,111	1,472	616	71	104
Lake Istokpoga (S-68)	401,617	495	238	85	42
S5A Basin (S-352-WPB Canal)	0	0	73	nc	0
East Caloosahatchee (S-77)	0	0	121	nc	0
L-8 Basin (Culv 10A)	26,520	33	65	65	2
Totals	2,967,745	--	--	--	549

WATERSHED MANAGEMENT

In 1987, the Florida Legislature passed the Surface Water Improvement and Management (SWIM) Act (Chapters 373.451 and 373.4595, F.S.), directing the state's five water management districts to develop and implement plans to preserve, protect, enhance, and restore priority water bodies within their respective jurisdictions. In 1989, the SFWMD produced the Lake Okeechobee SWIM Plan, which identified Lake Okeechobee as a priority water body threatened by phosphorus pollution. The primary source of phosphorus loading to Lake Okeechobee was found to be agricultural non-point source runoff from its northern basins, which upsets the balance of natural flora and fauna of the lake's ecosystems.

The strategy for managing the phosphorus loading from the watershed was described earlier in this report under the LOPA overview. **Table 10-2** summarizes the watershed categories of phosphorus reduction activities, the lead agency responsible for implementing the category, and the anticipated phosphorus load reduction percentage upon full implementation of the LOPP.

Table 10-2. Major categories of phosphorus reduction activities in the Lake Okeechobee watershed, with lead agencies and estimated percent of total load reduction [to meet the Total Maximum Daily Load (TMDL) goal of 140 metric tons].

Category	Lead Agency	Estimated Percent TP Load Reduction
Owner & Cost – Share BMPs	Agriculture – Florida Department of Agriculture and Consumer Services	25%
	Non-agriculture – Florida Department of Environmental Protection	
Other TP Reduction Projects	South Florida Water Management District	18%
Regional Public Works Projects	South Florida Water Management District	17%
Other Regional Projects	South Florida Water Management District	1%
Comprehensive Everglades restoration Plan Lake Okeechobee Watershed Project	United States Army Corps of Engineers and South Florida Water Management District	39%

A considerable effort has been expended in WY2004 on BMP implementation to reduce phosphorus discharges to the lake. The FDACS has developed an administrative rule (5M-3) that adopted different commodity BMPs. Through this rule, the implementation of an FDACS farm assessment, a Notice of Intent to implement a BMP plan, or an NRCS Conservation Plan will provide the landowner with a presumption of compliance with state water quality criteria. Landowners who choose not to participate in the FDACS program will be required to monitor phosphorus load in surface water runoff to demonstrate compliance with existing and future phosphorus targets and requirements through the District's LOWOD permitting program. The FDACS and NRCS have completed a significant amount of assessments, interim measure plans, and conservation plans, covering 400,000 acres in the watershed. Implementation of the BMPs identified within these documents is ongoing under the FDACS' non-regulatory, incentive-based program. To expedite BMP implementation, the FDACS and NRCS have obtained a federal grant to identify and train technical service providers and conservation planners in the watershed. UF-IFAS has also been contracted by the FDACS to provide training for third-party vendors to participate in BMP plan development. The FDACS and NRCS have also prepared a Public Law 566 (PL-566) Small Watershed Proposal (BMP planning, implementation, and cost-share in the Lower Kissimmee and S-191 basins) for consideration by the U.S. Congress, which if approved would greatly increase the federal funding for the program.

The FDEP has lead responsibility in implementing non-agricultural BMPs. Public education is essential for reducing phosphorus from urban areas. A fertilizer brochure was developed with the fertilizer industry and is being distributed in retail stores to promote the use of low or no phosphorus fertilizer. Through the Florida Yards and Neighborhoods Program, the UF-IFAS provides weekly articles in Okeechobee newspapers on proper lawn maintenance practices. The FDEP is installing sediment traps and creating grassy swales in residential communities to improve water quality. Implementation of these BMPs also follows a non-regulatory, incentive-based approach.

State funding has been provided for Lake Okeechobee restoration efforts that allow for early implementation of additional phosphorus reduction projects (**Table 10-3**). These landowner cost-share technologies/projects will provide a range of phosphorus reductions to the lake. All of these projects have some level of performance monitoring being conducted to facilitate the evaluation and potential future use of these types of systems.

Regional Public Works projects such as the Everglades Construction Project (ECP), Kissimmee River Restoration Project, and the Lake Okeechobee Critical Projects are contributing to the phosphorus load reduction to Lake Okeechobee. The "Other Regional Project" is defined as the expansion of the Nubbin Slough Critical Stormwater Treatment Area (STA). An effort is underway to expand the existing STA footprint (800 acres) by 1,200 acres and divert additional runoff from the watershed to the STA for storage and treatment. The remaining load reductions necessary to meet the lake TMDL by 2015 will come from the construction of CERP Watershed LOWOD Permitting Programs Modifications Project facilities that were discussed earlier in this report.

Table 10-3. TP load reduction projects that have been implemented ahead of schedule as a result of legislative funding.

General Project Category	Specific Project Name	Project Description
Phosphorus Source Control Grant Program	Tampa Farms Composting Facility	Composting chicken manure exported from watershed
	Milking "R" Chemical Treatment	Optimizing dairy stormwater treatment system
	Solid Waste Authority	Tri-county biosolids pelletization
	QED McArthur Farms 3	Dairy farm wastewater treatment system
	Candler Ranch	Runoff treatment - iron humate filter
	Davie-Dairy Cooling Pond	Concrete cooling ponds
	Evans Properties Bassett Grove	Citrus grove stormwater system retrofit
	Okeechobee Utility Authority Ousley Estates	Gravity sewer system replacing septic and package plants
	Lofton Ranch	Wetland restoration
	Smith Okeechobee Farms	Stormwater retention and wetland restoration
	Lazy S Ranch	Runoff treatment - iron humate filter
Dairy Best Available Technology	Dry Lake 1	Edge of farm stormwater retention/detention with chemical treatment
	Butler Oaks	
	Davie Dairy 1 and 2	
	Milking R Dairy	
Silica Soil Amendment Evaluation Project	Larson Dairy 6	Soil amendment application to bind residual phosphorus
	Milking R	
Isolated Wetland Restoration Program	Kirton Ranch	Wetland restoration on agricultural properties
	Hazellief	
	McArthur Farms	
	Williams Ranch	

4th St. Boat Ramp Project	Residential and commercial area around 4 th Street in Okeechobee	Urban stormwater retrofit including baffle box and regarding swales
Former Dairy Remediation	Lamb Island Dairy Remediation	Remediation of properties that were previously dairy utilizing stormwater detention, wetland treatment, lagoon remediation, and soil amendments
	Lamb Island Dairy Tributary Stormwater Treatment Project	
	Five former dairy sites	
Regional Public-Private Partnership	GreenCycle and QED	Dairy waste separation and treatment facilities and an organic fertilizer plant utilizing dairy and chicken manure
	Davie Dairy 1 and 2	Chemical treatment of 800 acres of off-site runoff
Other Projects*	Hydromentia	Aquatic Plant Based Water Treatment System Pilot Project – water hyacinths and algal turf scrubber
	Tributary Dredging and Structure Retrofits	Sediment removal and modification of water control structures for water quality improvement
	AquaFlorida	Conceptual design of a regional stormwater treatment area

*Load reductions were not included in the Lake Okeechobee Protection Plan for demonstration projects of short duration.

Regulatory programs also have a role in the Lake Okeechobee restoration efforts. Several programs are in place to provide assurances that the regulated facilities will meet water quality standards in waters of the state including: (1) Dairy Rule/National Pollutant Discharge Elimination System Permitting; (2) Environmental Resource Permitting; (3) Evaluation of Land Use Changes; (4) Domestic Wastewater Regulations; (5) Municipal Separate Storm Sewer System Regulations; and (6) LOWOD Permitting Programs Modifications to the LOWOD program to bring the permitting program in sync with the LOPP are described in a remaining portion of this section.

The LOWOD permitting program [Chapter 40E-61 Florida Administrative Code, (F.A.C.)] was a stand alone program designed in 1989 to identify high phosphorus source areas and to bring them into compliance with established phosphorus concentration limits through corrective actions. The primary function of the program was to permit and monitor parcels in 14 of the 31 “controllable” tributary sub-basins of Lake Okeechobee. These fourteen basins exceeded the SWIM TP discharge concentration performance standard of 180 parts per billion (ppb) to the lake at the time that the SWIM legislation was passed in 1987.

The LOPA and TMDL statutes impose many new responsibilities on the District that were not contemplated in 1989, when the LOWOD program was created. As part of these new responsibilities, the District is currently required to achieve phosphorus levels consistent with the new Lake Okeechobee TMDL at all of its facilities discharging into or from the lake by 2015. As a result, the LOWOD (Chapter 40E-61, F.A.C.) is under review and amendments are presently being recommended to better support the mandate of the LOPA. These amendments will shift the

program focus more toward water quality monitoring and assessment in lieu of a standard regulatory role in the watershed, although regulatory authority such as Environmental Resource Permitting (ERP) can also be exercised, if needed. In addition, other amendments being considered include (1) adding all land areas covered under the LOPA, (2) changing phosphorus concentration targets to reflect TMDLs, (3) addressing land use changes, and (4) recognizing the role of incentive-based BMP programs being implemented throughout the watershed.

The revised LOWOD program will support the LOPA mandate and the coordinating agencies through:

- Water quality monitoring and assessment of phosphorus source areas throughout the entire Lake Okeechobee Watershed Project Area, as defined in the January 1, 2004 Lake Okeechobee Protection Program Annual Report to the Florida Legislature. This report references the Lake Okeechobee Protection Act, and is available at the District's Website at http://www.sfwmd.gov/org/wrp/wrp_okee/projects/LOPPAnnualRptPosted122203.pdf
- Prioritizing high phosphorus source areas throughout the expanded Lake Okeechobee watershed to direct appropriate resources
- Assuring changes in land use will not result in increased phosphorus loads to Lake Okeechobee through the evaluation of pre- and post-land use scenarios
- The evaluation of BMPs on reducing phosphorus concentrations at the micro-basin and phosphorus loads to Lake Okeechobee at the sub-basin and basin level
- Permitting parcels not covered under an incentive-based BMP program

The District has begun the process of revising the LOWOD monitoring network. The monitoring that had been conducted at the parcel level under the LOWOD program has been shifted to a micro-basin network to develop base line data throughout the watershed. These data will also be used by the coordinating agencies, specifically the FDACS, to direct technical service providers to areas exhibiting poor water quality. In addition to the sites collected under the program, data collected from the District's ambient monitoring network, the USGS Comprehensive Everglades Restoration Plan monitoring network, and the Lake Okeechobee inflow sites will be used to evaluate the water quality throughout the watershed.

During the past year, data were collected at the newly established micro-basin monitoring sites (**Table 10-4**). Of the nine basins that were sampled, eight had TP concentration averages greater than those at the basin structure outlet. Four basins had TP concentrations at the structure outlet that were above the SWIM plan or TMDL target. A more detailed data analysis of each watershed will be provided to the coordinating agencies to direct BMP resources. Individual and general permits continue to be issued for properties outside the four priority basins. For those permits associated with a land use change, phosphorus budget information was evaluated to ensure that phosphorus loading would not increase to more than that of the existing land use.

Table 10-4. TP concentrations measured at sampling sites in Lake Okeechobee watershed basins compared to concentrations at the basin outlet structures.

LOWA Watershed Sampling Sites						Structure Outlet				Basin SWIM Plan Concentration Target
Basin	Mean (ppb)	Median (ppb)	Std Dev	N (samples)	N (sites)	Mean (ppb)	Median (ppb)	Std Dev	N (Samples)	
Taylor Creek/Nubbin Slough S-191	700	331	936	167	19	534	460	237	15	160*
S-133	176	147	100	69	8	128	120	33	9	180
S-154	804	355	1463	34	4	250	242	165	45	180
S-65E	305	210	263	46	12	83	68	33	55	180
S-65D	226	120	254	47	7	69	65	17	48	180
Slough Ditch S-84 (C-41A)	323	80	968	22	8	79	78	16	16	100
Hamey Pond Canal S-71 (C-41)	227	167	277	84	11	218	170	118	47	180
Indian Prairie S-72 (C-40)	194	200	88	27	5	226	200	130	39	180
Fisheating Creek	296	210	271	217	15	107	109	32	11	180

*Proposed TMDL for tributary

WATERSHED RESEARCH AND ASSESSMENT

The SFWMD, FDEP, and FDACS, in cooperation with other organizations and interested parties, have implemented a comprehensive research and assessment program for the watershed. This is an integral component of the overall restoration program. The data obtained will fill information gaps that have been identified by the interagency participants, assist in focusing on areas of concern, and determine performance of watershed management efforts. Water quality data collection is occurring at the basin level, in localized areas, and at project-specific levels. Some project-specific ecological data also is being collected. Baseline water quality data for the watershed (1991–2000) has been computed, as presented in the LOPP. Basin water quality data for WY2004 and localized area sampling under the LOWOD program are presented in the “Watershed Status” section of this chapter; project specific data is available in Chapter 3 of the 2005 SFER – Volume II (also, see http://www.sfwmd.gov/org/wrp/wrp_okee/). Long-term assessment will continue through the life of the program to quantify project performance and basin-level trends.

Research, demonstration, and assessment projects underway or completed this year are summarized in **Table 10-5**. The LOPA required that tributary sediment trapping be investigated (**Figure 10-9**) as a phosphorus reduction technology. However, results to date indicate that very little particulate phosphorus can be removed by this method due to the extreme small particle size; therefore, the LOPP does not recommend their widespread use in the watershed. The LOPA also required that on-farm and tributary water management practices (**Figure 10-10**) be assessed. Modeling results suggest that a substantial amount of phosphorus load can be reduced if certain land uses such as pastures and dairies retain one inch of runoff water and if tributary canal storm water retention is implemented. Water management is included within the FDACS typical suite of BMPs. The identification of phosphorus concentrations using remote sensing and hyperspectral Imaging (**Figure 10-11**) was not specifically identified in the LOPA, but identifying phosphorus sources and finding cost-effective ways to facilitate reductions is an implicit directive. Hyperspectral imagery may be a cost-effective and accurate method of mapping phosphorus concentrations in vegetation over large areas, and preliminary results suggest that it also may be effective in providing a coarse-scale estimate of TP in surface waters of this area, perhaps because phosphorus mainly occurs in algal cells or other seston that has a unique spectral signature. These areas remain focal points of ongoing research.

Watershed research and assessment projects are assessed and prioritized each year by the interagency team to ensure that key uncertainties and information needs are being addressed.

Table 10-5. Lake Okeechobee watershed research, demonstration, and assessment projects that are ongoing in 2004.

Project Name (Investigator)	Major Objectives / Conclusions	Status
Residuals and Chicken Manure Land Application (Southern Datastream)	To assess the potential impacts of residuals and chicken manure application on the quality of water reaching Lake Okeechobee. The specific project goals are to (i) document environmental problems associated with residual and chicken manure use through water quality monitoring, (ii) establish application rates for residuals and chicken manure that are economical and environmentally sound and (iii) educate landowners in the watershed on the proper management and use of the waste materials. This study is generating information on the reactivity, mobility and bioavailability of waste-bound phosphorus in soils that will aid in establishing Best Management Practices for residuals and chicken manure use in the Lake Okeechobee watershed.	Ongoing
Tributary Sediment Removal Demonstration (Environmental Research and Design, Inc.)	Evaluated the technical feasibility and economic viability of two sediment removal technologies [a continuous deflective separation (CDS) unit and a tributary sediment trap (TST)] in reducing phosphorus loading into Lake Okeechobee. The use of CDS and TST units for removal of particulate phosphorus in tributaries discharging to Lake Okeechobee does not appear to be a feasible nutrient reduction alternative. The use of both technologies appears to be more suited to an urban environment where particle sizes would likely be larger.	Complete
Water Quality Best Management Practice (BMP) for Beef Cattle Ranch Demonstration (Archbold Expeditions)	(i) To develop an understanding of the relationship between beef cattle operational practices and water quality, and (ii) to provide recommendations for the development of environmentally and economically sustainable cow/calf practices in the Lake Okeechobee watershed. Cattle stocking rates have no measurable effect on nutrient loads from the pastures, which may be related to high concentrations of phosphorus in the soil from past fertilization practices in improved pastures. The current project evaluates the feasibility of on-farm retention/detention of water in controlling phosphorus losses from beef cattle ranches.	Ongoing
Water Management Control Practices Assessment (R.J. Behar)	(i) Assessed water management practices in the watershed, on both individual properties and in tributaries; and (ii) investigated the potential for structural and/or operational alternatives to retain stormwater and reduce phosphorus loading to Lake Okeechobee. Hydrologic and water quality modeling indicates the potential to reduce approximately 48% of phosphorus loading from individual properties in the watershed using on-site stormwater retention where possible. Specifically, pastures and dairies were estimated to have a phosphorus load reduction of about 61 percent by retaining 1 in. of runoff. Retention of water in tributaries during the dry season is estimated to have a phosphorus load reduction of about 3.3 percent.	Complete
Reservoir-Assisted STA Optimization (Wetland Solutions Inc.)	(i) To maximize the long-term storage of TP in the STA footprints and the removal of TP mass from the Taylor Creek/Nubbin Slough Basin and Lake Okeechobee within the physical and cost constraints of the project. (ii) to minimize operational costs measured as dollars per pound of TP removed. A research and management plan addressing issues specific to the operation and management of the pilot and future STAs in the watershed has been developed. Implementation of the plan will commence with baseline characterization of the STA sites following construction and prior to operation. Initial characterization may take up to three months to complete. Routine monitoring will begin as soon as the STAs are operational.	Planning
Seepage Testing (Soil and Water Engineering Technology, Inc.)	To determine the lateral and vertical movement and extent of lagoon leakage. Preliminary investigations indicate varying degrees of leakage. Therefore, a more extensive is being planned at one site.	Ongoing

Table 10-5. Continued.

Project Name (Investigator)	Major Objectives / Conclusions	Status
Cow-Calf Water Quality BMP Demonstration (UF-IFAS)	To evaluate the effectiveness of cow-calf production BMPs with regards to reducing P loadings. Specific objectives include: (i) identify selected cow-calf BMPs and design hydrologic monitoring network for evaluating BMPs' effectiveness at watershed-scale for reducing P discharges; (ii) collect baseline (pre-BMP: 2003) and post-BMP (2004–2005) water quantity and quality data (surface and ground waters) and analyze the results to evaluate the effectiveness of the BMPs with regards to water quality and economics; (iii) use the monitoring data to test and modify selected hydrologic simulation models for their effectiveness in simulating the effectiveness of BMPs; and (iv) disseminate the results of the study to ranchers and state and federal agencies in the Lake Okeechobee basin.	Ongoing
Wetland BMP Research (UF-IFAS)	(i) To demonstrate and determine the efficacy of isolated wetlands located in land areas currently used for dairy and cow-calf operations, on phosphorus assimilation and storage; (ii) to design and optimize on farm or edge-of-the field treatment wetlands to maximize P removal performance (both mass removal per unit area basis, and effluent concentration basis) land areas used for cow-calf operation; (iii) review current hydrologic and phosphorus models for adaptation to the Okeechobee Basin wetland systems and to predict P assimilation capacity of the basin; (iv) to develop P assimilation coefficients/algorithms for use in water quality models to demonstrate the effectiveness of isolated and constructed wetlands to store P; and (v) to communicate the utility and effectiveness of isolated wetlands in P assimilation storage to dairy farmers and beef cattle ranchers through extension publications or other appropriate mechanisms.	Ongoing
Identification of Phosphorus Concentrations Using Remote Sensing and Hyperspectral Imaging (Agriculture Facilities Administration and Management Corporation)	Examined the feasibility of using a hyperspectral airborne sensor to collect watershed scale image data to identify areas with high phosphorus concentrations. Hyperspectral imagery appears to be an effective and accurate method of mapping vegetative phosphorus concentrations over large areas. This would help landowners and water managers to better evaluate where residual phosphorus has accumulated and which Best Available Technology would be best for a particular property.	Complete
Crop Phytoremediation of Phosphorus-Enriched Soils in the Lake Okeechobee Region (UF-IFAS)	To develop a comprehensive research program that will provide growers with practical guidelines for improved use of pasture production for remediation of phosphorus-impacted sites. The current project looks at the effectiveness of three forage species (stargrass, limpograss and bahiagrass) in reducing initial soil P levels of moderately impacted sites.	Ongoing
Natural Resources Economic Analysis and Desktop Evaluation of Alternative Nutrient Reduction Technologies (Hazen and Sawyer)	Provided a benefit-cost analysis of 12 phosphorus control alternatives (PCAs) to provide information for the development of the Lake Okeechobee Protection Plan. Benefits and costs of each alternative to the District, landowners, and the regional economy were described and quantified using the best available information. Cow-calf BMPs were ranked first among the 12 PCAs evaluated in Phase I. Phase II, which evaluated and ranked 18 combinations of the most effective on-farm and regional PCAs showed RASTAs with dairy farm optimization and enhanced cow-calf BMPs as the highest ranked combination.	Complete

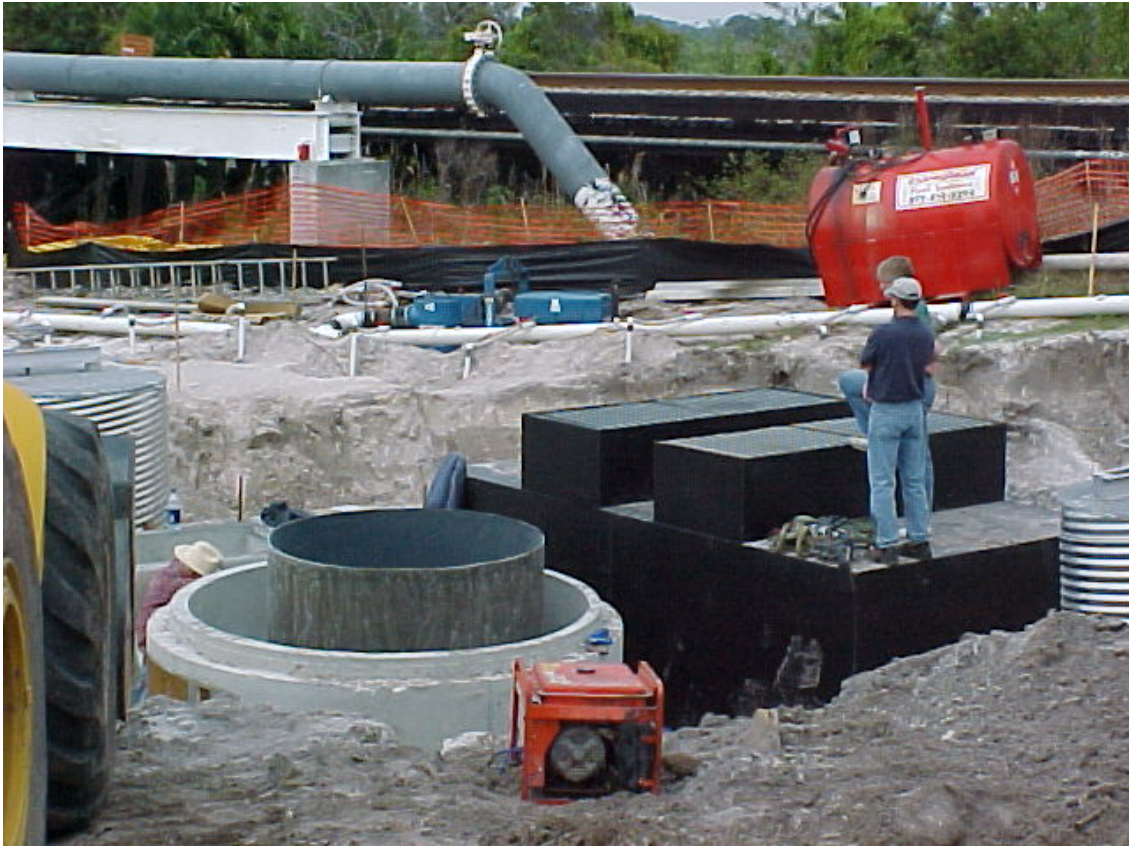


Figure 10-9. Installation of the continuous deflective separation (CDS) unit (left) and the tributary sediment trap (right) at the Lettuce Creek project site. (SFWMD photograph).



