Lake Okeechobee, covering over 1732 km$^2$ (669 mi$^2$), is the "liquid heart" of the once contiguous Kissimmee/Lake Okeechobee/Everglades system (Figure 1). The lake has an average depth of approximately 2.7 m (9 ft) and occurs as a broad, shallow, bedrock depression. The lake provides flood protection by functioning as a storage basin, serves as a primary source of water for consumptive uses in South Florida, supports a valuable commercial and sport fishery, and provides critical habitat for fish and wildlife.

Inflows enter Lake Okeechobee from the Kissimmee River basin, Taylor Creek, Nubbin Slough, Fisheating Creek, Nicodemus Slough, and the Lake Istokpoga basin (Indian Prairie Canal and Harney Pond Canal), and contiguous areas. Some drainage from the EAA is also periodically backpumped into the lake. The lake's largest outlets include the St. Lucie Canal eastward to the Atlantic Ocean and the Caloosahatchee Canal and River to the Gulf of Mexico. The four major agricultural canals (West Palm Beach, Hillsboro, North New River, and Miami) drain to the south into the Everglades region.

Physical, chemical, and biological attributes of the lake and its tributaries and distributaries have been significantly altered since construction of the Central and Southern Florida Flood Control Project. The alterations have been brought about by changes in hydrology (timing, direction, route of flow, lake stage), increased nutrient and contaminant inputs, and an introduction of exotic species of flora and fauna.

Prior to drainage, lake stage was controlled by rainfall and evapotranspiration; water quality was determined by basin geology; a large, dynamic, and heterogeneous littoral zone existed along the northwestern shore; and surface water outflows were southward via sheetflow to the northern Everglades. Currently, lake stage follows a regulation schedule designed to maximize storage capacity prior to the wet season and water availability during the dry season. The lake is considered to be highly eutrophic as a result of increased nutrient loading from agricultural and urban land in the drainage basin and backpumping of waters from the EAA. The extent and dynamics of the littoral zone are confined by the Herbert Hoover Dike. Large areas are dominated by cattails (Typha latifolia, T. domingensis), torpedo grass (Panicum repens), hydrilla (Hydrilla verticillata), or melaleuca (Melaleuca quinquenervia). Surface outflows are via channelized connections to the estuaries and southeastern wellfields.

A series of science and management plans have been developed for the lake in response to increasing concerns about water quality and supply. Four plans were reviewed prior to developing the restoration goals and science strategies outlined in this chapter: Lake Okeechobee Technical Advisory Committee report (LOTAC-I 1986), Lake Okeechobee Technical Advisory Council final report (LOTAC-II 1990), Lake Okeechobee SWIM Plan (SFWMD 1993b), and Lake Okeechobee Research Plan (SFWMD 1993a). An overview of science activities specific to water quality and environmental resources in each of the four documents follows.
Lake Okeechobee Technical Advisory Committee

In August 1985, the Governor requested the Secretary of the FDER take the lead in conducting a study of conditions that affect water conservation and quality and biological characteristics of Lake Okeechobee. In response, the Secretary established LOTAC-I. This committee reported phosphorus levels doubled in the lake over the period 1973-1984, the lake was losing its ability to assimilate phosphorus, and water demands stress available supply during periods of drought (LOTAC 1986). A list of management alternatives to reduce phosphorus loading by 40% and increase water supply were provided. LOTAC-I did not consider the potential impacts of nutrient diversion proposals upon other potential receiving systems. The committee recommended development and implementation of a coordinated monitoring and research plan with focus on phosphorus sources and dynamics, best management practices, downstream impacts of proposed diversions, effects of lake levels on biological communities, and comprehensive fish surveys.

Partially in response to this recommendation, the SFWMD initiated the Lake Okeechobee Ecosystem Study to assess the lake ecosystem status and trends, gain greater understanding of the causes of nuisance algal blooms, and assess ecosystem impacts of various lake levels. The results of this study were recently published in a dedicated issue of Archiv für Hydrobiologie (Aumen and Wetzel 1995). This publication is cited as a single document in the bibliography to this chapter; the 20 papers are not listed individually.

