Lake Okeechobee Conceptual Ecological Model
(DRAFT UPDATE 12/12/2006)

9.4.1 Introduction and Background:

Lake Okeechobee is a large (1,730 km^2) freshwater lake located at the center of the interconnected south Florida aquatic ecosystem (Figure 1). The lake is shallow (average depth <3 m), originated about 6,000 years ago during oceanic recession, and under pre-settlement conditions probably was slightly eutrophic with vast marshes to the west and south. The southern marsh was contiguous with the Florida Everglades, which received water as a broad sheet flow from the lake during periods of high rainfall (Gleason 1984).
Modern-day Lake Okeechobee differs in size, range of water depths, and connections with other parts of the regional ecosystem (Steinman et al. 2002). Construction of the Herbert Hoover Dike in the early to mid-1900s reduced the size of the lake's open-water zone by nearly 30%, resulted in a considerable reduction in average water levels, and produced a new littoral zone within the dike that is only a fraction of size of the natural one. The lake also has been impacted in recent decades by excessive inputs of nutrients from agricultural activities in the watershed (Flaig and Havens 1995, Havens et al. 1996). These nutrients have exerted the most dramatic impacts on the open-water region, where large algal blooms have occurred, along with accumulation of soft organic mud bottom sediments that cause the lake water to become highly turbid when they are resuspended during windy periods (Maceina and Soballe 1990). The littoral zone has been invaded by 15 species of exotic plants, most notably *Melaleuca quinquenervia* and *Panicum repens* (torpedograss), which have expanded over large areas, displacing native plants. Despite these human impacts, and a consensus that the lake's overall health has been greatly degraded by human actions, Lake Okeechobee continues to be a vital aquatic resource of south Florida, with irreplaceable natural and societal values

Ecosystem conceptual models were developed for Lake Okeechobee restoration planning purposes. These models indicate, *via* simple box-and-arrow diagrams, how key biological components of the ecosystem are affected by various cultural stressors. The models for Lake Okeechobee are complex because the lake is comprised of three distinct components that have dramatically different structure and function: a littoral marsh, a near-shore region, and an open water (pelagic) region. The lake conceptual models were developed in the context of this heterogeneity. The models also reflect the lake's present spatial extent, rather than the larger historical boundaries.