Figure 10-10. Example of an on-farm water management practice, specifically the use of a water control structure to retain storm water within on-site ditches. (SFWMD photograph).

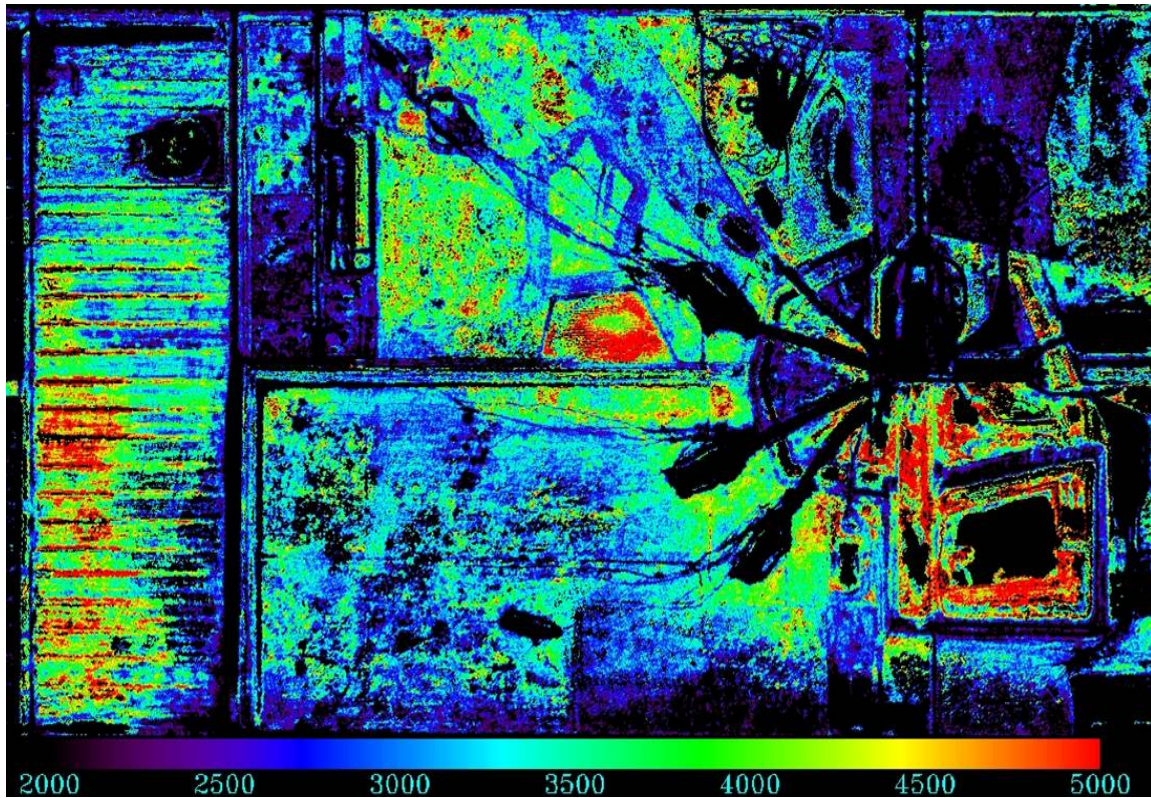


Figure 10-11. Hyperspectral image of Butler Oaks Dairy. Colors indicate the phosphorus concentrations in vegetation (red = highest, blue/violet = lowest). This method can account for more than 50 percent of the variation in measured TP in vegetation, based on comparison of hyperspectral model results versus field samples.

LAKE STATUS, MANAGEMENT, AND RESEARCH

LAKE STATUS

The current status of Lake Okeechobee is described in regard to (1) phosphorus budgets, (2) nutrient and phytoplankton dynamics, (3) submerged aquatic vegetation, and (4) emergent plants and wildlife. A substantive historical context is provided in this newly established chapter as part of the background information for the *2005 South Florida Environmental Report*. For the attributes covered under items (1) to (4), a subset has been adopted as quantitative performance measures for the LOPA (as defined in the January 2004 Lake Okeechobee Protection Program Annual Report, which is available on the District's Website at http://www.sfwmd.gov/org/wrp/wrp_okee/projects/LOPPAnnualRptPosted122203.pdf). These measures collectively describe the status of the ecosystem and its responses to restoration programs once they are implemented. Current values are presented in **Table 10-6**, which includes quantitative restoration goals. The Lake Okeechobee Protection Program Annual Report provides a technical foundation for the performance.

Table 10-6. Summary of Lake Okeechobee rehabilitation performance measures, goals for the lake rehabilitation program and the existing (baseline) conditions. Unless otherwise indicated, existing conditions are five-year averages (1999–2003), as specified in the Restoration Assessment Plan of the Lake Okeechobee Protection Program.

Performance Measure	Goal	Existing Condition
Total phosphorus (TP) Load	140 metric tons/y	528 metric tons/y
Pelagic TP	40 µg/L	122 µg/L
Pelagic TN:TP	> 22:1	13:1
Pelagic DIN:SRP	> 10:1	5:1
Plankton Nutrient Limitation	Phosphorus > Nitrogen	Nitrogen >>> Phosphorus
Diatoms:cyanobacteria*	> 1.5	0.65
Algal bloom frequency	< 5% of pelagic chlorophyll a exceeding 40 µg/L	15%
Water clarity**	Secchi disk visible on lake bottom at all near-shore SAV sampling locations from May–Sept	32%
Near-shore TP	Below 40 µg/L	77 µg/L
Submerged aquatic vegetation (SAV)***	Total SAV > 40,000 acres and vascular SAV > 20,000 acres	38,000 total SAV 18,000 vascular SAV
Extremes in low lake stage (current water year)	Maintain stages above 10 ft	Goal attained this water year
Extremes in high lake stage (current water year)	Maintain stages below 17 ft; stage not exceeding 15 ft for more than 4 months	Goal not attained this water year
Spring recession (current water year)	Stage recession from near 15.5 ft in January to near 12.5 ft in June	Goal attained this water year

* Mean for 1999–2003 period
 ** Frequency for period May 2000–2004
 *** Mean yearly acreages from 2000–2003 maps

Prior to considering historical or contemporary data from the lake, the reader should be familiar with the distinct habitats and “ecological zones” that have been identified in this ecosystem. From the perspective of primary producer assemblages, there are three distinct regions (**Figure 10-12**) that also have different water quality physical characteristics (Havens, 2003). Along the west and south shoreline, there is a littoral zone with a diverse community of emergent, submerged, and floating leaved plants, water depths ranging from 0 to 1 m, and TP concentrations ranging from 5 to 20 micrograms per liter, or $\mu\text{g L}^{-1}$ (Havens et al., 1999; Hwang et al., 1998; Havens et al., 2004). Lowest phosphorus concentrations occur when water levels in the lake are low and the main water input to the littoral zone is rainfall. Highest phosphorus concentrations occur when lake levels are high and phosphorus-rich pelagic water is transported into the littoral zone by wind-driven currents (Havens, 1997). Adjacent to the littoral zone, on a shelf of slightly deeper water, is an area referred to as the “near-shore zone” that supports submerged plants and wave-tolerant emergent plants such as giant bulrush (*Scirpus californicus*). Depths range from < 0.5 to 1.5 m and TP concentrations range from < 30 to > 60 $\mu\text{g L}^{-1}$, again increasing when the lake experiences higher water levels (Maceina, 1993; Havens, 1997). The deepest (2.5 to 5.0 m) central pelagic region supports no rooted vascular plants or benthic algae, because light penetration is limited to < 1 m by a high concentration of suspended seston (Havens, 1995b). This region has TP concentrations of > 100 $\mu\text{g L}^{-1}$, and sometimes of > 200 $\mu\text{g L}^{-1}$ following wind storms (Havens et al., 2001a).

Phlips et al. (1993a) documented that the pelagic and near-shore zones also could be differentiated into distinct regions or “ecological zones” (**Figure 10-13**) that differ in regard to factors that control phytoplankton biomass. The zonation was based on a multivariate analysis of monthly water chemistry and irradiance data collected over three years at approximately 80 pelagic stations, supplemented with nutrient addition bioassays at a smaller number of sites. The ecological zones appear to be determined by the type of underlying sediment material, water depth, and proximity to major inputs of phosphorus from the watershed. The “north zone” receives water from the major tributaries to the north of the lake, which have high concentrations of phosphorus. This region is moderately deep and has unconsolidated mud sediments. Nitrogen is most often limiting to phytoplankton growth in this zone, except during windy months, when light limitation occurs (Aldridge et al., 1995; Phlips et al., 1997). The “central zone” is deeper and also overlies soft mud sediments. Light limitation occurs during most of the year in this zone because mixed depth (approximate total depth) greatly exceeds photic depth. The “edge zone” corresponds to the near-shore zone described above, where depths are relatively shallow and submerged plants often develop a high biomass. Sediments are sand and peat, both of which are less readily resuspended than mud. When combined with the more shallow depth, the result is that the phytoplankton in this zone is more often limited by nitrogen than light. Between the “central zone” and “edge zone” there is a region that Phlips et al. (1993a) described as the “transition zone,” which has features intermediate between the two zones. This region of the lake frequently experiences algal blooms.

The “ecological zone” concept was developed during a time when water levels were relatively low. Under those conditions, spatial heterogeneity in Lake Okeechobee is maximized. In contrast, when water levels are high for prolonged periods of time, such that submerged plants are nearly eliminated from the “edge zone” and sediment transport from the “central zone” is enhanced, the lake becomes homogeneous (Havens et al., 2001a; Havens, 2004). Some long-term historical data in this chapter are given as averages from eight pelagic stations (**Figure 10-14**) that encompass the four ecological zones identified by Phlips et al. (1993a). Relative long-term trends are similar in the zones; however, absolute concentrations of the water chemistry variables differ as described above. Additional information regarding long-term trends for particular zones is presented in Phlips et al. (1995), Havens (1995a), and Havens et al. (1995). It is important to note that for contemporary information and research/modeling results presented in this chapter,

the focus tends to be on particular “ecological zones” or habitat regions described above, rather than on whole-lake averages.

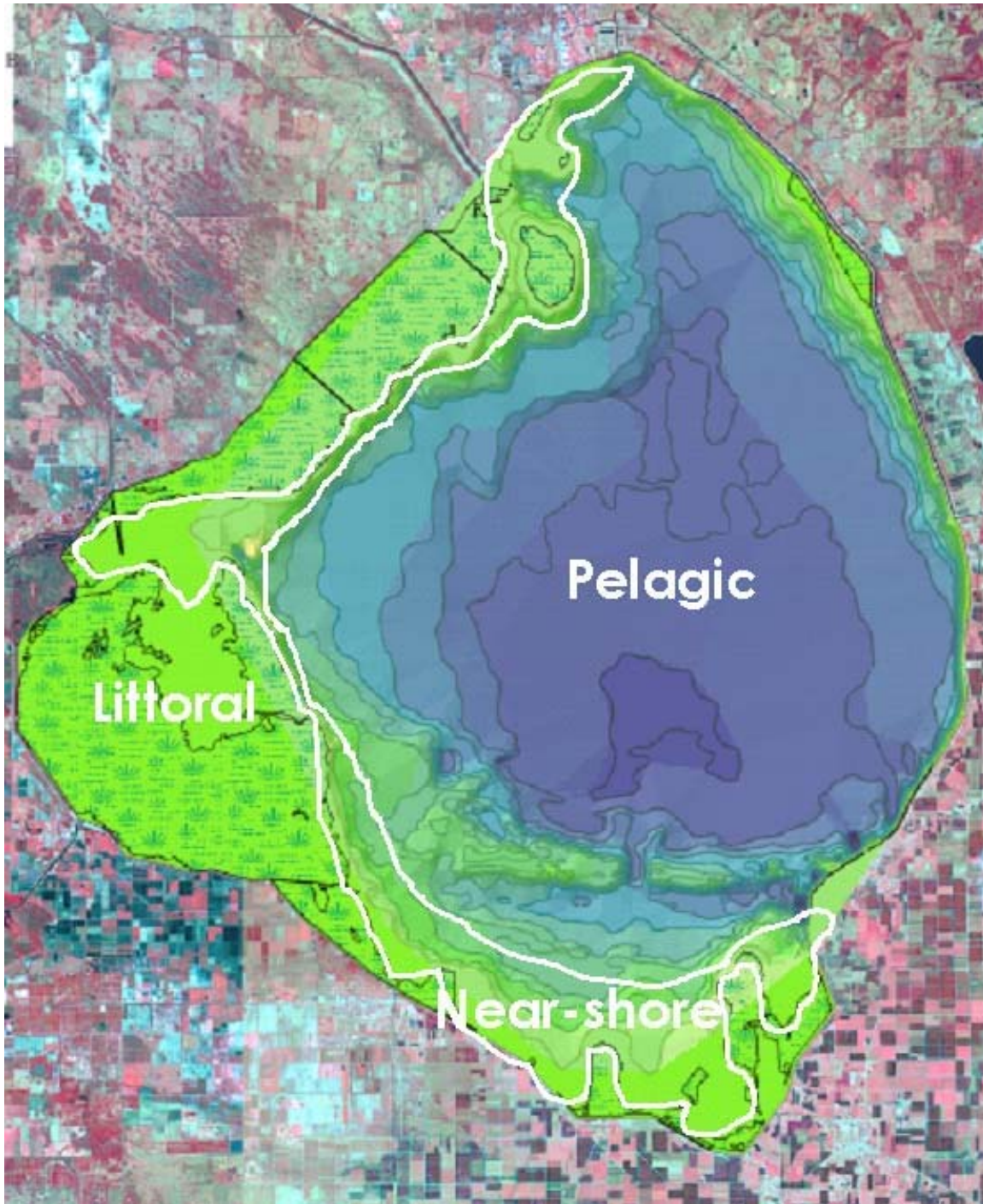


Figure 10-12. Three major habitat zones in Lake Okeechobee shown as an overlay on a 2002 lake bathymetric map. These zones are based on dominant primary producers (Havens, 2003).

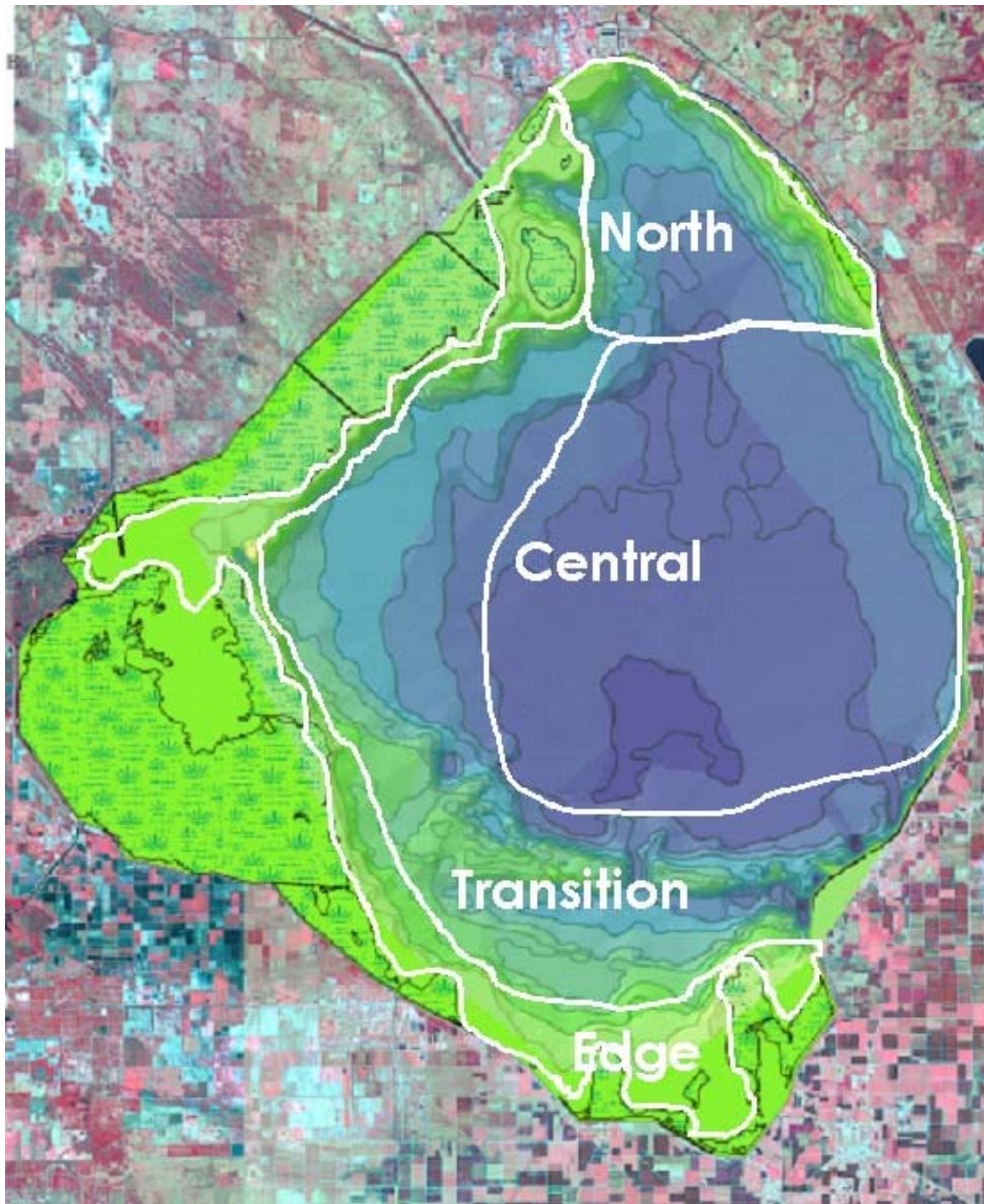


Figure 10-13. Four ecological zones encompassing the pelagic and near-shore habitat regions, as delineated by Philips et al. (1993) based on nutrient concentrations, underwater irradiance, and the relationship of phytoplankton biomass to those attributes.