Lake Okeechobee Technical Advisory Council

LOTAC-II was created by the Florida Legislature through the Surface Water Improvement and Management Act of 1987 and was continued by Executive Order through March 1990. The final goal of the LOTAC-II was to make findings and recommendations for permanently eliminating adverse environmental effects of past and proposed diversions of nutrient-rich water from the lake.

Preliminary results of research projects undertaken in response to recommendations in the LOTAC-I report (LOTAC-I 1986) were presented to LOTAC-II and were used in making recommendations. The findings and recommendations for Lake Okeechobee focused on the draft interim SWIM plan (SFWMD 1989) and included completion and implementation of the SWIM Plan and continuation of ongoing research efforts undertaken to address issues outlined in the 1986 LOTAC-I report. In particular, LOTAC-II stressed the need for interpreting monitoring data (water quality) to determine relationships between climatological and hydrological events and resultant runoff of phosphorus.

Surface Water Improvement and Management Plan

The SWIM Act adopted by the Florida legislature in 1987 required the SFWMD to: 1) implement the LOTAC-I recommendations except those that might have adverse impact elsewhere and 2) develop a SWIM plan for Lake Okeechobee to address point and nonpoint source pollution, destruction of natural systems, correction and prevention of surface water problems, and research for better management of surface waters and associated natural systems. The Lake Okeechobee SWIM Plan (SFWMD 1993b) contains a series of goals, objectives, and strategies in seven categories (water quality, environmental resources, water supply, flood protection, recreation, navigation, and public information). Specific science strategies include:

> Determine the extent to which Class I and Class III water quality standards are exceeded in the lake and within all inflows and upstream tributaries to the lake.

> Determine the phosphorus uptake capacity of lake sediments and identify key processes affecting its ability to assimilate and retain phosphorus.

> Perform an assessment of current water quality trends within the lake and at all tributary inflows.

> Update the Lake Okeechobee nutrient budget to reflect in-lake and tributary phosphorus loading trends and identify basins out of compliance with the phosphorus performance standard.
Identify and quantify nitrogen cycling, sources and sinks within the Lake Okeechobee watershed.

Develop appropriate nitrogen loading and concentration criteria for nitrogen inputs into the lake if necessary and appropriate.

Develop and maintain a quantitative database to monitor long-term changes in the lake's biological communities (i.e., phytoplankton, invertebrate, fish, macrophytic, and avian) in response to changing water quality and hydrological conditions.

Develop and implement management programs to enhance the native vegetation communities of the Lake Okeechobee littoral zone.

**Lake Okeechobee Research Plan**

The LORP (SFWMD 1993a) defines a series of research objectives and information needs to support the goal to protect and improve the water quality and ecosystem health of Lake Okeechobee. The plan addresses seven research objectives:

- Determine ecosystem status and trends. Measurement and documentation of the lake's current status, across its wide range of ecological attributes, will provide a foundation for long-term assessment of potential changes and selection of management strategies.

- Determine causes of algal blooms. The spatial and temporal extent of algal blooms, common during summer months, must be documented in order to address management options designed to reduce the blooms. Factors controlling blooms must be identified, especially their relationship to nutrient inputs.

- Determine water quality trends. Declining water quality has been the major focus of science efforts in Lake Okeechobee since the late 1960s. Nutrient concentrations in lake water and sediments are important to the entire biological system. Phosphorus has been identified as the most important parameter relative to declining ecosystem health; input from agricultural activities north of the lake is the largest source of phosphorus. Long-term water quality data are needed, along with information on the relationship between water quality and hydrologic conditions.

- Determine effectiveness of measures to improve water quality. Declining water quality has led to regulations designed to reduce inflow of nutrients, particularly phosphorus, the parameter most likely to respond to alterations in land management. Research and demonstration projects on BMPs have been implemented to reduce nutrient input and improve water quality. Evaluation of these should include relationships between BMPs, phosphorus loading, and ecosystem attributes; movement of water and nutrients between the open lake and littoral zone; and relationships between phosphorus loading and rainfall.