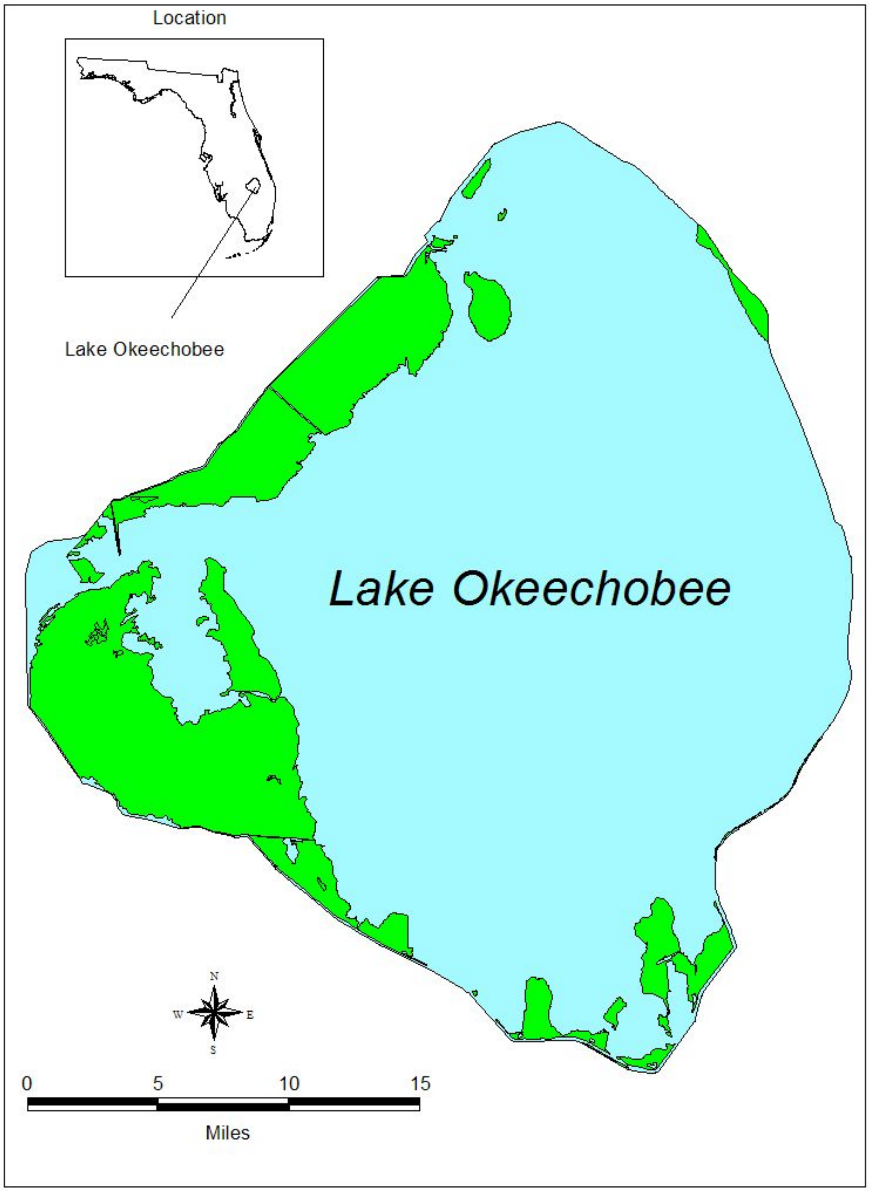


Figure 1: Lake Okeechobee .

9.4.2 Status of MAP Monitoring Components and Key Uncertainties

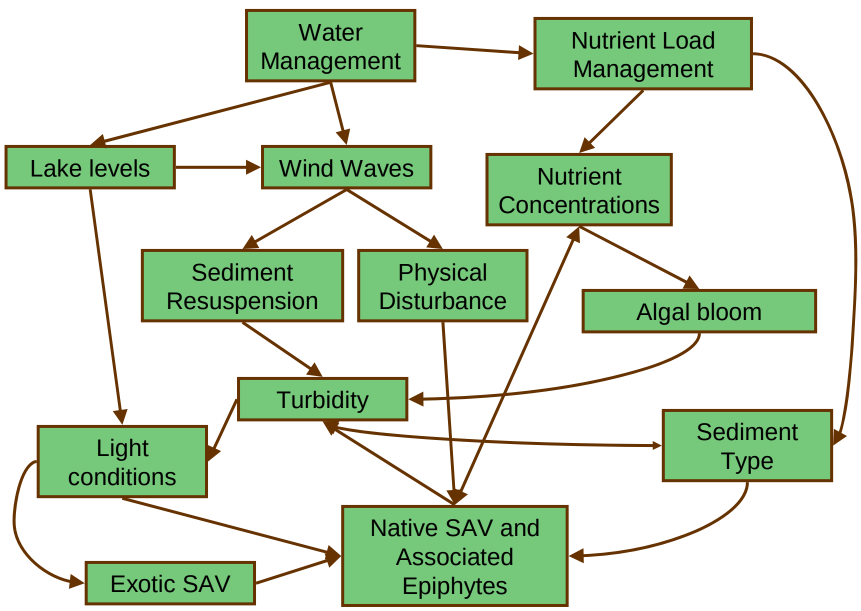
Monitoring components are related to the conceptual model outputs and reflect performance measure goals (Table 1). Additional planned, or ongoing research listed under **Key Uncertainties- Supporting Research** have been designed to elucidate or quantify model relationships for which specific quantitative information is insufficient, or lacking altogether.

Table 1.