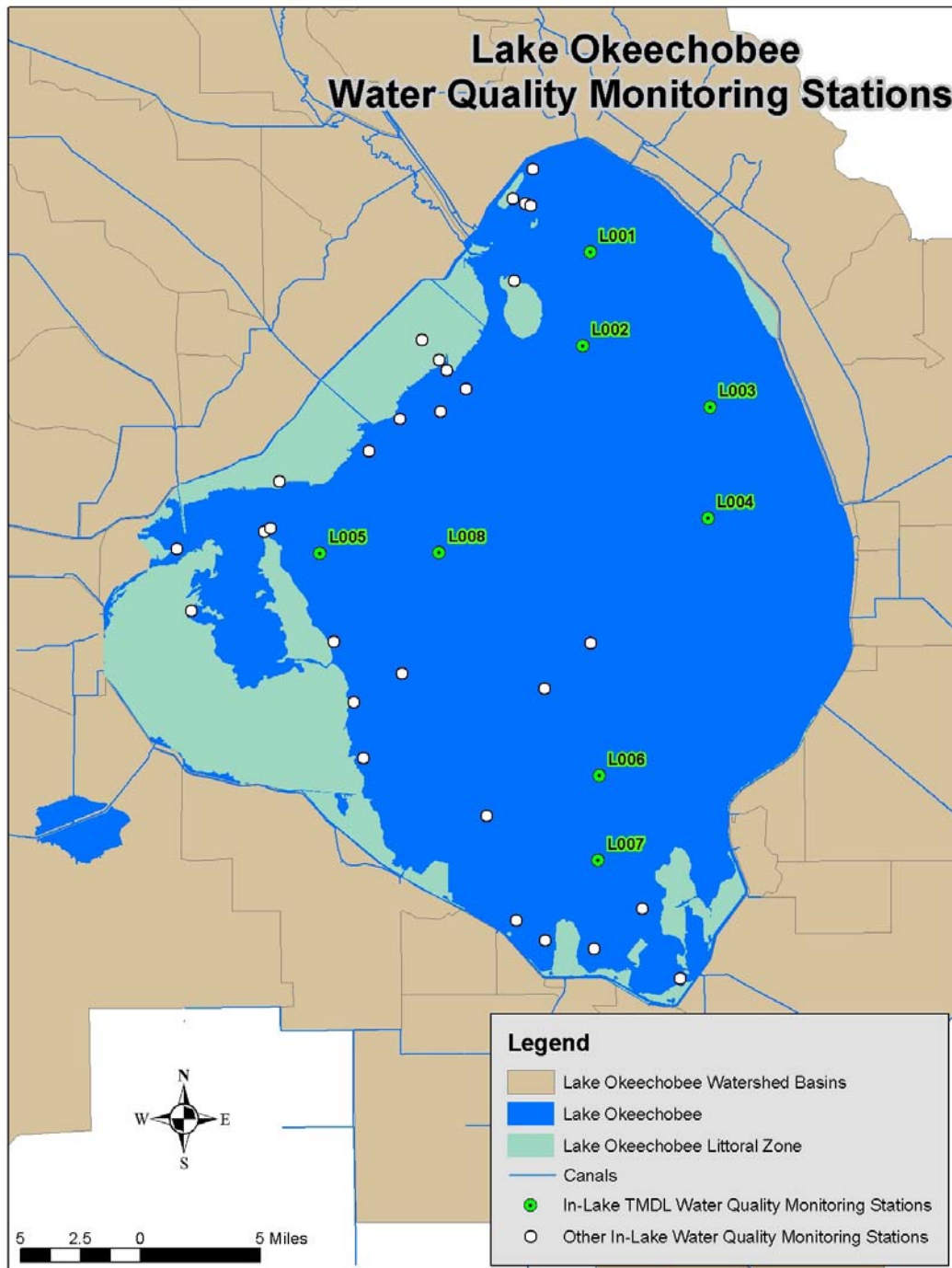


Figure 10-14. Water quality sampling stations in Lake Okeechobee, with the eight long-term stations used for TMDL assessment and phosphorus mass balance calculations indicated (L001–L008).

Phosphorus Budgets, Loads, and Lake Water Total Phosphorus

Understanding the phosphorus mass balance of a lake, and the relationship between external phosphorus loads, internal recycling, and lake water phosphorus concentrations is critical for making accurate predictions regarding lake responses to load reduction in the watershed. This section summarizes historical and contemporary information about the phosphorus budget of Lake Okeechobee.

METHODS

Yearly phosphorus budgets have been determined for Lake Okeechobee since 1973, following methods described in several journal articles, including James et al. (1995a). Phosphorus loads into and out of the lake are calculated from flows and concentrations measured at 32 stations around the lake and are presented by green squares (**Figure 10-8**), using a modified version of the computer program FLUX (Walker, 1983; 1989). Phosphorus and other nutrient concentrations and ratios in the lake are calculated from data collected at the eight stations noted above.

Phosphorus mass balances and historic trend analyses for Lake Okeechobee have traditionally been based on calendar year data, which is the case for all yearly summary information in the Lake Okeechobee program. Therefore, it should be noted that plots of 30-year historical data shown in this section have been extracted from published journal articles, are not modified, and are based on a calendar year. The purpose of the plots is to provide a general historical context. In the case of the 2004 phosphorus mass balance, WY2004 is used in order to provide consistency with other chapters of this report.

In the phosphorus mass balance, average annual lake mass (M_{lake}) is calculated from averaged monthly data, where each monthly mean is the average concentration from the eight pelagic stations times monthly lake volume. Year-to-year changes in lake mass (ΔM_{lake}) are based on start and end of year values. The net sedimentation coefficient (Vollenweider, 1975) is calculated as:

$$\sigma(y^{-1}) = [(M_{\text{in}} - M_{\text{out}}) - (\Delta M_{\text{lake}})] / M_{\text{lake}} \quad (\text{Equation 10-1})$$

Where, M_{in} is the yearly mass of TP entering the lake, M_{out} is the corresponding mass leaving the lake at outflows; other terms are as defined above. In all cases, the units are $\text{mt } y^{-1}$. In addition to these standard mass balance calculations, it is demonstrated how measured pelagic phosphorus concentrations compare with those calculated from a simple model of Vollenweider (1976):

$$P_{\text{lake}} = L_P / [q_s(1 + T_w^{0.5})] \quad (\text{Equation 10-2})$$

In order to illustrate effects of internal loading on historical trends in this shallow lake ecosystem, L_P is the areal loading rate ($\text{g m}^{-2} y^{-1}$), q_s is the hydraulic load (m), and T_w is the water residence time (y). Statistical relationships between mass balance and/or water chemistry attributes presented in this report were analyzed using SYSTAT Version 10.2 (SYSTAT Software Inc., CA). In some cases, data were log-transformed due to skewed distributions prior to carrying out statistical analyses.

RESULTS AND DISCUSSION

In the phosphorus mass balance for WY2004, inputs to the lake from tributaries totaled 549 mt, and outputs were 287 mt. This yearly budget should be considered in a historical context, and in this case, three decades of data were examined by taking results directly from a recently published journal article (Havens and James, 2004). From 1973 to 2003, the average mass of phosphorus in the lake was 415 mt, mean input and output mass values were 499 and 174 mt, respectively, and the mean sink was 297 mt (60 percent of inputs). The net sink term is substantially lower than the 80 percent reported by James et al. (1995a) based on a mass balance from 1973 to 1992, or the 78 percent reported by Janus et al. (1990) for the period from 1974 to 1989. Both of these authors noted that the net sink term in the mass balance was declining, and this trend continues in the updated evaluation of Havens and James (2004). When the net sedimentation coefficient is plotted over time, a significant downward trend is observed (**Figure 10-15**, Panel A). The trend is not explained by changes in water depth of the lake. Thus, for some reason, Lake Okeechobee appears to be losing its capacity to assimilate phosphorus. This may be due to saturation of phosphorus binding sites on lake sediment particles (Fisher et al., 2001) and/or to a reduction of water column calcium (James et al., 1995b), an element that plays a key role in sequestration of phosphorus in this lake under oxidized conditions (Olila and Reddy, 1993; Moore et al., 1998). Regardless of the cause, the result of this trend is that simple input-output models can no longer accurately predict TP concentrations in lake water (**Figure 10-15**, Panel B).

The yearly loading of phosphorus to the lake displays a high degree of variability that closely follows inflow water volume (**Figure 10-16**, Panel A). Inflow volume explains more than 70 percent of the year-to-year variation in TP loading (**Figure 10-16**, Panel B). Despite the decades of programs to control phosphorus loads to the lake, there is no long-term trend in this parameter. This is not to say that watershed programs have been without effect, but that one must examine the data in a manner not so heavily influenced by flow. Considering instead the TP concentration of inflowing water (**Figure 10-17**), there is an increase from the 1970s to the mid 1980s, and then a decline through the 1990s, to levels below those observed at the beginning of the period of record. The decline in inflow TP coincides with similar declines in major tributaries to the lake (Flaig and Havens, 1995). Toward the end of the 30-year period of record, the TP concentration of inflowing water stabilizes at near $150 \mu\text{g L}^{-1}$, with considerable interannual variability.

TP concentrations in lake water (average from the eight pelagic stations) increased during the 1970s and then remained relatively stable with a mean near $90 \mu\text{g L}^{-1}$ until 1995 (**Figure 10-15**, Panel B). TP concentrations then increased to $>100 \mu\text{g L}^{-1}$ in recent years. Mean depth of the lake also varies from year to year, but contrary to what has been noted in earlier reports (Canfield and Hoyer, 1988), there is no significant correlation between lake stage and TP. Likewise, inflow volume and inflow TP concentrations are not correlated (data not shown, see Havens and James, 2004). As noted by Canfield and Hoyer (1988) and Janus et al. (1990), TP concentrations in the lake water are not correlated with TP concentrations in the inflows on a yearly basis (data not shown, see Havens and James, 2004). This indicates the overriding influence of internal phosphorus cycling (between sediments and water) in controlling phosphorus concentrations in Lake Okeechobee.

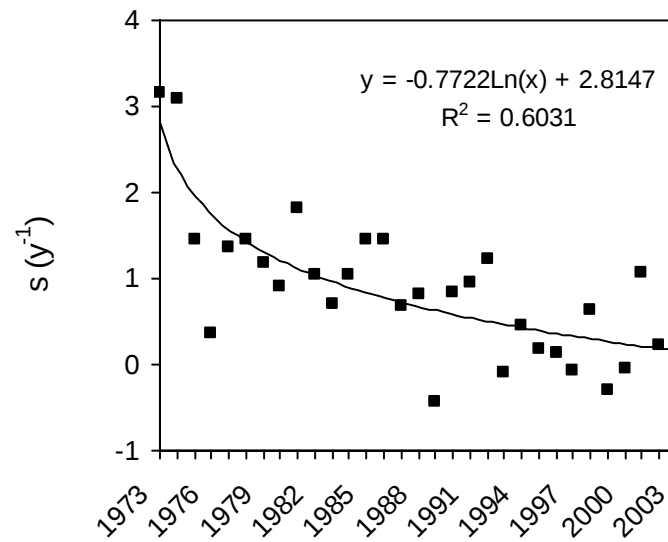
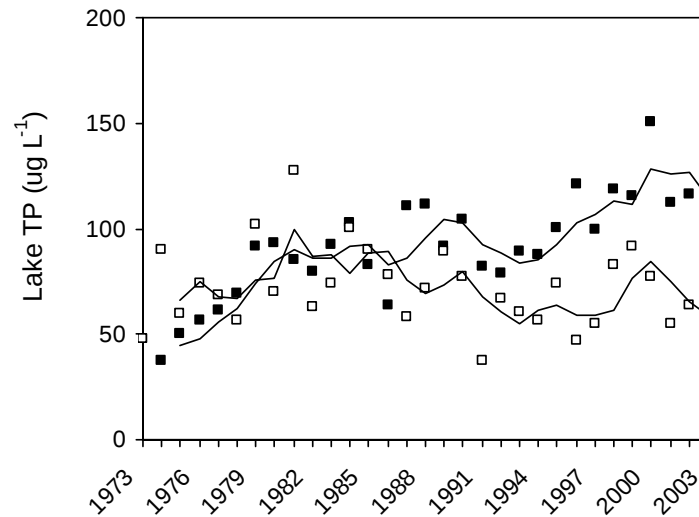
A**B**

Figure 10-15. Panel A: Historical changes in the net sedimentation coefficient(s), calculated from the yearly phosphorus budget of Lake Okeechobee, showing a downward trend over time. Panel B: Historical changes for TP concentrations in lake water, comparing measured values (filled squares), with corresponding yearly values calculated from a simple Vollenweider type model (open squares). Figures copied from Havens and James (in press, Lake and Reservoir Management).

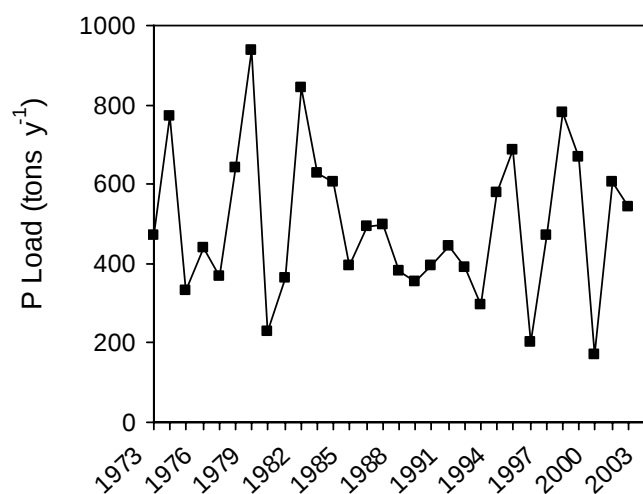
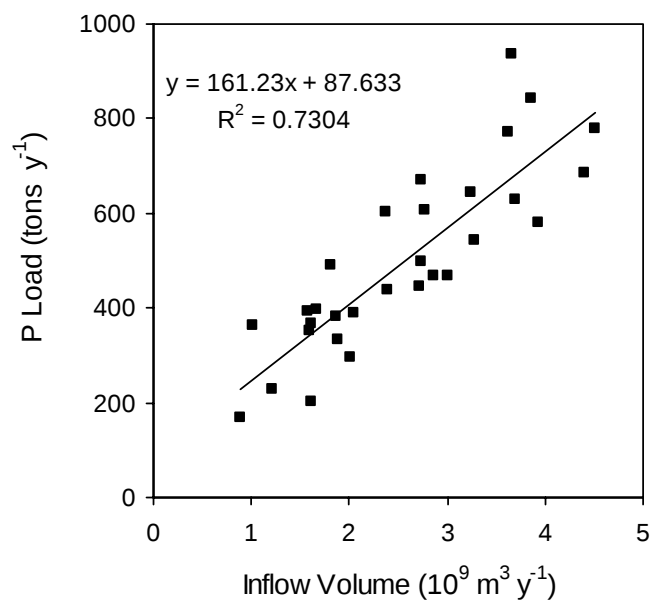
A**B**

Figure 10-16. Panel A: Historical trend in the yearly load of phosphorus entering Lake Okeechobee from its tributaries. Panel B: The relationship between yearly phosphorus loading and inflow water volume. Figures copied from Havens and James (in press, Lake and Reservoir Management).

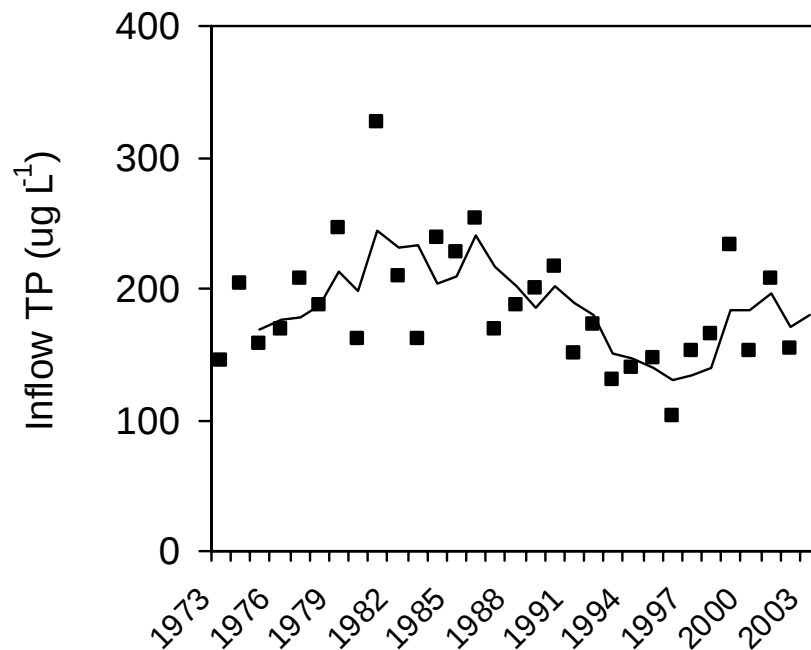


Figure 10-17. TP concentrations (flow weighted) in tributary inflow water to Lake Okeechobee. Data are yearly means from 1973–2003. Figure copied from Havens and James (in press, Lake and Reservoir Management).

The lack of correlation between lake water TP and external loads, and the historical decline in predictive ability of a simple input-output model, is consistent with results from other shallow eutrophic lakes with long histories of high external phosphorus loading (e.g., Sas, 1989; Jeppesen et al., 1991; Sondergaard et al., 1993). As noted by van der Molen and Boers (1994), who studied the responses of 49 shallow Dutch lakes to phosphorus load reduction, “for lakes without a reduction of external loading the phosphorus concentration is determined by the external loading and hydraulic loading” (i.e., can be explained with a simple model, which was the case for Lake Okeechobee in the 1970s), whereas “for lakes where external loading is reduced, the measured internal loading explains most of the variation in lake concentration” (as now is the case for Lake Okeechobee). It may be expected that years or decades after external phosphorus loads are substantially reduced, Lake Okeechobee would begin to display a decline of in-lake TP, when sediments and water reach a new equilibrium. This is the result predicted by more of the complex mechanistic models that are necessary to make predictions about this lake. Specifically, the SFWMD has been using a model called the LOWQM (Lake Okeechobee Water Quality Model), which is modified from the USEPA’s WASP (Water Analysis Simulation Package) to simulate long-term trends in water quality in the lake. The LOWQM is a mixed reactor model that does not consider ecological zones; however, it does explicitly simulate sediment-phosphorus interactions in the phosphorus and nitrogen cycles, and it predicts the biomass of cyanobacteria and two other algal groups (James et al., 1997). This model has been used to make long-term predictions about lake response to external phosphorus load reductions and in-lake sediment management alternatives, as further discussed below.

Nitrogen, Light, Nutrient Ratios, and Plankton Dynamics

Surface blooms of phytoplankton (suspended algae) are one of the most conspicuous problems of highly eutrophic lakes. They can cause aesthetic impairment, taste and odor problems for drinking water, and in some cases, they can have toxic effects on fish, wildlife, and domestic animals (Paerl, 1988; Paerl et al., 2001). Therefore, understanding how the occurrence of blooms is related to nutrient levels is critical to setting nutrient reduction goals for impacted lakes, as well as for making accurate predictions about how water quality will improve when nutrient loads are reduced. In shallow lakes with high amounts of sediment resuspension and possible light limitation, understanding how phytoplankton responds to underwater irradiance also is necessary for developing useful predictive models. This section summarizes historical changes in the lake's phytoplankton, and provides a synopsis of past studies regarding phytoplankton limiting factors in Lake Okeechobee.

METHODS

At the same eight locations where long-term TP data are collected, monthly samples are also collected for determination of total nitrogen (TN), dissolved inorganic nitrogen (DIN), and soluble reactive phosphorus (SRP), chlorophyll *a*, and Secchi disk transparency. All of these attributes have specified restoration goals and are also measured monthly at an array of approximately 30 stations in the near-shore zone (**Figure 10-14**, white circles). This section of the chapter considers how nutrient-chlorophyll relationships differ between the pelagic and near-shore zones since this is critical to understanding the factors controlling phytoplankton biomass and algal blooms in the lake, and to establishing long-term ecosystem restoration expectations. The SFWMD also conducts quarterly sampling of phytoplankton, bacteria, protozoa, and zooplankton at one station in each ecological zone, and performs measurements of integral primary productivity, bacterial productivity, and nutrient-addition bioassay experiments. Summary results are presented below to describe both major historical patterns and contemporary conditions in that community.

RESULTS AND DISCUSSION

When the phytoplankton assemblage of Lake Okeechobee was first quantified in the late 1970s, diatoms dominated in terms of their relative biovolume, followed by cyanobacteria (blue-green algae) and then chlorophytes (green algae) (Marshall, 1977). In the 1970s, when nutrient-addition bioassays were performed with the lake's phytoplankton, nitrogen and phosphorus limitation were approximately equal in occurrence (Brezonik et al., 1979). In contrast, the contemporary phytoplankton assemblage is strongly dominated by cyanobacteria. In nutrient-addition bioassays performed since 1995, there were no occurrences of phosphorus limitation. Likewise, Aldridge et al. (1995) documented that nitrogen was the limiting nutrient when they conducted phytoplankton nutrient-addition bioassays in the early 1990s. This apparent switch from phosphorus to nitrogen limitation in the lake, coincident with a change in phytoplankton community structure, has been linked to excessive TP loading, which has resulted in a surplus of SRP in the lake water (Havens, 1995a; Havens and Schelske, 2001). Further, the switch to cyanobacteria dominance is consistent with nutrient ratio theory and simple empirical models. The pelagic (eight stations) TN:TP ratio has declined from near 30:1 in the 1970s to below 15:1 in recent years (**Figure 10-18**, Panel A), and the DIN:SRP ratio has declined from over 16:1 to about 6:1 in the same time period. The critical ratios for cyanobacteria dominance are considered to be $TN:TP < 22:1$ (Smith et al., 1995) and $DIN:SRP < 10:1$ (Horne and Commins, 1987). Plotting percent cyanobacteria (yearly means) from Lake Okeechobee in the context of data reported by Smith (1985) further supports the concept that nutrient ratios have played a role in the observed change in dominance (**Figure 10-18**, Panel B).

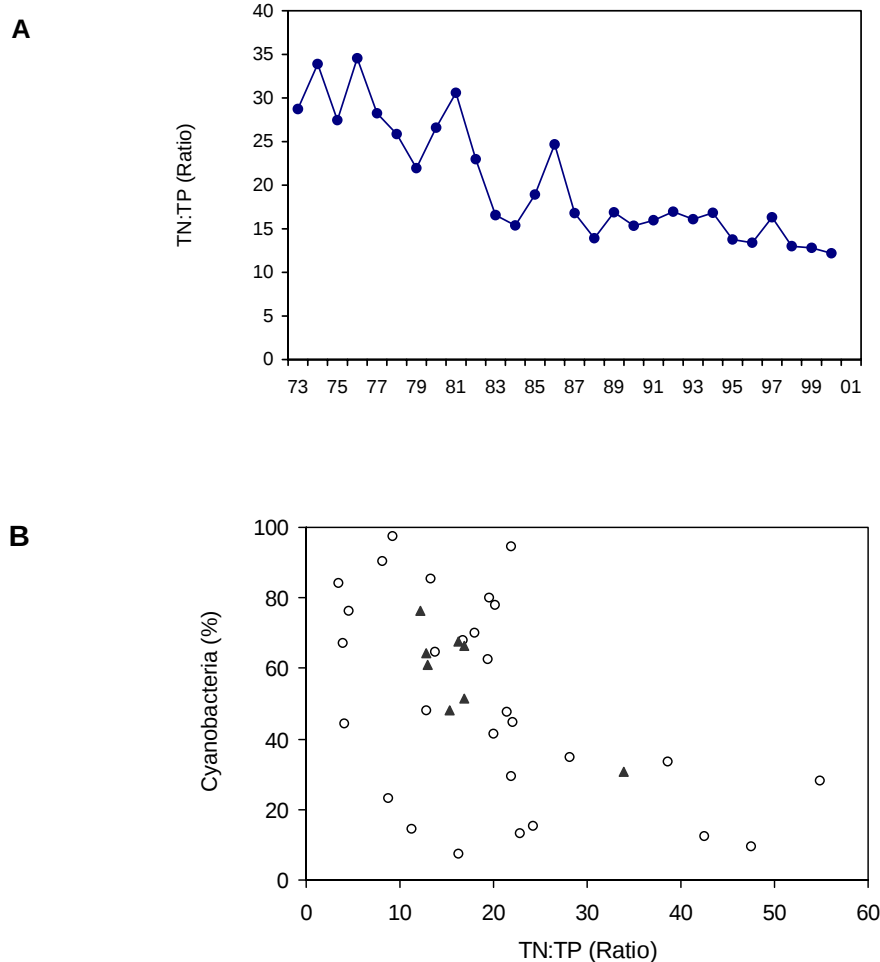


Figure 10-18. Panel A: Historic trend in the pelagic TN:TP ratio in Lake Okeechobee. Panel B: The percent of total phytoplankton biomass due to cyanobacteria plotted against pelagic TN:TP. Triangles are Lake Okeechobee data and open circles are data from Smith (1985). Figures copied from Havens et al. 2003).