- Determine sources and fates of critical elements. Thorough understanding of nutrient dynamics, in both the lake itself and the entire basin, is needed for analysis of water quality trends and BMP effectiveness. It important to know the potential long-term contribution of stored sediment phosphorus to water column phosphorus and its relationship to phosphorus loading.

- Determine effects of lake levels. Regulation of water level is one of the most viable management options for improving ecosystem health, while still maintaining adequate water supply during droughts and flood protection. Water level can affect many biological communities, including littoral zone vegetation, wading bird populations, algal blooms, the Everglades through changing water supply, and estuaries through changing discharges.

- Measure parameters related to numerical water quality standards. Lake Okeechobee is utilized as a source of drinking water and for human-contact recreation, and its waters must comply with Class I and III standards. It is necessary to know concentrations of applicable standards at inflows and relationships between the standards and point and nonpoint pollutant sources.
INFORMATION NEEDS

Restoration of Lake Okeechobee is dependent upon re-establishment of water quality, lake levels, and a littoral zone that will support a self-sustaining ecosystem. The key question is: Can hydrologic linkages between the Kissimmee River, Lake Okeechobee, and the Everglades be restored to a degree necessary to support a self-sustaining ecosystem similar to the historic system, while providing flood protection, water supply, and a sustainable economic system?

The Science Subgroup previously developed a series of ecological and hydrological restoration objectives for Lake Okeechobee (SSG 1993). For each objective, information needs were identified and approaches designed to meet those information needs. The results of this process are summarized in Figure 10 and outlined below. Under each critical science question is information on the approach and tasks recommended to answer the question.

**Hydrological Restoration**

**Objectives**

> Implement a more flexible regulation schedule that mimics historic natural hydrologic variability and enhances the expanded littoral zone ecosystem.

> Reestablish sheetflow for all (maximum) or all regulatory (minimum) discharges from the southern portion of Lake Okeechobee to convey historic flows to the central and southern Everglades.

**Critical questions and approaches.**

1. **What is the system-wide water budget on a yearly basis since levee construction?**

   The first step toward allocation and management of water on a system-wide scale is to develop an accurate water budget. This will allow storage for flood control, needs of consumptive users, and requirements for a sustainable ecological system to be assessed on a system-wide basis.

   > Acquire the necessary data to develop a system-wide water budget.

2. **What dynamic regulation schedule will better mimic natural hydrologic variability?**

   A natural-system-type hydrologic model, incorporating the expanded littoral zone, should be used to investigate water-level fluctuation over a range of environmental conditions. Once this model is developed, it should be tested against the water budget data collected as to its accuracy. This will then allow amendments to be made, so that better predictive scenarios may be evaluated.

   > Develop a "base" hydrologic model of lake stage that is coupled with inputs from the Kissimmee basin and rainfall.

   > Use the "base" model to investigate changes in lake stage associated with various restoration alternatives, including but not limited to: reduced east-west discharges, changes in agricultural/urban water demands, interbasin transfer of water from the Caloosahatchee urban areas into the lake, and changes in levee configuration.

3. **What are the potential impacts to the levee (structure, integrity, leakage) as a result of changes in regulation schedule?**

   > Perform engineering studies as required.
Figure 10. Goal, objectives, and information needs for Lake Okeechobee.
4. What will be the "ecological" consequences associated with changes in regulation schedule?

> Develop a family of models and conduct associated field monitoring to assess potential impacts to vegetation, fish, wading birds, and snail kites resulting from changes in lake stage.

5. What are alternative water delivery mechanisms to create a littoral zone on the northwest end of Lake Okeechobee? (e.g., reconfigure Paradise Run)

> Develop models of various water delivery scenarios.

6. What is the feasibility of conveying predrainage flows from Lake Okeechobee south to the Everglades?

> Investigate the use of both operational methods and structural modifications (i.e., enlargement of maximum conveyance capacity in channels and pumps) to eliminate regulatory releases from Lake Okeechobee to the St. Lucie and Caloosahatchee canals and substantially increase delivery of water from Lake Okeechobee to the WCAs.