Monitoring Components	**MAP Section**	**Status**
Water Quality		
YREG and OLIT Programs	3.4.3.1	Ongoing
Fish Fauna		
Fish Community Structure and Trophic Relationships in Submerged and Emergent Plant Communities	3.4.4.1	Fy06 If funded
Fish Population Density, Age Structure, and Condition Assessment	3.4.3.6	Pending GB approval
Vegetation		
Annual SAV mapping, Quarterly SAV monitoring	3.4.3.3	ongoing
Littoral Zone Vegetation Mapping	3.4.2.2	Fy06 If funded
Quarterly Periphyton Monitoring	3.4.4.4	ongoing
Quarterly Phytoplankton and Zooplankton Monitoring	3.4.3.1/3.4.3.4	ongoing
Megafauna		
Macroinvertebrate Monitoring	3.4.3.5	Fy06
Key Uncertainties- Supporting Research		
Influence of SAV beds on current velocity, and related sediment and nutrient transport	3.4.4.4	completed
Irradiance Requirements of SAV by species	3.4.4.4	ongoing
Irradiance Requirements for SAV germination by species	3.4.4.4	ongoing
Competitive interactions between SAV species	3.4.4.4	ongoing
Effects of hydroperiod on bulrush germination and growth	3.4.2.2	ongoing
Torpedograss methods of reproduction and dispersion	3.4.2.2	completed
Effects of hydroperiod and herbicide type on efficacy of Torpedograss control	3.4.2.2	ongoing

9.4.3 Submerged Aquatic Vegetation (SAV) Conceptual Model

The model below summarizes environmental interactions that are known to effect SAV areal distribution and density in Lake Okeechobee. Many of these parameters are currently being monitored and will be used in the development of assessment tools based on the hypotheses listed below.



9.4.4 SAV Hypotheses

9.4.4.1 Hypothesis 1

Lake stage is a major determining factor in the areal extent and density of submerged aquatic vegetation (SAV) in the littoral pelagic fringe zone of Lake Okeechobee.

Rationale. At higher lake stages, light penetration to the bottom is reduced and the area capable of supporting dense SAV is smaller. In addition, at higher lake stages the pelagic and littoral fringe zones of the lake become hydrologically connected resulting in increased turbidity which further decreases light availability for SAV growth (James and Havens 2005). Conversely, at lower lake stages, larger areas of the lake bottom receive adequate light to support SAV growth and much of the potential SAV growth zone becomes partially hydrologically uncoupled from the pelagic zone, and sheltered from prevailing wave action. This results in reduction in turbidity and further improvements in the light climate

9.4.4.2 Hypothesis 2

Major wind and wave events can result in large scale destruction of SAV by direct physical tearing and uprooting of plants.

Rationale. Following hurricanes Ivan, Frances, Jeanne and Wilma observational and monitoring data indicated a rapid and nearly instantaneous decline in SAV density and distribution. Following hurricanes Frances and Jeanne this decline exceeded 85%. Although this phenomenon would occur sporadically and is independent of the Comprehensive Everglades Restoration Program (CERP) effects, it has potential major consequences for the ecological health of Lake Okeechobee.

9.4.4.3 Hypothesis 3

Nutrient concentrations influence SAV areal coverage and density through their effects on phytoplankton density.

Rationale. Elevated nutrient concentrations stimulate dense phytoplankton blooms which reduce the light available for SAV growth. This causes reductions in SAV areal coverage and density and can lead to the development of a persistent turbid water state. When SAV density is high, or nutrient concentrations are low, plants out compete phytoplankton thereby maintaining a persistent clear water state (Phlips et al.1993).

9.4.4.4 Hypothesis 4

Under physical conditions that results in low light levels the exotic SAV species *Hydrilla* may have a competitive advantage over more desirable native SAV species.

Rationale. Mesocosm experiments conducted under natural light indicate that *Hydrilla* has a lower light requirement than any of the major native SAV species of Lake Okeechobee (Grimshaw and Sharfstein in preparation).