The percentage of nitrogen-fixing cyanobacteria in Lake Okeechobee is lower than what has been observed in other lakes with such low ratios of TN:TP and DIN:SRP (Havens et al., 2003). This has been attributed to the low underwater irradiance that characterizes the North, Central, and Transition zones of this lake. In these areas, the dominant cyanobacteria are non nitrogen-fixers such as *Planktothrix* and *Lyngbya*, which can maintain net growth at very low light levels (Havens et al., 1998). When the pelagic region experiences prolonged (weeks) calm, hot weather, blooms of nitrogen-fixing cyanobacteria (*Anabaena*, *Aphanizomenon*, *Microcystis*) develop over large areas of the pelagic zone (Jones, 1987). In contrast, the near-shore (Edge) zone displays frequent algal blooms, especially in sheltered embayments and during winter months when submerged vascular plant and periphyton growth are suppressed by short photoperiod and seasonally deeper water (Phlips et al., 1995b). In that region of the lake, there is tight coupling between increased biovolume of nitrogen-fixing cyanobacterial, density of heterocysts (specialized cells where nitrogen-fixation occurs), nitrogen-limitation as evidenced by nutrient-addition bioassays, and depletion of DIN from the water (Phlips et al., 1997). In contrast, the pelagic zone typically displays little or no phytoplankton growth response to added nitrogen, less frequent DIN depletion, and limitation of phytoplankton by light.

The striking difference between the pelagic and near-shore zones is also evidenced by looking at relationships between nutrients and chlorophyll *a*. In the pelagic zone, there is no statistically significant relationship, whereas in the near-shore zone, chlorophyll *a* is significantly correlated with both TN and TP. In the pelagic zone, chlorophyll *a* concentrations typically are two or threefold lower than in the near-shore zone, and this is again attributed to pelagic light limitation (Havens, 2004). The seston (and its associated nutrients) in the pelagic zone is largely comprised of resuspended sediment particles, whereas in the near-shore zone, a large percentage of the particulate nitrogen and phosphorus in the water column occurs in algal cells (Havens, 1995b). With regard to lake restoration, it is expected that in the near-shore zone, there will be substantive reductions in phytoplankton chlorophyll *a* and algal blooms when external phosphorus loads are reduced (Walker and Havens, 1995; Havens and Walker, 2001), but anticipate that chlorophyll *a* may not change appreciably from its present moderate values in the pelagic zone. From a resource-use perspective, this kind of heterogeneous response is not a concern because the near-shore and littoral zones provide nearly all of the ecosystem services, including drinking water, wildlife habitat, fisheries spawning habitat, and recreational uses (Aumen, 1995).

With regard to other components of the plankton, which were studied extensively from 1995 to 2002, only a brief overview will be presented. Havens et al. (1996b) performed a series of zooplankton enclosure experiments in the lake's four ecological zones, and documented that grazing by zooplankton does not control phytoplankton biomass or species dominance in this lake. Havens and East (1996) conducted grazing studies using radio-labeled phytoplankton, and documented that there also is little transfer of carbon and energy from phytoplankton to zooplankton, and Havens et al. (2000) showed that major pathways for carbon and energy flow in this lake's pelagic food web are from bacteria > protozoa > zooplankton > fish. These results occur because the dominant zooplankton are small species that only graze small algae and bacteria, and the dominant algae are rather large and therefore not available as food for the zooplankton. Together, these results have two implications for resource management: (1) the algae that form blooms in this lake are unchecked by grazers, which allows them to attain a higher biomass than if they were being actively consumed, and (2) the pelagic food web is not efficient at transporting energy upward to fish (Havens et al., 2000). With a substantial reduction of water column phosphorus concentrations, it is expected that a reduction in the prevalence of large cyanobacteria, reduced occurrence of blooms, and perhaps a more efficient food web. Likewise, the lake's benthic invertebrate community, which in much of the pelagic sediments has become extremely dominated by pollution-tolerant oligochaete worms (Warren et al., 1995), is

expected to change back slowly to a more diverse community, and also provide a better quality food source for the lake's fishery. It remains to be determined how the biomass and productivity of fish in the lake will change in response to a simultaneous reduction in total biomass of plankton and benthos, in addition to improvements in the quality of those assemblages as food resources; both trends are expected to accompany reduced nutrient levels in the lake.

Submerged Aquatic Vegetation

SAV plays a key role in shallow lakes because it influences the biomass of phytoplankton and the transparency of water by a variety of mechanisms. These include stabilization of sediments by roots, reduction of shearing stress to sediment surfaces, uptake of nutrients by attached periphyton, and precipitation of phosphorus with calcium when intense photosynthesis results in high water column pH (Murphy et al., 1983; Dennison et al., 1993; Scheffer, 1998; Vermaat et al., 2000). Lakes with dense SAV can have clear water and low phytoplankton biomass, and then switch to having turbid water with algal blooms if the plants are lost (Scheffer, 1989; 1998). Some lakes even have shallow areas with SAV and clear water adjacent to deeper areas with no SAV and turbid water (Scheffer et al., 1994). This is the situation that exists in Lake Okeechobee as suggested by Philips et al. (1993b), and then documented by Havens et al. (2004b). The near-shore zone switches between a SAV/clear water state when water levels are low to a phytoplankton/turbid water state when there are periods of prolonged high water levels (Havens et al., 2001a; Havens, 2003; Havens et al., 2004).

METHODS

The SAV community is sampled in two projects that vary in temporal and spatial scale. On a quarterly basis, the SFWMD collects SAV samples along 15 transects (**Figure 10-19**) that extend from the shoreline to deeper water in the south, west, and north near-shore regions known to support SAV under favorable conditions. No transects are located along the east shore, which has deeper water and high turbidity, and does not support SAV. Along each transect, there are a number of fixed sampling locations with known GPS coordinates. The station closest to the shore is sampled first, and then subsequent stations are sampled out to deeper water until a station is encountered with no plants. Triplicate samples of approximately 0.3 m² are collected at each station with a pair of garden rakes modified to produce a tong-like device. Dry weight biomass is determined for each species of vascular plant and macro-algae (e.g., *Chara*). Additional details on the sampling methods and laboratory processing are provided in Havens et al. (2004). Maps showing results of transect surveys are updated on quarterly basis on the District's Website at http://www.sfwmd.gov/org/wrp/wrp_okee/2_wrp_okee_inlake/quarterlysampling.html.

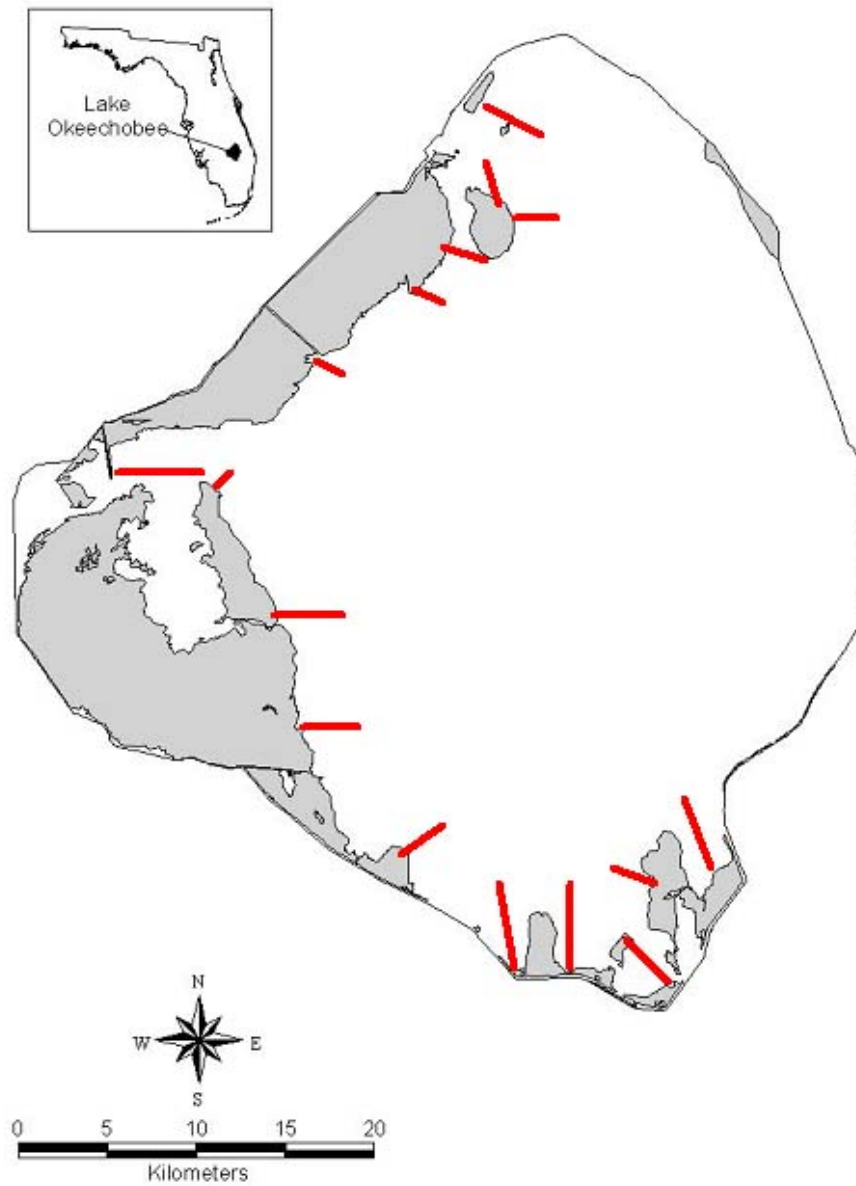


Figure 10-19. Map of Lake Okeechobee showing the locations of near-shore transects where quarterly sampling of submerged aquatic vegetation (SAV) biomass occurs.

On a yearly basis, the entire near-shore zone is mapped in order to determine the spatial extent of each SAV species. Mapping is done during a period of two to three weeks in July–August (the peak of SAV biomass) on a 1 x 1 km resolution sampling grid developed in Geographic Information Systems (GIS) and loaded into Global Positioning Systems (GPS) units so that the center-point of each grid cell can be located in the field. Samples are collected in the same manner as in the quarterly sampling, but only species presence/absence and a qualitative estimate of biomass (sparse, moderate, dense) are made. Depth, transparency, and sediment type also are recorded. Sampling is done in consecutive rows of grid cells, again working toward deeper water until a cell is encountered with no plants. Depending on the spatial extent of SAV, between 300 and 600 sites are sampled per year in this project. Because field data are entered into electronic logging devices in the field and then downloaded into GIS, map development occurs almost immediately after sampling. Additional details regarding field sampling and map development are provided in Havens et al. (2002). Maps for SAV taxa from 2000–2003 can be viewed on the South Florida Water Management District's Website at http://www.sfwmd.gov/org/wrp/wrp_okee/2_wrp_okee_inlake/savmaps.html.

RESULTS AND DISCUSSION

Quarterly sampling of SAV indicates a seasonal pattern in biomass, with maxima in late summer and minima in winter (Havens et al., 2004). Interannual variation in water level also influences SAV biomass, and on a lake-wide basis, approximately 50 percent of the variation in biomass of the plants can be predicted using a multiple regression model with two variables, depth and suspended solids. On a station-by-station basis, these two attributes also are most important for predicting biomass (Havens, 2003), but account for a smaller percentage of the variability between stations and dates, suggesting the importance of other factors such as sediment type, wind exposure, and perhaps bottom slope in determining biomass of particular SAV species at any given time and place in the lake. The District's ongoing experimental research and model development to address this issue is described in a subsequent section of this chapter.

In addition to total biomass, the quarterly SAV sampling program has provided insight into succession in the plant community following recovery from high water stress. In the late 1990s, most of the SAV biomass had been eliminated from the lake due to several years of high water and impacts of windstorms (Havens et al., 2001). After the 2000–2001 drought, the SAV community developed a high biomass and there was a succession of taxa, starting with nearly a mono-culture of *Chara*, then a diverse assemblage of *Vallisneria*, *Potamogeton*, and *Najas*, and most recently, increased dominance of *Hydrilla*. Havens et al. (2004b) described a conceptual model based on these results, suggesting that the near-shore region has three possible endpoints depending on water depth and wind conditions: (1) turbid water with phytoplankton dominance; (2) clear water with *Chara* dominance; or (3) clear water with vascular plant dominance (**Figure 10-20**). Future experimental research dealing with community assembly (Keddy, 1999) will test this hypothesis. Understanding the mechanisms driving the near-shore zone to one of these states is critical to lake management because the clear water/vascular plant state is the one that provides the greatest level of ecosystem services, including public water supply and a recreational fishery.

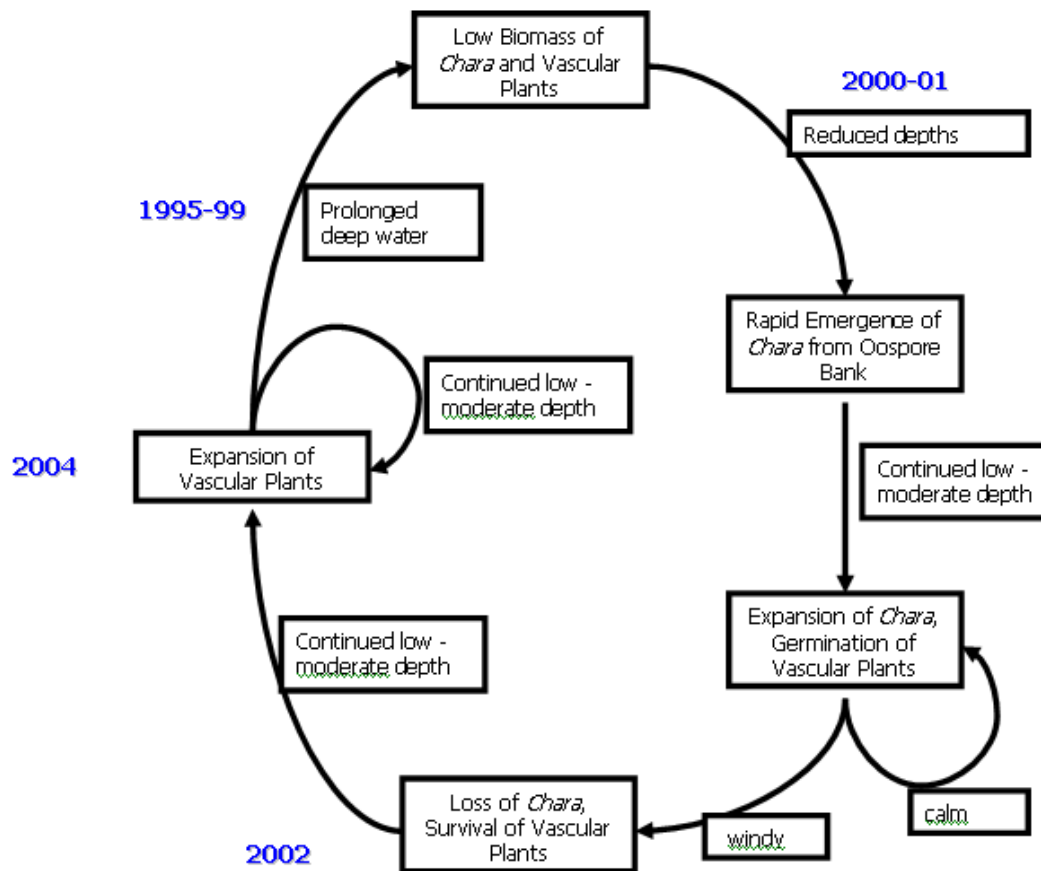


Figure 10-20. Conceptual model to explain occurrence of three states in Lake Okeechobee – no submerged plants, dominance by *Chara*, or dominance by vascular submerged plants. Developed on the basis of information presented in Havens et al. (2004).

The most recent SAV map (August 2004) indicates approximately 22,000 hectares of plants (**Figure 10-21**); this is a substantial increase over the 12,600 hectares found in August 2003 (**Figure 10-22**), and is attributed to low water conditions that occurred in spring 2004. This allowed for good light penetration in the near-shore water column, which in turn led to increased growth rates of plants. The spatial extent and biomass of SAV may have been substantially reduced by wind, wave, and high water caused by three hurricanes that passed directly over or just to the north of the lake in August and September 2004 (Hurricanes Charley, Frances, and Jeanne). Quantitative analysis of the hurricane impact is ongoing, and it is anticipated that these results will be presented in the 2006 *South Florida Environmental Report*. As indicated by the quarterly survey results noted above, the SAV assemblage was dominated by *Chara* in 2000–2001, and then switched to a mixed community of vascular plants in 2002–2004. In 2005, *Chara* expanded out into deeper water areas, and once again became the dominant plant in the submerged assemblage.

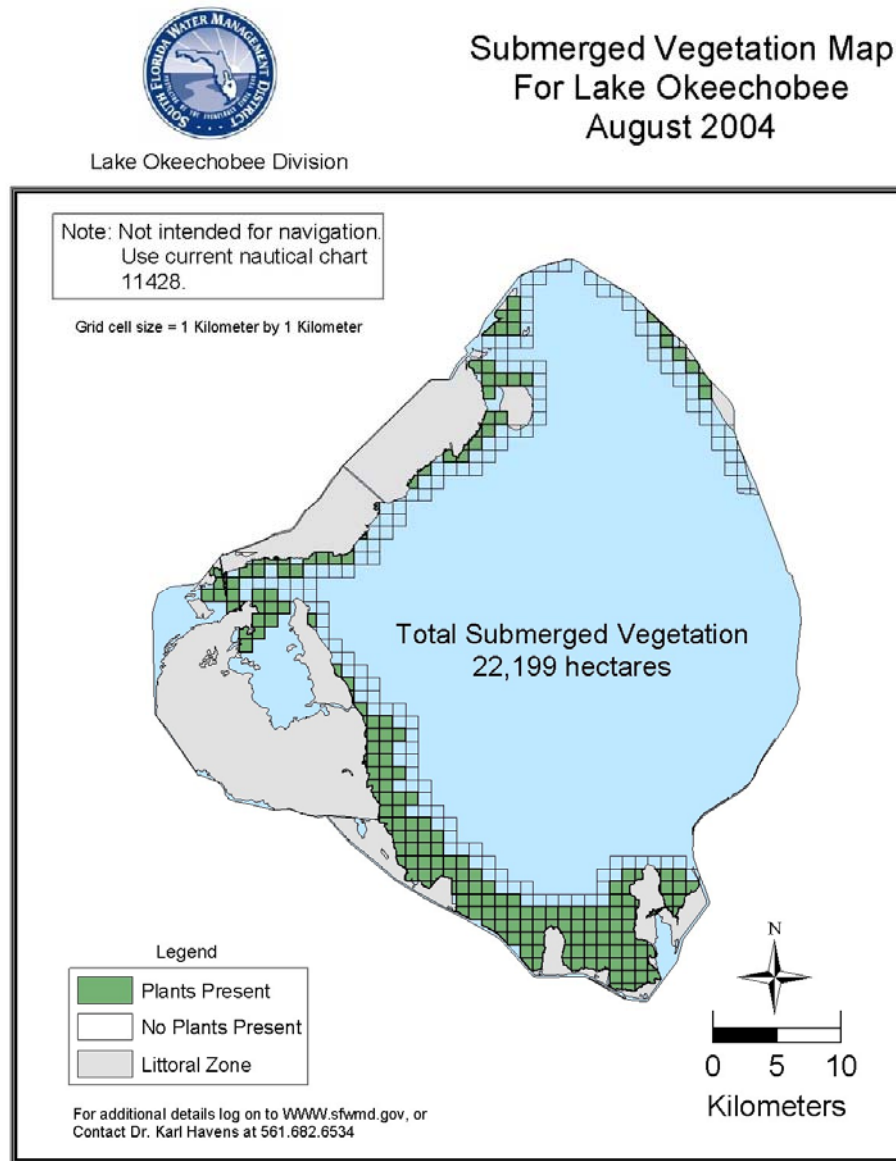


Figure 10-21. Map of SAV developed in August 2004. Grid cells correspond to sampling locations. White and green cells indicate no plants and plants, respectively. As indicated in the text, these data are qualitative. The spatial distribution of individual species can be found on the District's Website at http://www.sfwmd.gov/org/wrp/wrp_okee/2_wrp_okee_inlake/savmaps.html.