Ecological Restoration

Objectives

> Minimally, expand Lake Okeechobee's littoral zone by 200 km$^2$ (77 mi$^2$) on the northwest side and allow for increased water levels, consequently hydrologically integrating the lake and the Kissimmee River. Maximum restoration requires reestablishing the total lost littoral zone present prior to drainage and flood protection works.

> Integrate the islands at the southern end of the lake into an overall lake management plan.

> Eliminate (maximum) or control (minimum) exotic species from the Lake Okeechobee littoral zone.

> Reduce nutrient inputs to Lake Okeechobee to predisturbance levels; restore the lake's natural trophic status and phosphorus-limited condition; reduce algal bloom frequency, intensity, and composition to natural conditions.

> Eliminate (maximum) or reduce (minimum) point and nonpoint sources of pollution to Lake Okeechobee to meet Class I/III water quality standards.

> Restore Lake Okeechobee water quality, basin land-use characteristics, and littoral zone to predisturbance conditions for enhancement of wading bird, waterfowl, and threatened/endangered populations.

> Establish and maintain a recreational and commercial fishery that is consistent with the natural water quality and biological productivity of a restored Lake Okeechobee.

Critical questions and approaches.

Note: All questions and associated approaches were formulated under the assumption that a portion of the northwestern dike would be removed and the littoral zone would expand into this area.

1. What will be the spatial extent and hydrologic character of the expanded littoral zone along the northwest shoreline?

Prior to changing the configuration of the Northwest levee, the spatial extent and hydrology of the expanded littoral zone under the range of lake regulation schedules must be known. This information can be obtained by integrating proposed additions to the littoral zone into existing surface water models. The first step will be to conduct a grid-based topographic survey in the area behind the existing levee. Using this information, expected water depths and hydroperiods over the entire littoral zone can be determined over a range of lake stage, rainfall, and routing scenarios.
> Conduct a grid-based topographic survey of northwest area behind the Herbert Hoover Dike.

> Incorporate this area into grid-based spatial hydrologic models.

> Integrate output from the hydrologic models into GIS databases.

2. **What are the water quality impacts associated with changes lake stage and littoral zone configurations?**

   Water quality has been the major focus of science activities in Lake Okeechobee. Existing water quality monitoring efforts in the lake should be enhanced to include the expanded littoral zone. Using data from past and ongoing monitoring efforts, models of phosphorus transport from open water sediment to the littoral zone should be developed. Additional models of water movement and phosphorus transport over the range of lake stage and littoral zone configurations should be developed. Output from these models can be used to develop specific recommendations on the configuration and water delivery to an expanded littoral zone.

   > Develop models of phosphorus transport from sediments in the open water to the littoral zone.

   > Develop hydrologic models to investigate potential for nutrient input via lake water to areas in the existing littoral zone that are isolated from eutrophic water.

3. **How will vegetative and animal communities respond in the expanded littoral zone?**

   Hydrology is the dominant forcing function on littoral zone vegetative and animal communities. Because of the diversity in the littoral communities a range of ecosystem attributes should be modeled and monitored. The Science Subgroup recommends using, at a minimum, vegetation, game and nongame fish, wading birds, and snail kites as ecological endpoints in modeling and monitoring efforts. A GIS modeling and data management approach is the only feasible method of managing the data layers required. Using output from the spatial hydrologic and nutrient-transport models as templates, additional modules should be developed to investigate vegetative community types and the spatial distribution and dynamics expected to develop in the expanded littoral zone. These models should be designed to incorporate management options such as lake stage regulation and prescribed fire.

   Once hydrology and vegetation models are developed, additional models of responses of various animal communities to changes in configuration, extent, composition, and hydrology of the littoral zone should be developed. Again, these models can be used to investigate impacts of various management actions on animal communities. Once the expanded littoral zone is established, long-term monitoring of vegetative and animals communities should be conducted. This will provide basic information on relationships between forcing functions (hydrology, fire, drought, etc.) and response endpoints (vegetation, wading birds, etc.). Statistical relationships between forcing functions and key ecosystem attributes can be refined. Long-term monitoring will also provide critical information to determine if ecological restoration goals are being met. These monitoring programs should be integrated with those developed for other subregions in the South Florida Ecosystem. The Science Subgroup recommends monitoring vegetation, game and nongame fish, wading birds, and snail kites as part of an integrated approach to evaluate success of restoring part of the littoral zone. These monitoring efforts will supplement the water quality and algal community monitoring programs outlined in the Lake Okeechobee Research Plan (SFWMD 1993).