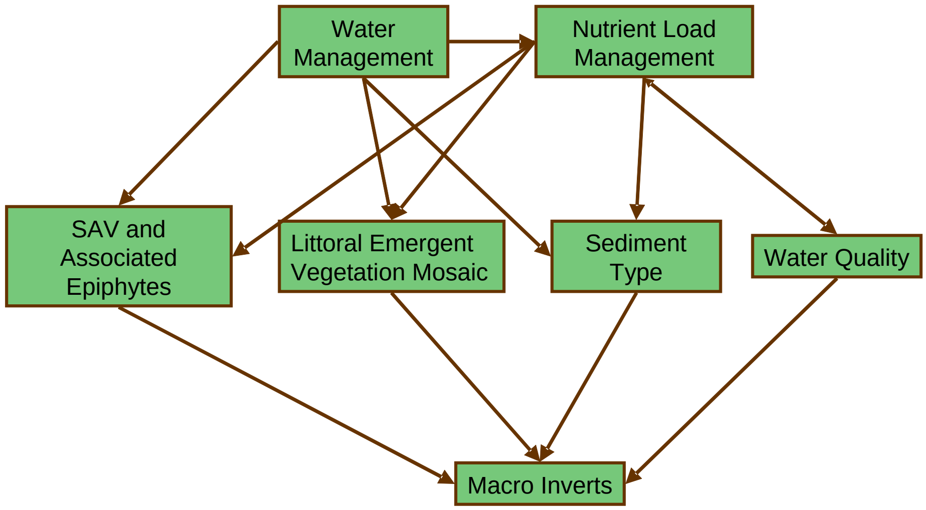
9.4.4.5 Hypothesis 5

Changes in the extent of mud sediments in the pelagic littoral fringe zone of Lake Okeechobee resulting from changes in nutrient loading and runoff influence the potential area available for colonization by SAV.

Rationale. In Lake Okeechobee SAV colonizes peat and sand sediment but does not grow in mud sediment. Changes in nutrient loading and runoff are expected to reduce and/or cap mud sediments and increase the area potentially available for colonization by SAV.

9.4.5 Macroinvertebrate Conceptual Ecological Model

The model below summarizes environmental interactions that are known to affect macroinvertebrate distribution, abundance and species diversity in Lake Okeechobee. A number of these parameters are currently being monitored and will be used in the development of assessment tools based on the hypotheses listed below.



9.4.6 Macroinvertebrate Hypotheses

9.4.6.1 Hypothesis 1

The presence of dense SAV and emergent plant beds results in higher macroinvertebrate diversity and fewer pollution-tolerant organisms.

Rationale. Research has suggested that macroinvertebrate densities in eutrophic lakes are higher in vegetated areas than they are in non-vegetated areas (Edwards and Cowell 1992, Petridis 1993, Kurashov et al. 1996). In Lake Okeechobee, Warren and Vogel (1991) have found that macroinvertebrate biomass and diversity were highest in dense plant beds under low to moderate lake stage (Havens and Gawlik 2005). The presence of dense SAV and emergent plant beds as a result of water management and nutrient load reduction activities should result in more habitat and improved water quality, thus facilitating a reduction in the density and number of pollution-tolerant macroinvertebrate taxa.

9.4.6.2 Hypothesis 2

The macroinvertebrate assemblage is more diverse and comprised of fewer pollution-tolerant taxa in regions of the lake underlain by sand and peat sediments than it is in areas underlain by mud sediments.

Rationale. The 1990-91 Lake Okeechobee benthic macroinvertebrate survey conducted by Warren et al. (1995) showed that the macroinvertebrate assemblage inhabiting the mud sediments was comprised of a small number of organic pollution and low dissolved oxygen-tolerant species. They also found that species richness was higher at sites located in sand and peat sediments, relative to those found at the sites located in mud sediments. Changes in nutrient loading and runoff are expected to reduce and/or cap mud sediments thereby increasing the percentage of the macroinvertebrate assemblage comprised of non-pollution tolerant taxa.