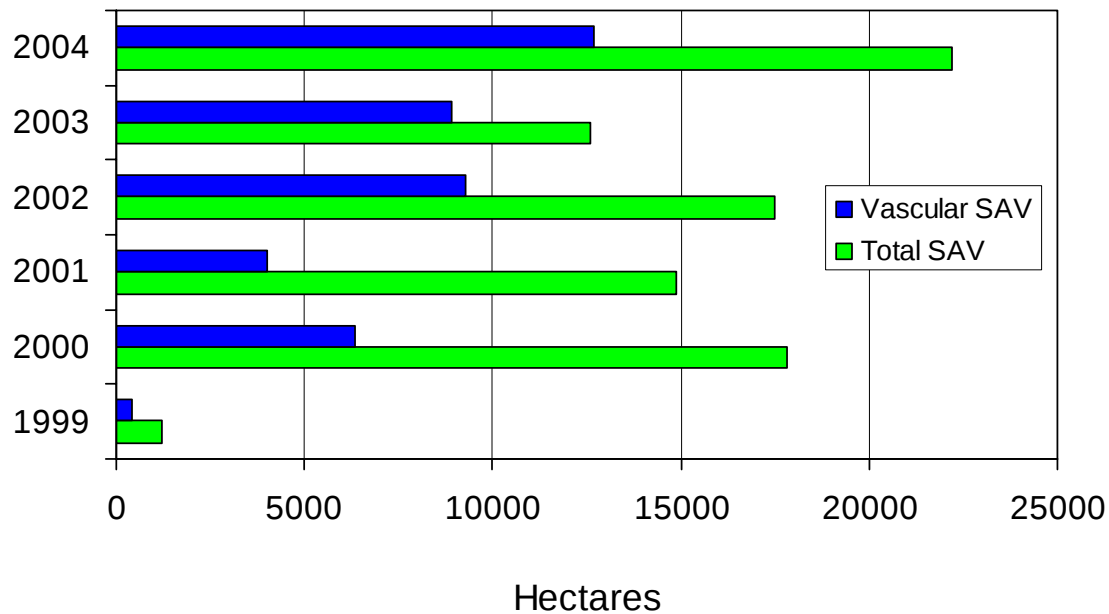


Figure 10-22. Spatial extent of total and vascular SAV in Lake Okeechobee during the six years when spatial sampling has been conducted. The 1999 data is an estimate based on qualitative surveys from boat, without a defined sampling grid. The difference between total and vascular SAV reflects the spatial extent of the lake's bottom with a monoculture of *Chara*.

The yearly maps of SAV coverage are used to provide scores for one of the priority performance measures that is reported to the U.S. Congress for RECOVER (see Chapter 7 of the 2005 SFER – Volume I for additional information on RECOVER). The performance target for this measure is to maintain 20,000 hectares of total SAV, with at least 50 percent due to vascular taxa. Under existing circumstances, this spatial extent is attained in certain years, although in a relatively high percentage of years it is lower due to sustained high water.

Emergent Aquatic Vegetation

The western 25 percent (400 km²) of Lake Okeechobee is a diverse littoral community that provides spawning and foraging habitat for fish, wading birds, migratory water fowl, and the federally endangered Everglades snail kite (*Rosthrhamus sociabilis plumbeus*) (Aumen, 1995; Bennetts and Kitchens, 1997). The littoral zone has been extensively studied, with a primary focus on effects of hydroperiod and sediment type on emergent plants (Richardson et al., 1995), responses of periphyton and invertebrates to increased nutrient inputs (Havens et al., 1999; 2001b; 2004a), and temporal variations in vegetation structure (Richardson and Harris, 1995). In recent years, there has been more intensive focus on the interface between the littoral and near-shore zones because this area appears to be most dynamic in terms of changes in vegetation structure (Hanlon and Brady, in review).

METHODS

GIS maps of the entire littoral zone are developed every five to seven years by the SFWMD. Images of the area are taken with 1:12,000 scale color infrared (CIR) aerial photography. Major vegetation classes (23 total) are delineated from their unique CIR signatures using a transfer stereoscope, and vegetation maps are developed in ESRI's Arc Info[®]. The process also includes extensive ground-truthing. The most recently completed map (1996) has classification accuracy near 90 percent. A current map is under development, and it is anticipated that this updated version will be presented in next year's report.

In addition to this large-scale effort, the SFWMD develops maps every other year to assess the spatial extent and distribution of torpedograss because this exotic plant is the focus of an ongoing eradication program. Mapping is also performed every other year to quantify spatial extent of the "bulrush zone," a band of emergent plants dominated by bulrush (*Scirpus californicus*) that occurs about 300 m from the littoral edge and extends for approximately 30 km along the western shoreline, in the area referred to above as the near-shore zone. The dynamic emergent plant community that occurs between bulrush and the littoral zone also is mapped in this project.

The SFWMD also has an ongoing remote sensing project to determine whether accurate vegetation maps can be developed using hyperspectral and radar data. These methods may be most useful for programs that require vegetation classification at a rather coarse level, such as the mapping of yearly torpedograss (*Panicum repens*) distribution.

RESULTS AND DISCUSSION

The most recent littoral zone vegetation map (Hanlon and Brady, in review) indicates that there are 31,500 ha of emergent plants (**Figure 10-23**). Cattail and mixed cattail with other emergent plants were the most abundant classes, covering more than 10,000 ha. Torpedograss is the second most abundant class (5,400 ha), followed by spikerush (3,900 ha), fragrant water lily (3,300 ha), and willow (2,000 ha). These results are quite different from what was reported in a vegetation map developed in the early 1970s (Pesnell and Brown, 1976), when the littoral zone had less than 8,000 ha of cattail, located only along the western edge of that region, with dominant taxa in the interior regions being beakrush, spikerush, mixed native grasses, and cord grass. Beakrush and cord grass are short hydroperiod plants that occurred in the higher elevation areas of the littoral zone where monocultures of torpedograss now occur. Much of the habitat formerly occupied by spikerush in the longer hydroperiod areas has now been taken over by cattail and water lily. These later changes are linked to higher water levels and/or transport of phosphorus into the interior littoral zone along boat trails (Havens, 1997; Hanlon and Brady, in review).

Mapping of bulrush and other shoreline emergent plants indicates that in the late 1990s, when water levels were high for several years and substantial wave energy reached the littoral edge, there were losses of emergent vegetation 300 m to 500 m wide and up to several km long along the western shore. Those areas became open water by 1999. The spatial extent of bulrush also was reduced, but not to the extent observed for other plants. During 2000–2002, the emergent plant community recovered in the area between the bulrush and littoral zones, when over 800 ha of spikerush and mixed grasses developed in that area. This response may be partially responsible for the changes in population dynamics of largemouth bass described in the next section of this chapter.

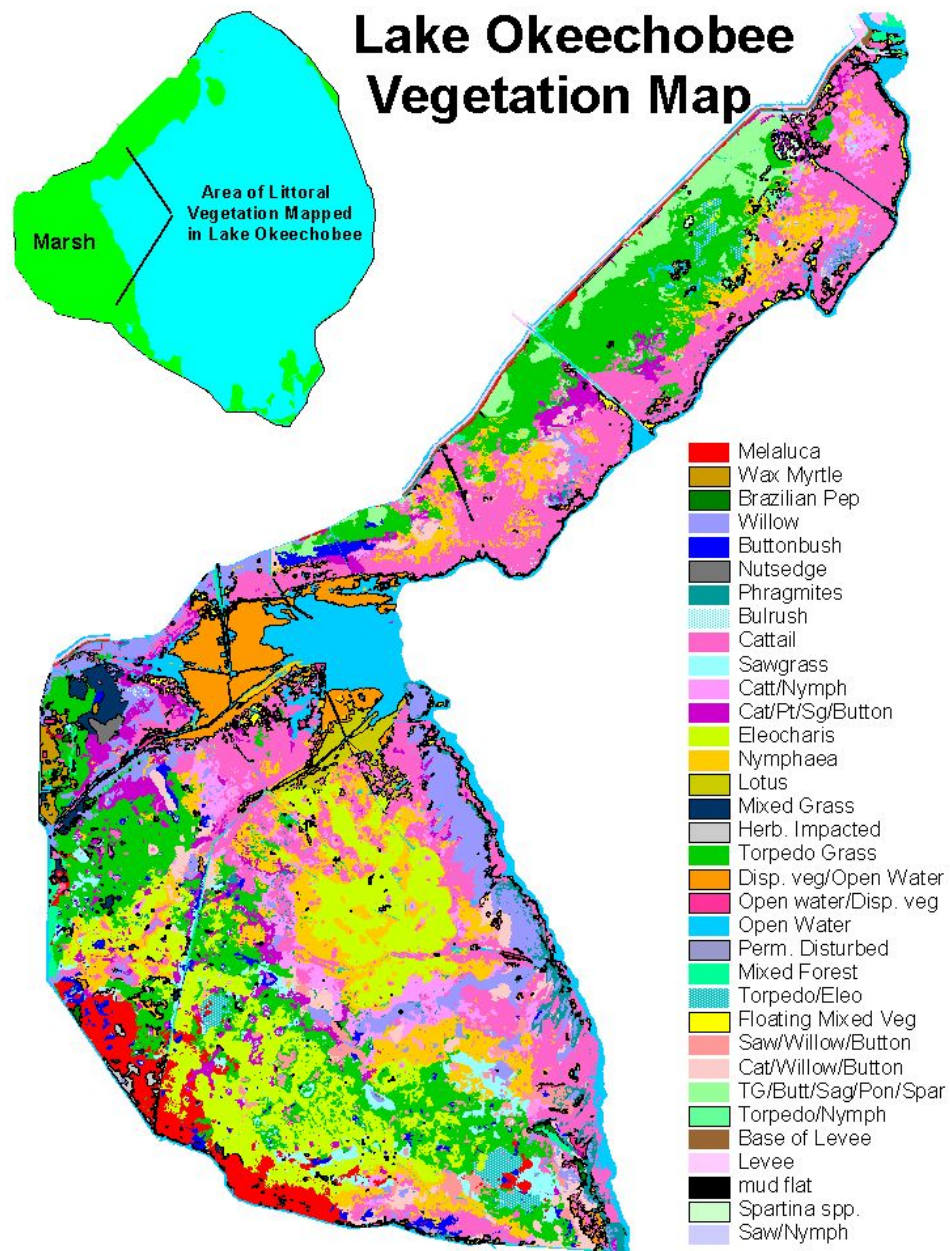


Figure 10-23. Geographic Information System map of vegetation in the littoral zone of Lake Okeechobee, based on aerial photography taken in 1994 and 1996.

Population Dynamics of Largemouth Bass

The fish assemblage of Lake Okeechobee includes over 25 taxa that vary in relative biomass among the pelagic, littoral, and near-shore zones (Furse and Fox, 1994; Bull et al., 1995). Dominant species (based on their numeric density) include: threadfin shad (*Dorosoma petenense*), black crappie (*Pomoxis nigromaculatus*), bluegill (*Lepomis macrochirus*), white catfish (*Ameiurus catus*), gizzard shad (*Dorosoma cepedianum*), redear (*L. microlophus*), and Florida gar (*Lepisosteus platyrhincus*). At this time, long-term sampling is performed by the Florida Fish and Wildlife Conservation Commission (FWC) for just two species of economic importance: largemouth bass (*Micropterus salmoides*) and black crappie. Largemouth bass are particularly important, with over 500 permitted fishing tournaments occurring on the lake each year, influxing over \$20 million to the local economy. This update focuses on changes in the population dynamics of largemouth bass in response to changes in aquatic vegetation that ultimately were controlled by water level (Havens et al., in review). Starting in 2005, RECOVER is expected to include systematic sampling of all species of fish in the lake, so that updates in 2006 and beyond will include more comprehensive information.

METHODS

In October 1999–2003, the FWC conducted annual sampling at 22 sites around Lake Okeechobee by electrofishing. The areas sampled for fish covered the entire spatial extent of the near-shore zone, plus the interior littoral zone area known as Moonshine Bay. Electrofishing gear consisted of a 5.5 m aluminum boat equipped with a 90 horsepower engine, 5,000 watt generator, and a VVP-15 coffelt electroshocker unit. Within each of the 22 sites, three repetitions of 15-minute duration were conducted totaling 990 minutes of effort. All stunned largemouth bass were collected, measured to the nearest millimeter of total length, weighed to the nearest gram, and released live. Length structure was analyzed by apportioning length frequency distributions into 2-cm length groups (i.e., those measuring between 2 cm and 3.99 cm equaled the 2-cm length group). Length frequency plots and catch rates (CPUE; fish minute⁻¹) were then generated for each of the four years. Annual length frequency plots were examined for changes in distribution patterns while observed catch rates were used to evaluate changes in density. Length frequency plots and catch rates were then compared to corresponding annual vegetation density data to evaluate possible linkages between recruitment success and vegetation expansion.

RESULTS AND DISCUSSION

There was a dramatic change in both the density and population size structure of largemouth bass during this study (**Figure 10-24**), coinciding with the onset of the diverse community of SAV and emergent shoreline plants in 2002 (**Figure 10-25**). During the bass surveys conducted in 1999–2001, common features were low CPUE values, ranging from 0.11 to 0.18 fish minute⁻¹, and a near absence of juvenile fish, indicating failed recruitment. In sharp contrast, the CPUE in 2002 was 0.41 fish minute⁻¹, and there was strong recruitment, as evidenced by large numbers of 10 to 22 cm fish in the population. This pattern continued in 2003, when the CPUE was 0.48 fish minute⁻¹. Sampling for 2004 is ongoing at this time, and it is expected that these results will be presented in the *2006 South Florida Environmental Report*. The fish results indicate that (1) the establishment of a structurally diverse aquatic plant community, rather than simply a community with high biomass, is essential for successful bass recruitment in this lake, and (2) the recovery of such a plant community can take up to two years if it has been previously eliminated by stress, in this case due to high water.

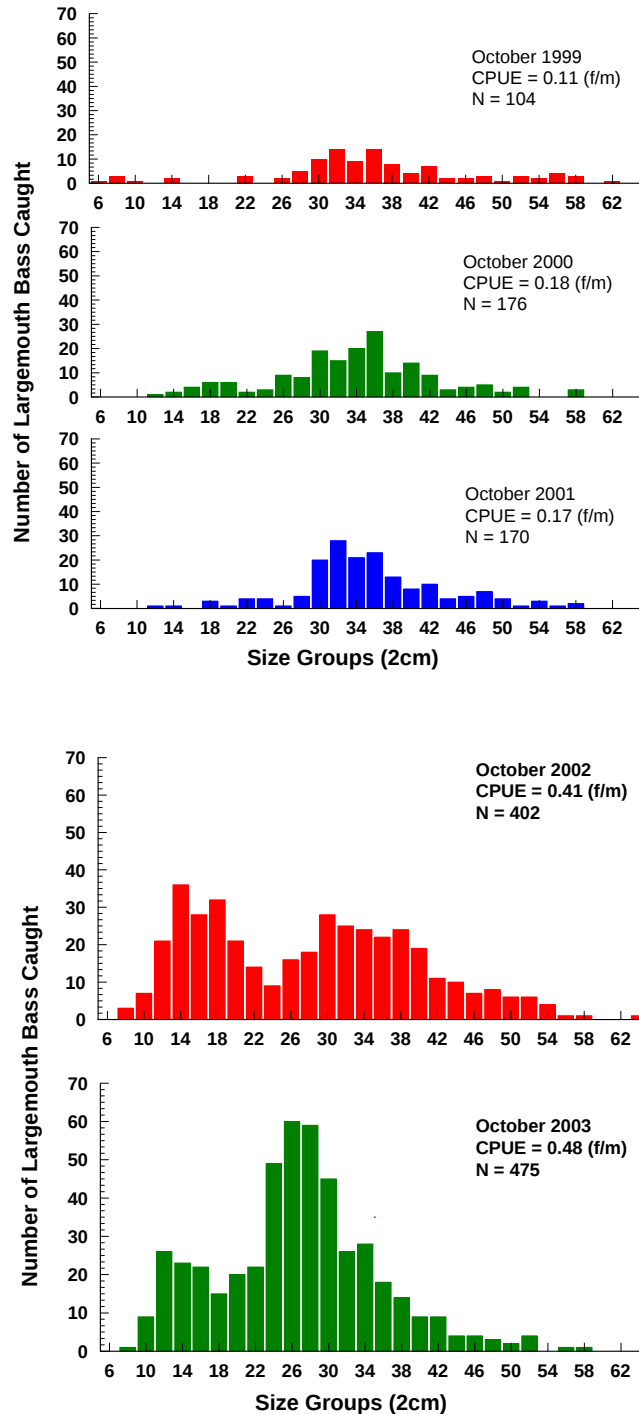


Figure 10-24. Size frequency distributions of largemouth bass caught in near-shore zone of Lake Okeechobee in 1999 to 2002 by electroshocking. Note the successful recruitment in 2002 and 2003, the years when a high density of diverse vascular SAV occurred in the lake. This figure is copied from Havens et al. (in press, *Hydrobiologia*).

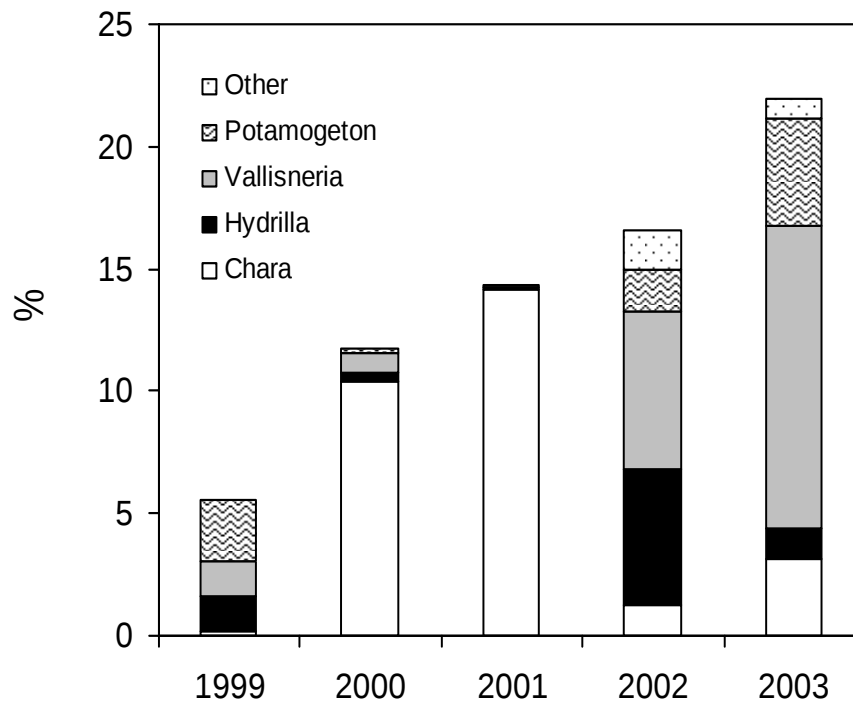


Figure 10-25. Relative biomass of submerged aquatic vegetation in the near-shore zone of Lake Okeechobee from 1999–2003. The switch from a *Chara*-dominated community to diverse vascular plants in 2002 corresponded with successful recruitment of largemouth bass.

STATUS OF LAKE PERFORMANCE MEASURES IN 2004

The previous sections provide detailed status updates on various components of the lake ecosystem. **Table 10-6** summarizes this information in the form of quantitative performance measures, restoration goals, and existing conditions. The scientific basis for the performance measures and targets were previously described.

LAKE MANAGEMENT

This section describes three recent initiatives within the lake: (1) a lake sediment management feasibility study; (2) a large-scale habitat restoration project; and (3) lake regulation schedule modification. A fourth initiative within the lake is exotic plant control, which is covered in Chapter 9 of the 2005 SFER – Volume I. The general goal of in-lake restoration is to produce improved habitat and/or water quality in a time frame that is much shorter than the anticipated time that it will take the lake to respond to the LOPA phosphorus load reductions or CERP-influenced changes in water level.

Lake Sediment Management Feasibility Study

Although inputs of phosphorus from the watershed ultimately determine the trophic status of a lake, internal recycling can be particularly important in eutrophic lakes, especially in shallow lakes where there is greater interaction between sediments and overlying water (Sas, 1989). This situation exists in Lake Okeechobee (Olila and Reddy, 1993). The lake is broad and shallow, and this creates an environment where bottom sediments enriched in phosphorus can be physically suspended into the water column by wind-induced waves. Once introduced into the water column, phosphorus that is loosely bound to sediment particles or dissolved in the sediment porewater can become available to phytoplankton, stimulating their growth. Internal phosphorus loading also occurs as a result of natural chemical and biological processes. Together, these internal releases of phosphorus to the water column are hypothesized to contribute to increased frequency of blue-green algae blooms and decreased water quality in the lake. Moreover, if internal loading is not addressed, the lake possibly may not respond to reductions in external phosphorus inputs (Steinman et al., 1999), or the response may be significantly delayed.

The Lake Okeechobee Sediment Management Feasibility Study, conducted by Blasland, Bouck & Lee, Inc., Tetra-Tech, Inc., Environmental Quality Inc., and Haysmar, Inc., was a three-year evaluation of the economic, engineering, and ecological feasibility of sediment treatment or removal (BBL, 2003). It included evaluation of expected benefits to lake water quality based on two different predictive models, a pilot dredging/on-shore sediment disposal study (**Figure 10-26** and **10-27**), and was completed in late 2003. The study design, results, and conclusions were presented in the January 2004 annual report to the Florida Legislature. The main conclusions are: (1) dredging is not a feasible or effective measure for reducing internal phosphorus loads in Lake Okeechobee; (2) chemical treatment might be effective, but should only be considered if the lake fails to respond as expected to external load reductions, due to environmental concerns about alum additions; and (3) the recommended alternative is to focus on phosphorus load reductions in the watershed.



Figure 10-26. Photographs from the pilot sediment dredging project, carried out in the central zone of Lake Okeechobee, where phosphorus-rich flocculent sediments occur. Clockwise from upper left: hydraulic dredge unit, dredge head, dredging in rough water, pumping sediment from dredge unit to barges, end of line at the barge, and sediment disposal site. (SFWMD photographs).