   > Develop models of vegetative community response to hydrologic conditions in littoral zone.

   > Develop models of the responses of fish, wading birds, and snail kites to predicted hydrologic and vegetative conditions in the littoral zone.

   > Develop and implement long-term monitoring programs at appropriate spatial and temporal scales for vegetation, fish, wading birds, and snail kites in the littoral zone.
4. What will be the impacts on the southern islands under different regulation schedules?

The approach would be the same as for the expanded littoral zone. Topographic data for the islands should be integrated into existing hydrologic models. The output from these models can be used to determine potential impacts under different regulation schedules so as not to negatively impact these areas.

- Conduct a grid-based topographic survey of islands in the southwest portion of the lake.
- Incorporate these islands into grid-based spatial hydrologic and nutrient-transport models.
- Integrate output from the hydrologic models into GIS databases.

5. What are the impacts of exotic plants on the Lake Okeechobee system and how can these impacts be mitigated?

The first step is to determine the distribution of exotic plant species. Next, relationships between lake stage, altered fire regime, water quality, and distribution/abundance of exotics should be determined via gradient analysis. This will provide information useful in understanding the mechanisms associated with dispersal, establishment, and maintenance of exotic plant communities. A better understanding of the distribution and density patterns of exotic plants can also be used to predict potential impacts to fish and wildlife habitats. This will provide information needed to help develop a priority list for species to control. The next step is to develop control mechanisms for those exotics that have the greatest impact on the system. Since the goal is to develop a sustainable system, development and implementation of biological control mechanisms should be given top priority. For example, the SFWMD has ongoing projects to investigate biocontrol mechanisms for melaleuca and the relationships between hydroperiod and growth of melaleuca seedlings (SFWMD 1993b).

- Map distribution of exotic plant species.
- Perform gradient analysis to determine controlling factors in distribution and spread of exotics.
- Develop a priority list of exotics to control.
- Develop biologic control mechanisms for all exotic species.

6. Are exotic and native fish competing for resources?

The habitat and dietary requirements of exotic fish in Lake Okeechobee need to be determined over the range of life stages. This will allow potential impacts to native species to be assessed.

- Conduct census surveys and feeding studies as necessary to assess resource partitioning between native and exotic fish.

7. What is the relative role of internal recycling vs. external loading in development of phytoplankton blooms?

This question is being addressed comprehensively in the SFWMD Lake Okeechobee Research Plan. This task is intended to reaffirm the need for this information.

- Collect data and analyze trends (spatial and temporal) in nutrient concentration, nutrient loading, and bloom development, composition, and magnitude.
8. **What is the response of the aquatic invertebrate community to the changes in water/sediment quality?**

Analysis of spatial and temporal trends in invertebrate community structure over the range of water/sediment quality conditions will provide information needed to assess impacts not only to invertebrates but also potential impacts to higher trophic levels. Existing chemical, physical, and biological data can be used to develop a stratified random sampling approach. This will allow rigorous statistical analysis to determine changes in invertebrate community structure and the causative factors.

> Collect data and perform gradient analysis on benthic invertebrate communities over the range of sediment type/quality.

9. **What contaminants are likely to be impacting fish and wildlife communities?**

A wide range of chemical contaminants has the potential to impact fish and wildlife communities in Lake Okeechobee. Due to the wide range of chemicals and effects, a systematic approach is needed to address potential effects. First, a list of contaminants most likely to impact fish and wildlife in the lake needs to be developed. Once this is done, appropriate studies can be designed to address the magnitude and extent of the problem. This process should be part of a system-wide reconnaissance.

> Develop a list of contaminants that warrant investigation.

> Acquire data on local, regional, and global sources; transport mechanisms; fate; and effects of these contaminants.

> Design appropriate monitoring programs (endpoints, methods, etc.) to assess extent and magnitude of impacts due to contaminants of concern.

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