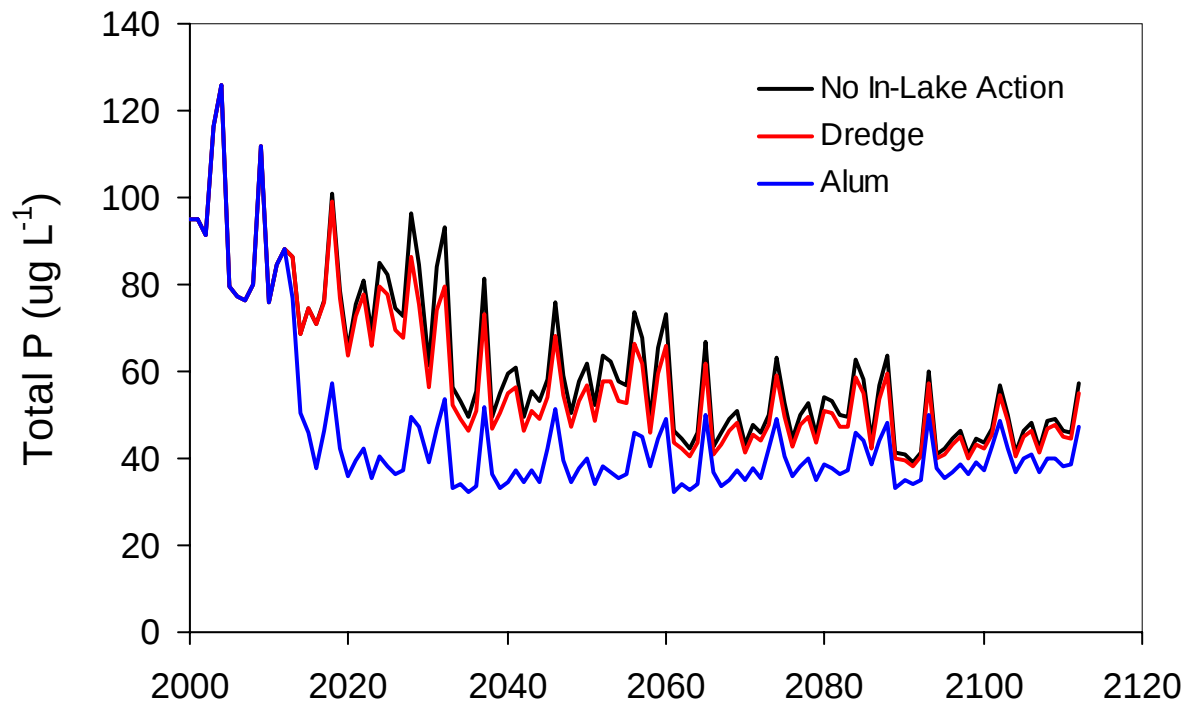


Figure 10-27. Simulation results from the Lake Okeechobee Water Quality Model showing expected trajectory of TP under three scenarios. Dredging was not found to significantly change the future trend in lake water TP, when compared to a plan with only watershed TP reductions. Alum treatment could hasten lake recovery but there are many unknown environmental consequences that would need to be examined before such an alternative was undertaken. Alum might be considered as a supplementary action if the rate of lake response to external load reduction is slower than expected.

Lake Regulation Schedule Modification

Water levels in Lake Okeechobee are controlled in part by a USACE regulation schedule (USACE, 1999) that was adopted in 2000. The schedule, known as the Water Supply and Environment (WSE), is designed to provide necessary flood protection in the regional system, but in a manner that balances the needs of water supply, navigation, and protection of natural habitat in the lake (e.g., the littoral zone) and downstream ecosystems (east and west coast estuaries and the Everglades Protection Area). There are distinct zones where different discharge rates are specified (a typical component of USACE schedules for lakes and reservoirs) (**Figure 10-28**). These zones vary with season, so that just prior to the hurricane season (June through November), the lowest water levels are maintained in the lake, whereas later in the year, higher water levels are allowed under the schedule's operating rules. However, the unique feature of the WSE is that it has a large zone of "conditional releases" called Zone D. In this zone, release decisions are made based not only on the water level in the lake, but also on tributary hydrologic conditions,

short-term climate outlook, and factors known to influence long-term climate and rainfall in South Florida (Enfield et al., 2001), including El Niño and Atlantic Multi-Decadal Oscillation (AMO), which is a long term cyclic pattern of water temperatures in the North Atlantic Ocean. These decisions are made by following a set of ‘decision trees’ that are an integral part of the WSE schedule; they specify whether or not to release water in Zone D, and separately consider releases to the south (where the water can be stored in the WCAs), or to the east and west (where the water is lost to tide). Thus, the WSE is a proactive schedule that aims to hold water in the lake when drought conditions are anticipated and release water when conditions are expected to be wet. Decisions regarding volumes of water to release from the lake at various outlets are also adjusted based on input from experts in lake, estuarine, and Everglades’ ecology. This is done by considering a suite of science-based performance measures documented in the Adaptive Protocols for Lake Operations (SFWMD, 2003), which has been developed to complement the WSE schedule.

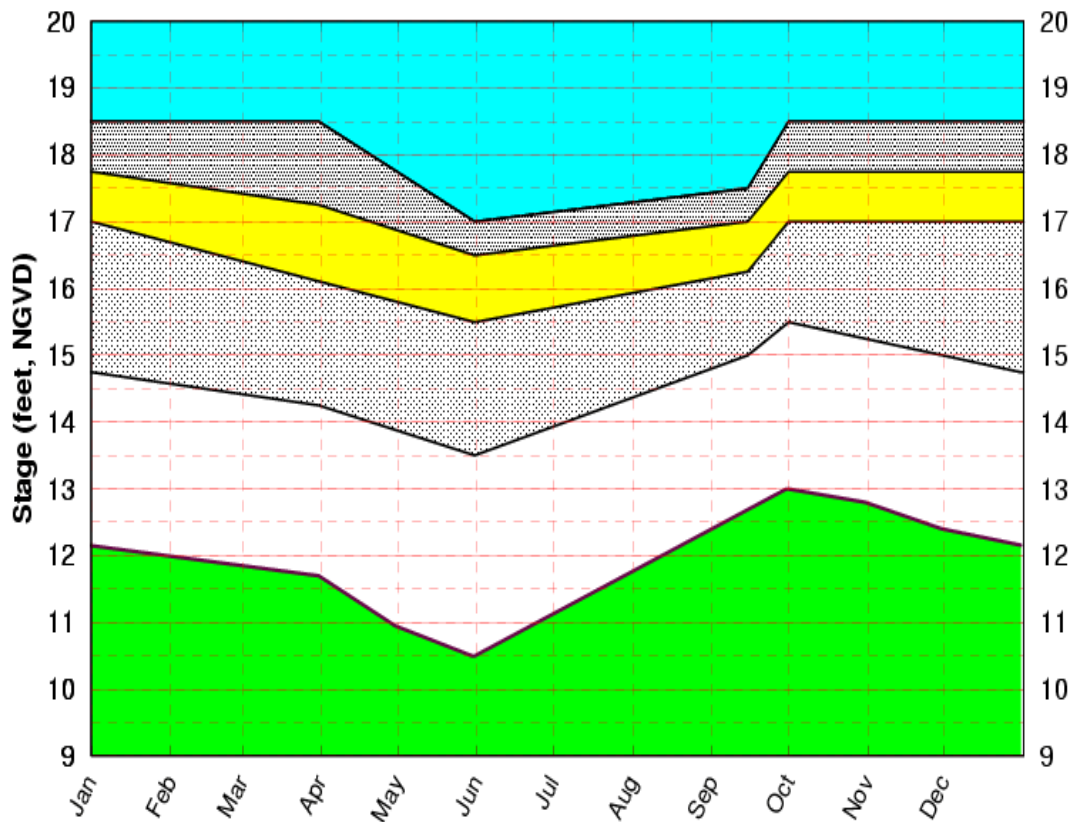


Figure 10-28. The Lake Okeechobee operating schedule, Water Supply and Environment (WSE), showing zones of flood control release (Zones A-C), flood release depending on hydrologic, meteorological, and ecological conditions (Zone D), a zone where flood control releases are not called for under any circumstances (Zone E), and a zone of water use restrictions (not part of the WSE schedule, but related to the State of Florida Water Supply Authority).

As an example of how the WSE works, consider two situations where the water level in the lake is exactly the same. In one situation, tributary conditions are very wet and the long-term climate outlook is wet because El Niño conditions exist and the AMO is in the “warm phase” (warmer than normal water temperatures in the North Atlantic). Under these conditions, the decision trees of the WSE schedule may call for “up to maximal releases to tide and the WCAs.” The amount of water to release is then determined after consultation with scientists regarding the level of risk to the lake of high water, and the potential for impacting key biota in downstream systems at different flow rates. In a second example, water level of the lake is the same, but tributary conditions are normal and the long-range climate outlook indicates a greater than average probability of low rainfall. Under these conditions, the decision tree may indicate that no regulatory (flood protection) discharges are required. The SFWMD would still release water from the lake for water supply as long as the lake levels are not so low that water use restrictions are called for. Under certain circumstances (as specified in SFWMD, 2003) it may also release water for downstream environmental benefits, for example, to prevent saltwater impacts on freshwater plants in the Caloosahatchee River.

During operation of Lake Okeechobee under the WSE schedule, the SFWMD and USACE have identified areas where performance can be improved. For example, during 2004 the use of El Niño/AMO was formally adopted by the USACE as part of the process for determining long-range climate outlook, based on research performed by the SFWMD in cooperation with the NOAA Climate Prediction Center. This increased the accuracy in making such long-range predictions. Notably, there is also tendency for the schedule to be more conservative than anticipated when the lake is in Zone D; releases are called for when stage is rising, but then stopped when stage reaches a plateau. In 2002–2003, this allowed a stepwise rise in water levels in the lake, prolonged deep water conditions in the lake’s near-shore zone, and resulted in a loss of nearly 40 percent of the submerged plant community that had recovered in 2000–2002. In addition to impacting the lake, this progressive rise in stage threatened the estuaries because when stage of the lake is near Zone C, damaging high discharges can occur for flood protection purposes.

In response to these observations and considerable input from environmental and water supply stakeholders, the SFWMD and USACE implemented a planned temporary deviation from WSE during the 2003–2004 dry season (December through May) to allow low volume water releases to occur in Zone D even when the schedule and its decision trees did not specify those releases. The releases were done as pulses that mimicked natural runoff events, and their maximal flow rates were reduced during March to May, which is known to be the spawning season for oysters in the St. Lucie Estuary (SLE) and for larval fish in the Caloosahatchee Estuary. (Refer to Chapter 12 of the 2005 SFER – Volume I for further information on the SLE and Caloosahatchee Estuary.) This temporary deviation allowed for nearly 0.8 ft of water release from Lake Okeechobee and maintained good ecological conditions in the estuaries. In fact, the rate of oyster larval settling in the St. Lucie was the highest recorded in recent years. More importantly, the deviation operation was designed to preserve water supply; the process included performance indicators to reduce or stop flows from the lake when water supply impacts were projected to occur. Recognizing the benefits of this operation, the SFWMD has requested that the temporary deviation be extended to the 2004–2005 dry season. Currently, the SFWMD and USACE also are working with stakeholders to identify further adjustments to the WSE schedule, so that we can achieve improved conditions for the lake and estuaries, recognizing that the degree of improvement is limited by the fact that alternative water storage locations are not yet available in the regional system. The schedule will continue to be refined as those projects are completed under CERP, at which time it will be possible to truly optimize performance of the lake.

Lake Okeechobee Habitat Restoration

Approximately 7,000 acres at the southern end of Lake Okeechobee (**Figure 10-29**) are occupied by three low lying islands: Torry, Kreamer, and Ritta. Anecdotal information suggests that prior to settlement, Torry and Kreamer islands were covered by dense stands of pond apple (*Anona glabra*), and the endangered Okeechobee gourd (*Cucurbita okeechobeensis*). All three islands were settled in the early 1900s, and were cleared, ditched, and bermed to produce cropland, but all had been abandoned by the mid 1970s.

The Lake Okeechobee SWIM Plan Update (SFWMD, 1993), RECOVER, and the South Florida Multi-Species Recovery Plan (USFWS, 1999) have all identified one or more of these islands as potential restoration targets with specific goals of reestablishing natural hydrologic connections between the islands' wetland habitats and the lake, and in the case of Torry and Kreamer islands, preserving Okeechobee gourd habitat and increasing the spatial extent of willow and/or pond apple to benefit wading bird populations. Removal of the man-made structures (such as dikes and some drainage canals) will increase the usage of the interior marsh by wading birds and other wildlife and will reestablish adult fish spawning grounds and larval and juvenile fish nursery grounds.

The Okeechobee gourd, strongly associated with Torry muck soil, was once commonly found in the extensive pond apple forest surrounding the southeastern shore of Lake Okeechobee in Palm Beach County, and in the Everglades, but was almost completely destroyed as early as 1930 (USFWS, 1999). It was present on Ritta, Torry, and Kreamer islands, but the conversion of local swamps and marshes to agricultural practices resulted in the decline in these annual high-climbing gourd plants. Whereas agricultural conversion was the principal form of habitat destruction for the gourd prior to 1940, current water management practices appear to be the greatest threat, along with exotic plant proliferation (USFWS, 1999). This plant is currently state and federally listed as an endangered species.

The first objective of the restoration project is to restore a natural hydrologic connection between the wetland habitat inside Ritta and Kreamer islands and the surrounding lake (**Figures 10-30** and **10-31**, respectively). Currently, no restoration work is scheduled for Torry Island because the one remnant agricultural levee already is breached, allowing substantial transfer of water between the island and the lake (**Figure 10-32**). Funding for this effort was provided from the state-appropriated Lake Okeechobee Protection Program, through a cooperative agreement between the FWC and SFWMD. This project includes the removal of the levees and ditches as well as any abandoned concrete water control structures associated with these features. This is being accomplished by backfilling the adjacent ditches with this material, and also involves the removal of exotic vegetation from the islands.



Figure 10-29. Location of three islands where habitat restoration work is occurring in cooperation with the Florida Fish and Wildlife Conservation Commission.

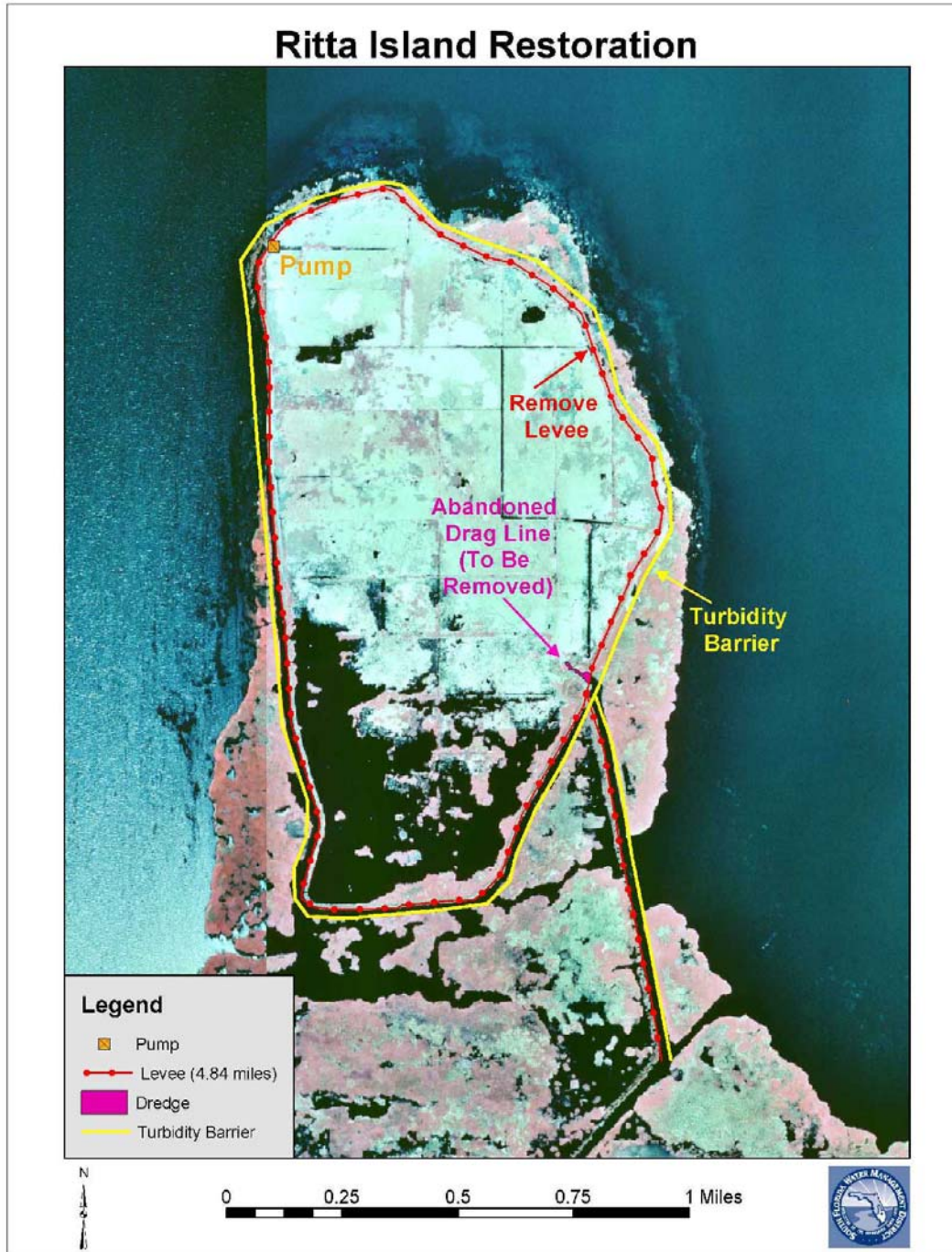


Figure 10-30. Habitat restoration plan for Ritta Island.



Figure 10-31. Habitat restoration plan for Kreamer Island.



Figure 10-32. Habitat restoration plan for Torrey Island.

ASSOCIATED PROJECTS

This project could interface with an environmental education center that has been proposed by the City of Belle Glade, Florida. While details are subject to change depending on funding, current restoration efforts focus on an existing man-made lake, the surrounding wetlands on Torry Island, and a series of existing dikes that will serve as walkways around the interior and exterior of the wetlands. An approximate 100-acre section of degraded wetland encircled by one of these dikes is being replanted in native pond apple as part of this restoration effort. The City of Belle Glade is removing exotic plants adjacent to and along the walkways to provide both access and a clear view of the wetlands of Torry Island.

CURRENT STATUS

A total of 6.76 miles of berm is scheduled to be degraded on two of the three islands; 4.84 miles of perimeter levee on Ritta Island will be completed by summer 2004. A 1.92-mile stretch of levee remnants on the south and east perimeters of Kreamer Island will be considered for removal in fall 2004, pending the outcome of the Ritta Island berm removal effort. Berm degradation is being accomplished by pushing the levee material back into the lakeside and island-side channels from where it was originally dredged. This is anticipated to cause the lakeside channel to lose approximately 1 ft in depth, resulting in a depth of approximately 5 ft at 14 ft mean sea level, with no navigational hazards expected.

LAKE RESEARCH AND MODEL DEVELOPMENT

The lake research/modeling program presently is focused on three main areas related to key uncertainties identified above: (1) developing a predictive understanding of how SAV responds to variations in underwater irradiance; (2) quantifying the role of SAV in the near-shore phosphorus cycle; and (3) enhancing an existing hydrodynamic model of the lake (Jin et al., 2000 a–c) so that it provides spatially explicit predictions regarding lake-wide water quality and near-shore SAV dynamics. As previously noted, there is also an ongoing research program aimed at optimizing methods for control of torpedograss and other exotic and nuisance plants. Further information on exotic species can be found in Chapter 9 of the 2005 SFER – Volume I.

Predicting SAV Responses to Water Level Changes

Long-term ecological assessment of the lake has identified a number of hypotheses regarding how SAV responds to prolonged periods of high water, intense wave action, and drought. Succession of SAV in the near-shore region has also been observed following two large-scale droughts that essentially reset the landscape to soil and a buried seed bank. While this information is useful, it falls short of the details needed to calibrate and verify models that can be used to predict future SAV community structure and function under conditions with the LOPA and CERP in place. CERP, in particular, is expected to alter substantially the lake's water level regime; the District is providing anticipated benefits in terms of spatial extent of SAV and littoral zone habitat expected to be improved under different planning alternatives. The District has developed a generic SAV model (**Figure 10-33**) in Stella modeling software and is conducting controlled experiments to provide parameter values for this model.

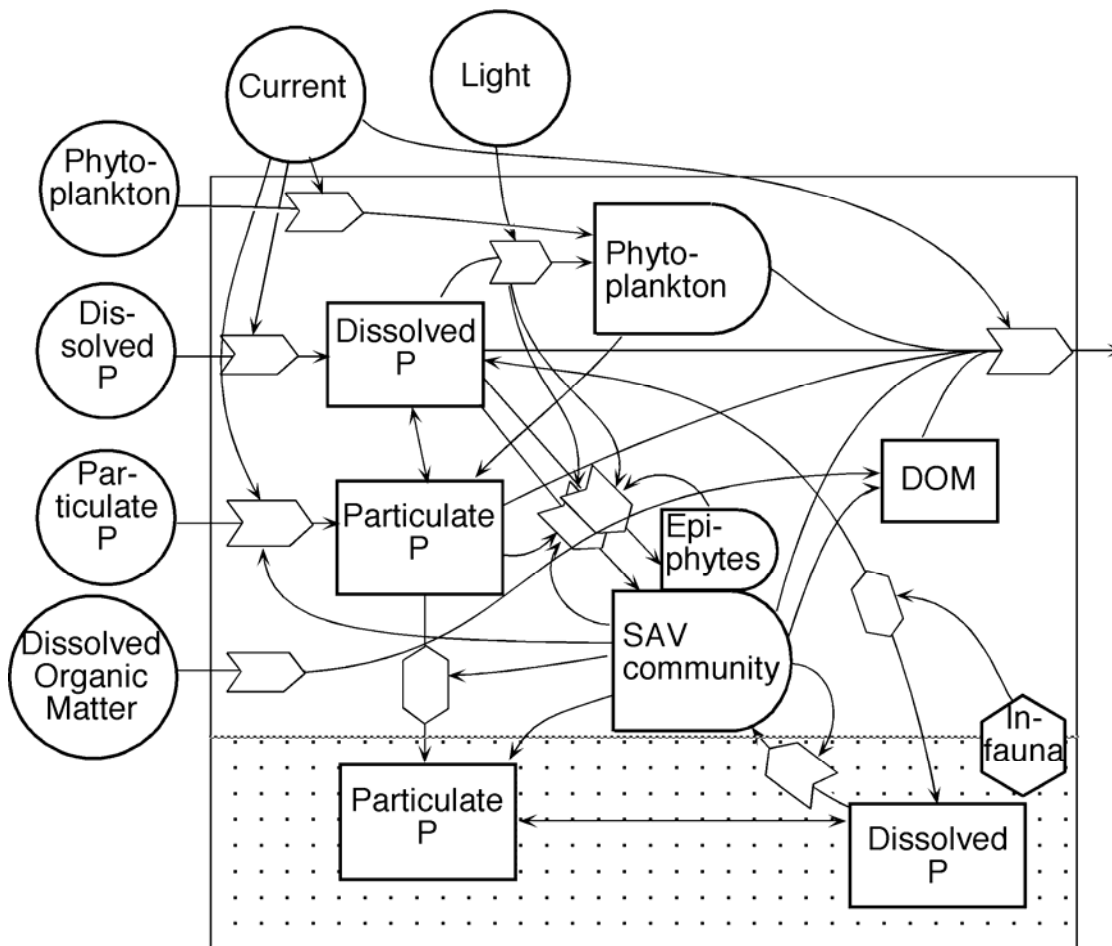


Figure 10-33. Flow diagram for the phosphorus component of an SAV model developed by the SFWMD. This model is being calibrated with field and experimental research data and will be linked with the Lake Okeechobee Environment Model so that submerged vegetation responses to changes in water level can be predicted in lake and regional planning alternatives.

LIGHT EFFECTS ON SAV GROWTH

Controlled experiments conducted in 2002–2004 used a large, above-ground tank (approximately 8,000 liters) located adjacent to the SFWMD ecological research laboratory (**Figure 10-34**, Panel A). The tank is filled with water trucked in from Lake Okeechobee and collected from an SAV-dominated near-shore location. Plants used in each experiment are collected from healthy beds in the lake, potted in natural lake sediment, and then subjected in replicate (five per treatment) to a range of light intensities from below 10 to more than 150 $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$. Treatments were produced by using varying numbers of window screens layered over support structures above sections of the tank. To date, the experiments have been conducted with *Vallisneria* (Grimshaw et al., 2002) and *Chara* (Grimshaw et al., in review), and an ongoing study is examining growth responses of *Hydrilla*. A future experiment will deal with *Potamogeton*. Collectively, these are the dominant SAV taxa in the lake.

The results provide information regarding effects of irradiance on leaf elongation, biomass accrual, and absolute growth rate (**Figure 10-34**, Panel B) that, when combined with information regarding the relationship between water depth and underwater irradiance, can be used to estimate growth of plants in particular near-shore regions of the lake, or more importantly, to parameterize the Stella SAV model mentioned above. The information provided from the experiments includes the critical light level at which there is no net growth of mature SAV.

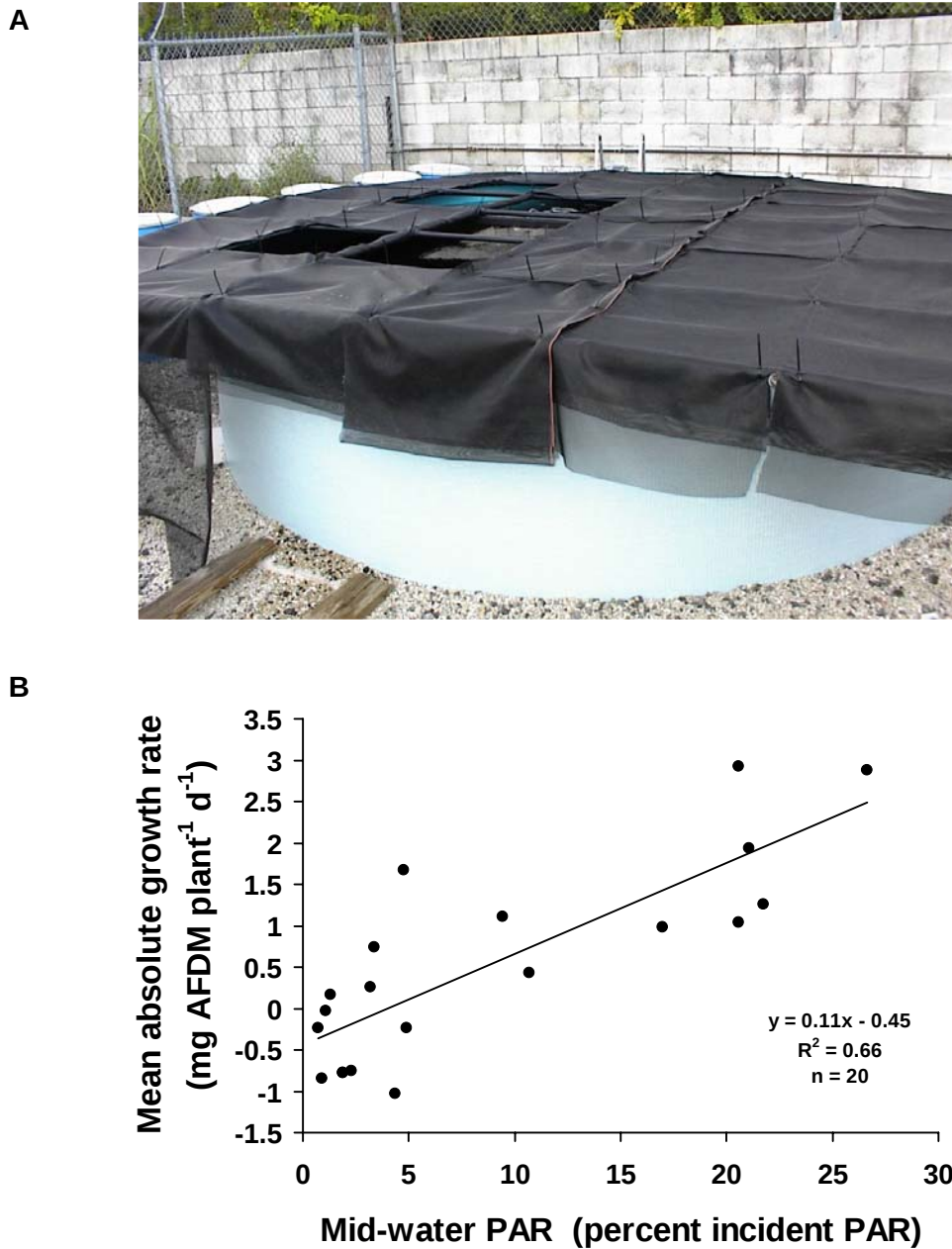


Figure 10-34. Panel A: Large tank used to conduct experiments to examine effects of light on growth of submerged plants (SFWMD photograph). Panel B: Results of an experiment dealing with *Vallisneria americana* (known locally as eelgrass or tapegrass). These data allow the identification of the minimum light requirement for net growth of mature plants and also provide information to calibrate the SAV model. PAR = photosynthetically active radiation (the portion of the light spectrum used by plants); data from Grimshaw et al., 2002.

LIGHT EFFECTS ON SAV GERMINATION AND SEEDLING GROWTH

In the SAV model, it is assumed that when light does not reach the lake bottom, there can be vegetative expansion of existing plant beds, but seeds do not germinate (and even if they do, seedlings cannot survive and grow). However, it is uncertain what levels of bottom irradiance are necessary to elicit germination and sustain seedling net growth. This may be the most sensitive stage of the plant's life cycle, because if stage rises rapidly, seedlings are much more prone to being in a dark environment than mature plants with leaves higher in the water column. In 2000, the District performed the first study to examine germination responses to irradiance (**Figure 10-35**), focusing on *Vallisneria* and *Chara* (Harwell and Havens, 2003). Intact sediment cores were used because preliminary studies indicated that seeds would not germinate from homogenized sediments. Only two treatments (100 and 500 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$) were established because at the time of the study, the lake was experiencing a rapid decline in water levels and these irradiances encompassed the range of what was observed in the shoreline region. The results indicated that there was no effect of irradiance at these high levels on germination success. However, it was concluded that *Chara* germination was much more pronounced than that of vascular plants, especially when cores were desiccated before reflooding. This helps to explain why *Chara* was the first species to colonize the near-shore landscape in 2000 after the lake's recession. The oospores of *Chara* may be (1) considerably more abundant than seeds of vascular plants, (2) have greater long-term survival, and/or (3) be more tolerant of desiccation.



Figure 10-35. Experimental setup for seed germination experiments in progress. Results to date indicate that seeds of eelgrass (*Vallisneria americana*) do not germinate unless exposed to light. Ongoing studies are being performed to determine minimum light requirements for germination and seedling survival/growth. (SFWMD photograph).

In 2003–2004, the District conducted experiments to examine whether dark conditions suppress germination of *Chara* and vascular SAV. Results to date with *Chara* and *Vallisneria* confirm this hypothesis, with nearly 100 percent germination of plants under lighted ($100 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$) conditions, and no germination in the dark. Currently, growth rates of the resulting seedlings are being observed under a range of irradiance conditions previously studied for mature plants. It is anticipated that these germination experiments will be repeated in 2005 under a range of irradiance conditions to determine if there is a critical irradiance at which germination is stimulated to occur. All of these results will feed into the process of calibrating the SAV model.

QUANTIFYING THE ROLE OF SAV IN NEAR-SHORE PHOSPHORUS CYCLING

Submerged plants can influence the phosphorus cycle in shallow regions of lakes by a variety of processes including: (1) stabilization of sediments (Vermaat et al., 2000); (2) uptake of phosphorus by periphyton attached to the plants (Burkholder et al., 1990; Hansson, 1990); and (3) creation of physical and chemical conditions that favor removal of particulate and soluble phosphorus from the water column to the sediments (Jeppesen et al., 1998). Given the documented inverse relationship between SAV and phytoplankton in the lake's near-shore zone (Phlips et al., 1995), it is critical to incorporate SAV influences on phosphorus into near-shore water quality models. The Lake Okeechobee Environment Model (LOEM), as described below, is being developed to include an interface with the Stella SAV model.

To quantify various processes of phosphorus transformation and uptake associated with actively growing plants, the SFWMD has been conducting experiments in small (1 m^3) flow-through tanks (**Figure 10-36**, Panel A) located on the southern shore of the lake, immediately adjacent to South Bay, one of the largest SAV dominated regions. Water is pumped into a head tank and then transferred by gravity to the experimental tanks at known rates of flow. This design allows the measurement of inputs and outputs of water and phosphorus from the tanks and the growth of SAV under near-natural conditions. Experiments have been conducted with *Vallisneria* and *Hydrilla*, quantifying phosphorus transfer into epiphyton, plant tissues, and sediments during periods of active growth and senescence (triggered by covering the tanks with shade screens). This work has provided preliminary lake-specific parameter values for the phosphorus cycling component of the Stella SAV model (**Figure 10-36**, Panel B). Greater detail regarding this work in-progress will be provided in next year's annual report, after completing studies on phosphorus uptake and recycling using $^{32}\text{P-PO}_4$ (in the laboratory) and flow/ phosphorus depletion studies in large SAV beds on the lake. One of the greatest challenges is taking results from small-scale studies and generalizing them to the scale of beds of plants that cover hundreds of hectares in the lake and are influenced by varying flow regimes.

A



B

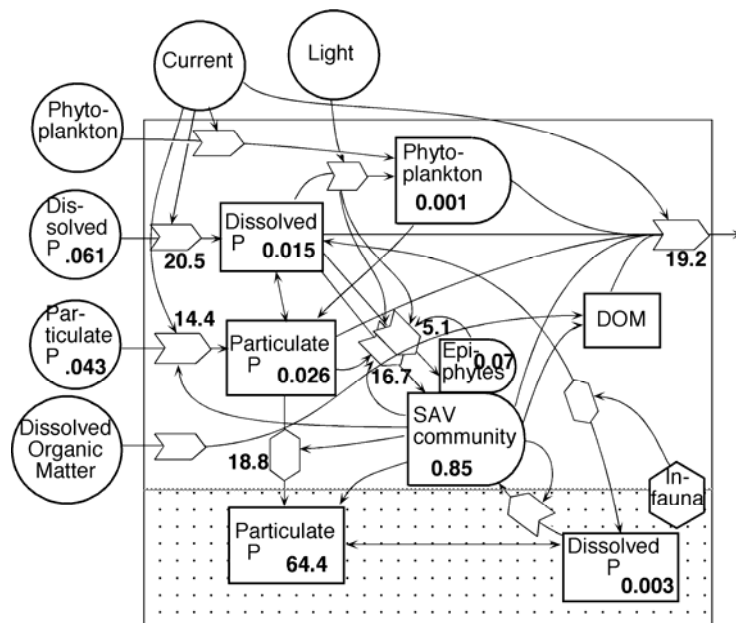


Figure 10-36. Panel A: Flow through lakeside tanks used to conduct studies to determine role of SAV in the lake's phosphorus cycle. Panel B: Stella SAV model developed by the SFWMD showing parameters used in the model based on experimental research. (SFWMD photograph)

QUANTIFYING HABITAT VALUE OF PLANT COMMUNITIES

A key issue regarding restoration of hydroperiod, reduction of external nutrient loads, and removal of exotic plants is what benefits this will provide for the lake's sport fish and wildlife populations. The expectation is that they both will benefit; however, certain aspects of the program, such as a reduction in nutrients (which support a productive food web) could actually lead to reduced fish productivity. It is assumed that this will be offset by the large-scale improvements in habitat quality. To date, there has not been any comprehensive evaluation of how the lake's fauna responds to major changes in plant habitat structure. Over the past year, the SFWMD's Lake Okeechobee Department began to examine differences between two dominant plants (torpedograss and spikerush) in regard to their ability to support forage fish, macroinvertebrates, and a diverse periphyton assemblage. Future research is needed to identify such relationships between flora and fauna for all of the lake's major plant assemblages. This is identified as a priority research area both in the LOPP and by RECOVER, and it could also provide critical information for future adjustments to the lake's Minimum Flows and Levels criteria.

DEVELOPMENT OF THE LAKE OKEECHOBEE ENVIRONMENT MODEL

For several years, the SFWMD has used the Lake Okeechobee Water Quality Model (LOWQM) to forecast responses of the lake to long-term management scenarios, such as dredging and large-scale phosphorus load reduction. As indicated, this model treats the lake as a mixed reactor, and it does not consider the unique zones that have been described in detail in this chapter. The model does not have features that explicitly respond to changes in water level, and it does not include submerged or emergent plants. It is expected that the LOWQM will continue to be used for planning studies that require long-term (e.g., 100 or more years) model runs. However, there is a need for a more complex spatially explicit model to address questions regarding how changes in water level will influence nutrient transport into the littoral zone, how changes in loads will affect phosphorus concentrations in the near-shore versus pelagic zone, and how water transparency and biomass of submerged plants in the near-shore zone will be influenced both by changes in water level and reduced phosphorus loads.

The objective of this program is to develop an integrated model (Lake Okeechobee Environmental Model, or LOEM) that includes hydrodynamic, sediment transport, and water quality sub-models. The LOEM (**Figure 10-37**) can simulate hydrodynamic, sediment transport, and water quality processes in the lake (Jin et al., 2000; 2002; 2004). The current model has been calibrated and verified for 3-D hydrodynamic, sediment, and water quality modeling. The SAV model is under development and it is anticipated that the LOEM will be ready for application in August 2005.

Future work in support of the LOEM will include research dealing with nutrient uptake and storage in submerged plant beds and studies to determine which factors cause switches from relatively simple early successional plant communities to more complex communities that become established two to three years after recovery from major disturbance (Havens et al., 2004b). Priority research will need to be integrated with the studies of how plant community structure affects the lake's fishery, wading birds, migratory water fowl, and other key biota.

The LOEM also is being used in a larger effort to evaluate how Hurricanes Charley, Frances, and Jeanne (August to September 2004) affected sediment resuspension, transport, water quality, and submerged plant distribution in the lake. It is anticipated that this additional information will be presented in the *2006 South Florida Environmental Report*.

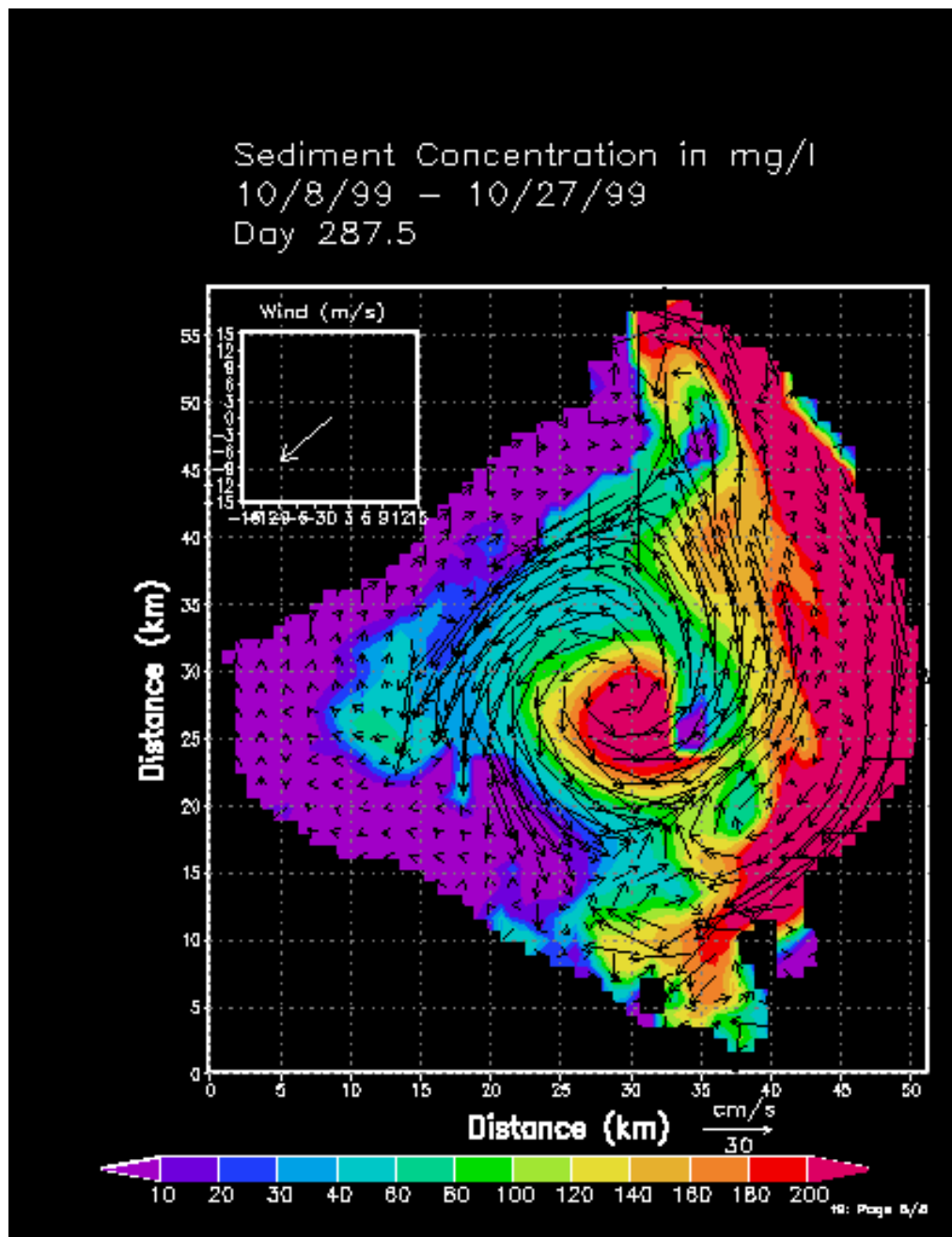


Figure 10-37. Representative result from the LOEM. In this case, the lake response to a Category I hurricane (i.e., Hurricane Irene) is simulated. Arrows are velocity vectors for surface water movement, and colors indicate concentrations of suspended sediments in the lake water. In this model run, it was estimated that large amounts of mud sediment were uplifted and carried mainly to Pelican Bay (southeast) and Fisheating Bay (west). Subsequent sampling after the hurricane confirmed that this had occurred at the predicted magnitude.

CONCLUSIONS

There is a comprehensive array of state and federal projects occurring in the watershed of Lake Okeechobee, and within the lake, to address the key issues of excessive phosphorus loading, harmful high water levels, and exotic plants. Projects are being implemented in a cooperative manner by the SFWMD, FDEP, and FDACS. Significant progress has been made to control the spread of exotic plants in the lake, watershed projects have been implemented to reduce phosphorus transport from agricultural lands and capture runoff water during high rainfall periods, and modifications to the lake regulation schedule are under consideration. Because of the complex nature and long history of problems, full implementation of the LOPA will require more than a decade and improvements in lake water quality are expected to be slowed by internal nutrient recycling. Ongoing research in the watershed is helping to optimize the design of phosphorus reduction/flow attenuation measures, and research in the lake is providing guidance for adaptive management of water levels and exotic plants. Restoration of water quality and ecosystem functions in Lake Okeechobee is critical to South Florida because the lake is the central part of both the natural and man-made regional aquatic system.

LITERATURE CITED

- Aldridge, F.J., E.J. Philips and C.L. Schelske. 1995. The Use of Nutrient Enrichment Bioassays to Test for Spatial and Temporal Distribution of Limiting Factors Affecting Phytoplankton dynamics in Lake Okeechobee, Florida. *Archiv für Hydrobiologie, Advances in Limnology*, 45: 177-190.
- Aumen, N.G. 1995. The History of Human Impacts, Lake Management, and Limnological Research on Lake Okeechobee, Florida (USA). *Archiv für Hydrobiologie, Advances in Limnology*, 45: 1-16.
- BBL. 2003. Evaluation of Alternatives for the Lake Okeechobee Sediment Management Feasibility Study. Final Report to the South Florida Water Management District. Blasland, Bouck, and Lee, Inc., Boca Raton, FL.
- Bennetts, R.E. and W.M. Kitchens. 1997. The Demography and Movements of Snail Kites in Florida. Technical Report 56, U.S. Geological Survey, Biological Resources Division, Florida Cooperative Fish and Wildlife Research Unit, Miami, FL.
- Brezonik, P.L., E.C. Blancher, V.B. Myers, C.L. Hilty, M. Leslie, C.R. Kratzer, G.D. Marbury, T.L. Crisman and J.J. Messer. 1979. Factors Affecting Primary Production in Lake Okeechobee, Florida. Technical Report, Florida Sugar Cane League, Belle Glade, FL.
- Brezonik, P.L. and D.R. Engstrom. 1998. Modern and Historic Accumulation Rates of Phosphorus in Lake Okeechobee, Florida. *Journal of Paleolimnology*, 20: 31-46.
- Bull, L.A., D.D. Fox, L.J. Davis, S.J. Miller and J.G. Wulschleger. 1995. Fish Distribution in Limnetic Areas of Lake Okeechobee, Florida. *Archiv für Hydrobiologie, Advances in Limnology*, 45: 333-342.
- Burkholder, J.M., R.G. Wetzel and K.L. Klomparens. 1990. Direct Comparison of Phosphate Uptake by Adnate and Loosely Attached Microalgae within an Intact Biofilm Matrix. *Applied and Environmental Microbiology*, 56: 2882-2890.
- Canfield, D.E. and M.V. Hoyer. 1988. The Eutrophication of Lake Okeechobee. *Lake and Reservoir Management*, 4: 91-99.
- Dennison, W.C., R.J. Orth, K.A. Moore, J.C. Stevenson, V. Carter, S. Kollar, P.W. Bergstrom and R.A. Batiuk. 1993. Assessing Water Quality with Submersed Aquatic Vegetation. *BioScience*, 43: 86-94.
- Enfield, D.B., A.M. Mestas-Nuez and P.J. Trimble. 2001. The Atlantic Multidecadal Oscillation and its Relation to Rainfall and River Flows in the Continental USA. *Geophysical Research Letters*, 28: 2077-2080.
- FDEP. 2001. The State of Florida's Draft TP Total Maximum Daily Load (TMDL) for Lake Okeechobee. Florida Department of Environmental Protection, Tallahassee, FL.
- Fisher, M.M., K.R. Reddy and R.T. James. 2001. Long-Term Changes in the Sediment Chemistry of a Large Shallow Subtropical Lake. *Lake and Reservoir Management*, 17: 217-232.
- Flaig, E.G. and K.E. Havens. 1995. Historical Trends in the Lake Okeechobee Ecosystem. I. Land Use and Nutrient Loading. *Archiv für Hydrobiologie Monographische Beitrage*, 107: 1-24.

- Fonyo, C., R. Fluck, W. Boggess, J. Dinkler and L. Stanislawski. 1991. Biogeochemical Behavior and Transport of Phosphorus in the Lake Okeechobee Basin. Report, Departments of Agricultural Engineering and Food and Resources Economy, University of Florida, Gainesville, FL.
- Furse, J.B. and D.D. Fox. 1994. Economic Fishery Valuation of Five Vegetation Communities in Lake Okeechobee, Florida. *Proceedings of the Southeastern Association of Fish and Wildlife Agencies*, 48: 575-591.
- Gleason, P.J. and P.A. Stone. 1975. Prehistoric Trophic Status and Possible Cultural Influences on the Enrichment of Lake Okeechobee. Report, Central and Southern Florida Flood Control District [currently known as the South Florida Water Management District], West Palm Beach, FL.
- Grimshaw, H.J., K.E. Havens, B. Sharfstein, A. Steinman, D. Anson, T. East, R.P. Maki, A. Rodusky and K.R. Jin. 2002. The Effects of Shading on Morphometric and Meristic Characteristics of *Vallisneria americana* Transplants from Lake Okeechobee, Florida. *Archiv für Hydrobiologie*, 155: 65-81.
- Grimshaw, H.J., K.E. Havens, B. Sharfstein, A. Steinman, D. Anson, R.P. Maki, A. Rodusky and K.R. Jin. 2002. The effects of shading on morphometric and meristic characteristics of Wild Celery, *Vallisneria americana* Michx., transplants from Lake Okeechobee, Florida. *Archiv für Hydrobiologie*, 155 (1): 65-81.
- Grimshaw, H.J., B. Sharfstein and T. East. 2004. The Effects of Shading on *Chara zeylanica* and its Epiphytes. *Archiv für Hydrobiologie*, in review.
- Hanlon, C. and M.A. Brady. Long-Term Changes in the Littoral Landscape of Lake Okeechobee. *Wetlands*, in review.
- Hansson, L.A. 1990. Quantifying the Impact of Periphytic Algae on Nutrient Availability for Phytoplankton. *Freshwater Biology*, 24: 265-273.
- Harwell, M.C. and K.E. Havens. 2003. Experimental Studies on the Recovery Potential of Submerged Aquatic Vegetation after Flooding and Desiccation in a Large Subtropical Lake. *Aquatic Botany*, 77: 135-151.
- Havens, K.E. 1994. Seasonal and Spatial Variation in Nutrient Limitation in a Shallow Subtropical Lake (Lake Okeechobee, Florida, USA), as Evidenced by Trophic State Deviations. *Archiv für Hydrobiologie*, 131: 39-53.
- Havens, K.E. 1995a. Secondary Nitrogen Limitation in a Subtropical Lake Impacted by Non-Point Source Agricultural Pollution. *Environmental Pollution*, 89: 241-246.
- Havens, K.E. 1995b. Particulate Light Attenuation in a Large Subtropical Lake. *Canadian Journal of Fisheries and Aquatic Science*, 52: 1803-1811.
- Havens, K.E. 1997. Water Levels and Total Phosphorus in Lake Okeechobee. *Lake and Reservoir Management*, 13: 16-25.
- Havens, K.E. 2003. Submerged Aquatic Vegetation Correlations with Depth and Light Attenuating Materials in a Shallow Subtropical Lake. *Hydrobiologia*, 493: 173-186.
- Havens, K.E. Influence of Water Depth on Plankton and Nutrient Dynamics in Offshore and Near-Shore Regions of a Large Subtropical Lake. *Archiv für Hydrobiologie*, in review.

- Havens, K.E., N.G. Aumen and V.H. Smith. 1996a. Rapid Ecological Changes in a Large Subtropical Lake Undergoing Cultural Eutrophication. *Ambi.*, 25: 150-155.
- Havens, K.E., J.R. Beaver, T.L. East, A.J. Rodusky, B. Sharfstein, A. St. Amand and A.D. Steinman. 2001b. Nutrient Effects on Producers and Consumers in the Littoral Plankton and Periphyton of a Subtropical Lake. *Archiv fur Hydrobiologie*, 152: 177-201.
- Havens, K.E., V.J. Bierman, Jr., E.G. Flaig, C. Hanlon, R.T. James, B.L. Jones and V.H. Smith. 1995. Historical Trends in the Lake Okeechobee Ecosystem. VI. Synthesis. *Archiv fur Hydrobiologie Monographische Beitrage*, 107: 99-109.
- Havens, K.E. and T.L. East. 1997. Carbon Dynamics in the Grazing Food Chain of a Subtropical Lake. *Journal of Plankton Research*, 19: 1687-1711.
- Havens, K.E., T.L. East and J.R. Beaver. 1996b. Experimental Studies of Zooplankton-Phytoplankton-Nutrient Interactions in a Large Subtropical Lake (Lake Okeechobee, Florida, USA). *Freshwater Biology*, 36: 579-597.
- Havens, K.E., T.L. East, A.J. Rodusky and B. Sharfstein. 1999. Littoral Periphyton Responses to Nitrogen and Phosphorus: An Experimental Study in a Subtropical Lake. *Aquatic Botany*, 63: 267-290.
- Havens, K.E., D.D. Fox and S. Gornak. Aquatic Vegetation and Largemouth Bass Population Responses to Water Level Variations in Lake Okeechobee, Florida (USA). *Hydrobiologia*, in press.
- Havens, K.E., M.C. Harwell, M.A. Brady, B. Sharfstein, T.L. East, A.J. Rodusky, D. Anson and R.P. Maki. 2002. Large-Scale Mapping and Predictive Modeling of Submerged Aquatic Vegetation in a Shallow Eutrophic Lake. *The Scientific World Journal*, 2: 949-965.
- Havens, K.E. and R.T. James. 2004. The Phosphorus Mass Balance of Lake Okeechobee: Implications for Eutrophication Management. *Lake and Reservoir Management*, in press.
- Havens, K.E., R.T. James, V.H. Smith and T.L. East. 2003. N:P Ratios, Light Limitation, and Cyanobacteria Dominance in a Subtropical Lake Impacted by Non-Point Source Nutrient Pollution. *Environmental Pollution*, 122: 379-390.
- Havens, K.E., K.R. Jin, A.J. Rodusky, B. Sharfstein, M.A. Brady, T.L. East, N. Iricanin, R.T. James, M.C. Harwell and A.D. Steinman. 2001a. Hurricane Effects on a Shallow Lake Ecosystem and its Response to a Controlled Manipulation of Water Level. *The Scientific World Journal*, 1: 44-70.
- Havens, K.E., E.J. Phlips, M.F. Cichra and B.L. Li. 1998. Light Availability as a Possible Regulator of Cyanobacteria Species Composition in a Shallow Subtropical Lake. *Freshwater Biology*, 39: 547-556.
- Havens, K.E. and C.L. Schelske. 2001. The Importance of Considering Biological Processes when Setting Total Maximum Daily Loads (TMDL) for Phosphorus in Shallow Eutrophic Lakes. *Environmental Pollution*, 113: 1-9.
- Havens, K.E., B. Sharfstein, M.A. Brady, T.L. East, M.C. Harwell, R.P. Maki and A.J. Rodusky. 2004b. Recovery of Submerged Plants from High Water Stress in a Large Subtropical Lake in Florida, USA. *Aquatic Botany*, 78: 67-82.

- Havens, K.E., B. Sharfstein, T.L. East and A.J. Rodusky. 2004a. Phosphorus Uptake in the Littoral Zone of a Subtropical Lake. *Hydrobiologia*, 517: 15-24.
- Havens, K.E. and W.W. Walker, Jr. 2002. Development of a Total Phosphorus Concentration Goal in the TMDL Process for Lake Okeechobee, Florida (USA). *Lake and Reservoir Management*, 18: 227-238.
- Havens, K.E., K.A. Work and T.L. East. 2000. Relative Efficiencies of Carbon Transfer from Bacteria and Algae to Zooplankton in a Subtropical Lake. *Journal of Plankton Research*, 22: 1801-1809.
- Hiscock, J.G., C.S. Thourot and J. Zhang. 2003. Phosphorus Budget-Land Use Relationships for the Northern Lake Okeechobee Watershed, Florida. *Ecological Engineering*, 21: 63-74.
- Horne, A.J. and M.L. Commins. 1987. Macronutrient Controls on Nitrogen Fixation in Planktonic Cyanobacterial Populations. *New Zealand Journal of Marine and Freshwater Research*, 21: 423-433.
- Hwang, S.J., K.E. Havens and A.D. Steinman. 1999. Phosphorus Kinetics of Planktonic and Benthic Assemblages in a Shallow Subtropical Lake. *Freshwater Biology*, 40: 729-745.
- James, R.T., B.L. Jones and V.H. Smith. 1995a. Historical Trends in the Lake Okeechobee Ecosystem II. Nutrient Budgets. *Archiv für Hydrobiologie Monographische Beitrage*, 107: 25-47.
- James, R.T., J. Martin, T. Wool and P.F. Wang. 1997. A Sediment Resuspension and Water quality model of Lake Okeechobee. *Journal of the American Water Resources Association*, 33: 661-679.
- James, R.T., V.H. Smith and B.L. Jones. 1995b. Historical Trends in the Lake Okeechobee Ecosystem III. Water Quality. *Archiv für Hydrobiologie, Monographische Beitrage*, 107: 49-69.
- Janus, L.L., D.M. Soballe and B.L. Jones. 1990. Nutrient Budget Analyses and Phosphorus Loading Goal for Lake Okeechobee, Florida. *Verhandlungen Internationale Vereinigung der Limnologie*, 24: 538-546.
- Jeppesen, E., P. Kristensen, J.P. Jensen, M. Sondergaard, E. Mortensen and T. Lauridsen. 1991. Recovery Resilience Following a Reduction in External Phosphorus Loading of Shallow, Eutrophic Danish Lakes: Duration, Regulating Factors and Methods for Overcoming Resilience. *Memorie dell'istituto Italiano di Idrobiologia*, 48: 127-148.
- Jeppesen, E., M. Sondergaard, M. Sondergaard and K. Cristoffersen. 1998. *The Structuring Role of Submerged Macrophytes in Lakes*. Springer-Verlag, NY.
- Jin, K.R., J.H. Hamrick and T. Tisdale 2000. Application of a Three-Dimensional Hydrodynamic Model for Lake Okeechobee. *Journal of Hydraulic Engineering*, 126: 758-771.
- Jin, K.R., Z.G. Ji and J.H. Hamrick. 2002. Modeling Winter Circulation in Lake Okeechobee, Florida. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, ASCE, 128: 114-125.
- Jin, K.R. and Z.G. Ji. 2004. Modeling of Sediment Transport and Wind-wave Impact in Lake Okeechobee. *Journal of Hydraulic Engineering*, ASCE, in press.

- Jones, B.L. 1987. Lake Okeechobee Eutrophication Research and Management. *Aquatics*, 9: 21-26.
- Keddy, P. 1999. Wetland Restoration: The Potential for Assembly Rules in the Service of Conservation. *Wetlands*, 19: 716-732.
- Maceina, M.J. 1993. Summer Fluctuations in Planktonic Chlorophyll *a* Concentrations in Lake Okeechobee, Florida: The Influence of Lake Levels. *Lake and Reservoir Management*, 8: 1-11.
- Marshall, M.L. 1977. Phytoplankton and Primary Productivity Studies in Lake Okeechobee during 1974. Technical Publication 77-2, South Florida Water Management District, West Palm Beach, FL.
- Moore, P.A., Jr. and K.R. Reddy. 1994. Role of Eh and pH on Phosphorus Geochemistry in Sediments of Lake Okeechobee, Florida. *Journal of Environmental Quality*, 23: 955-964.
- Murphy, T., K. Hall and I. Yesaki. 1983. Co-precipitation of Phosphate and Calcite in a Naturally Eutrophic Lake. *Limnology and Oceanography*, 28: 58-67.
- Olila, O.G. and K.R. Reddy. 1993. Phosphorus Sorption Characteristics of Sediments in Shallow Eutrophic Lakes of Florida. *Archiv fur Hydrobiologie*, 129: 45-65.
- Paerl, H.W. 1988. Nuisance Phytoplankton Blooms in Coastal, Estuarine and Marine Environments: A Review of Recent Evidence on the Effects of Enrichment. *Limnology and Oceanography*, 33: 823-847.
- Paerl, H.W., R.S. Fulton, P.H. Moisaner and J. Dyble. 2001. Harmful Freshwater Algal Blooms, with an Emphasis on Cyanobacteria. *The Scientific World Journal*, 1: 76-113.
- Pesnell, G.L. and R.T. Brown. 1977. The Major Plant Communities of Lake Okeechobee and their Associated Inundation Characteristics as Determined by Gradient Analysis. Technical Publication 77-1, South Florida Water Management District, West Palm Beach, FL.
- Phlips, E.J., F.J. Aldridge and C. Hanlon. 1995. Potential Limiting Factors for Phytoplankton Biomass in a Shallow Subtropical Lake (Lake Okeechobee, Florida, USA). *Archiv fur Hydrobiologie, Advances in Limnology*, 45: 137-155.
- Phlips, E.J., F.J. Aldridge, P. Hansen, P.V. Zimba, J. Ihnat, M. Conroy and P. Ritter. 1993a. Spatial and Temporal Variability of Trophic State Parameters in a Shallow Subtropical Lake (Lake Okeechobee, Florida, USA). *Archiv fur Hydrobiologie*, 128: 437-458.
- Phlips, E.J., M.F. Cichra, K.E. Havens, C. Hanlon, S. Badylak, B. Rueter, M. Randall and P. Hansen. 1997. Relationships Between Phytoplankton Dynamics and the Availability of Light and Nutrients in a Shallow Subtropical Lake. *Journal of Plankton Research*, 19: 319-342.
- Phlips, E.J., P.V. Zimba, M.S. Hopson and T.L. Crisman. 1993b. Dynamics of the Plankton Community in Submerged Plant Dominated Regions of Lake Okeechobee, Florida, USA. *Verhandlungen Internationale Vereinigung der Limnologie*, 25: 423-426.
- Pollman, C.D., W.M. Landing, J.J. Perry, Jr. and T. Fitzgerald. 2002. Wet Deposition of Phosphorus in Florida. *Atmospheric Environment*, 36: 2309-2318.
- Postel, S. and S.R. Carpenter. 1997. Freshwater Ecosystem Services. G. Daily, ed. In: *Nature's Services*. Island Press, Washington, D.C.

- Richardson, J.R. and T.T. Harris. 1995. Vegetation Mapping and Change Detection in the Lake Okeechobee Marsh Ecosystem. *Archiv fur Hydrobiologie, Advances in Limnology*, 45: 17-39.
- Richardson, J.R., T.T. Harris and K.A. Williges. 1995. Vegetation Correlations with Various Environmental Parameters in the Lake Okeechobee Marsh Ecosystem. *Archiv fur Hydrobiologie, Advances in Limnology*, 45: 41-61.
- Sas, H. 1989. Lake Restoration by Reduction of Nutrient Loading: Expectations, Experiences, Extrapolations. Academia Verlag, Germany.
- Scheffer, M. 1989. Alternative Stable States in Eutrophic Shallow Freshwater Systems: A Minimal Model. *Hydrobiological Bulletin*, 23: 73-85.
- Scheffer, M. 1998. *Ecology of Shallow Lakes*. Chapman and Hall, London, UK.
- Scheffer, M., M. Van den Berg, A. Breukelaar, C. Breukers, H. Coops, R. Doef and M.L. Meijer. 1994. Vegetated Areas with Clear Water in Turbid Shallow Lakes. *Aquatic Botany*, 49: 193-196.
- SFWMD. 1993. Surface Water Improvement and Management (SWIM) Plan Update for Lake Okeechobee. South Florida Water Management District, West Palm Beach, FL.
- SFWMD. 2002. Surface Water Improvement and Management (SWIM) Plan Update for Lake Okeechobee. South Florida Water Management District, West Palm Beach, FL.
- SFWMD. 2003. Adaptive Protocols for Lake Okeechobee Operations. South Florida Water Management District, West Palm Beach, FL.
- Smith, V.H. 1985. Predictive Models for the Biomass of Blue-Green Algae in Lakes. *Water Resources Bulletin*, 21: 433-439.
- Smith, V.H., V.J. Bierman, Jr., B.L. Jones and K.E. Havens. 1995. Historical Trends in the Lake Okeechobee Ecosystem. IV. Nitrogen:Phosphorus Ratios, Cyanobacterial Dominance, and Nitrogen Fixation Potential. *Archiv fur Hydrobiologie Monographische Beitrage*, 107: 69-86.
- Sondergaard, M., P. Kristensen and E. Jeppesen. 1993. Eight Years of Internal Phosphorus Loading and Changes in the Sediment Phosphorus Profile of Lake Sobygaard, Denmark. *Hydrobiologie*, 253: 345-356.
- Steinman, A.D., K.E. Havens, H.J. Carrick and R. VanZee. 2001. The Past, Present, and Future Hydrology and Ecology of Lake Okeechobee and its Watershed. J. Porter and K.G. Porter, eds. pp. 19-37. In: *South Florida Hydroscape: The River of Grass Revisited.*, Lewis Publishers, FL.
- USACE. 1999. Central and Southern Florida Project: Comprehensive Review Study, Final Integrated Feasibility Report and Programmatic Environmental Impact Statement. U.S. Army Corps of Engineers, Jacksonville, FL. (Available on CD-ROM).
- USFWS. 1999. South Florida Multi-Species Recovery Plan – A Species Plan, An Ecosystem Approach. U.S. Fish and Wildlife Service, Southeast Region, Atlanta, GA.
- van der Molen, D.T. and P.C.M. Boers. 1994. Influence of Internal Loading on Phosphorus Concentration in Shallow Lakes Before and After Reduction of the External Loading. *Hydrobiologia*, 275: 379-389.

- Vermaat, J.E., L. Santamaria and P.J. Roos. 2000. Water flow Across and Sediment Trapping in Submerged Macrophyte Beds of Contrasting Growth Form. *Archiv fur Hydrobiologie*, 148: 549-562.
- Vollenweider, R.A. 1975. Input-Output Models with Special Reference to the Phosphorus Loading Concept in Limnology. *Schweiz. Zeit. Hydrol*, 37: 53-84.
- Vollenweider, R.A. 1976. Advances in Defining Critical Loading Levels for Phosphorus in Lake Eutrophication. *Memorie dell'Istituto Italiano di Idrobiologia*, 33: 53-83.
- Walker, W.W., Jr. 1983. FLUX – A Computer Program for Estimating Mass Discharges. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.
- Walker, W.W., Jr. 1989. Software and Documentation Updates for BATHTUB and FLUX. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.
- Walker, W.W., Jr. and K.E. Havens. 1995. Relating Algal Bloom Frequencies to Phosphorus Concentrations in Lake Okeechobee. *Lake and Reservoir Management*, 11: 77-83.
- Warren, G.L., M.J. Vogel and D.D. Fox. 1995. Trophic and Distributional Dynamics of Lake Okeechobee Sublittoral Benthic Invertebrate Communities. *Archiv fur Hydrobiologie, Advances in Limnology*, 45: 317-332.