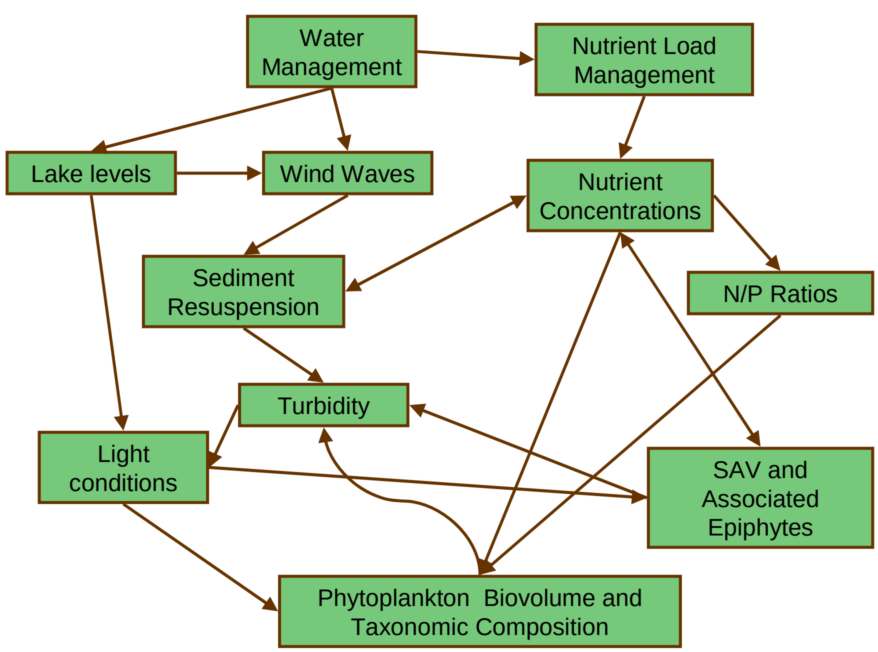
9.4.6.3 Hypothesis 3

Reduction in nutrient loads will result in increased macroinvertebrate diversity and a reduction in the number of pollution-tolerant macroinvertebrate taxa.

Rationale. Macroinvertebrate diversity in a Lake Champlain wetland declined as nutrient loading increased (Schwartz and Gruendling 1985). In Lake Erie decreased diversity and increased number of pollution-tolerant taxa occurred with increased nutrient loading (Krieger 1984). Warren et al. (1995) documented a large decrease in Lake Okeechobee benthic macroinvertebrate diversity compared to measurements made 20 years previously (Joyner 1974). Reducing nutrient loading in Lake Okeechobee is expected to result in a reversal of this trend and a return to an increasingly diverse macroinvertebrate community with a reduced number of pollution-tolerant taxa.

9.4.7 Phytoplankton Conceptual Ecological Model

The model below summarizes environmental interactions that are known to affect phytoplankton distribution, abundance and species diversity in Lake Okeechobee. Phytoplankton has been routinely monitored in Lake Okeechobee for more than a decade and the results will be used in the development of assessment tools based on the



hypothesis listed below.

9.4.8 Phytoplankton Hypotheses

9.4.8.1 Hypothesis 1

Lake water levels influence phytoplankton growth.

Rationale. At high lake stage both turbidity and phosphorus levels are elevated in the pelagic region due to wind driven resuspension of phosphorus laden mud sediments. The reduced light availability under these conditions has a negative impact on phytoplankton growth. High lake levels also result in greater horizontal mixing which increases nutrient transport into the less turbid near shore and littoral areas thereby increasing phytoplankton growth rates and the frequency of occurrence and intensity of algal blooms in these areas (Maceina 1993, James and Havens 1996, James and Havens 2005).

9.4.8.2 Hypothesis 2

Nutrient concentrations directly influence phytoplankton biovolume and taxonomic composition.

Rationale. Prolonged high rates of external loading of phosphorus (P) from the watershed have resulted in a surplus of phosphorus relative to algal demands. The enrichment of P has altered the nitrogen to phosphorus ratio (N:P) shifting conditions from a P limited to an N limited system, whenever the system isn't light limited (East and Sharfstein 2006). P limitation favors dominance of the more desirable non-bloom forming algal species while N limitation favors dominance by undesirable noxious bloom forming cyanobacteria. These bloom forming cyanobacteria can remain buoyant in the water column and obtain nitrogen from the atmosphere by the process of nitrogen fixation (Horne 1977) thus having a competitive advantage over the non nitrogen-fixing, non bloom-forming species. Consequently, the frequency of severe cyanobacterial blooms increases under these conditions.

9.4.8.3 Hypothesis 3

Underwater irradiance (light level) regulates phytoplankton taxonomic composition.

Rationale. Low light conditions favor the proliferation of low light adapted non bloom-forming species while high light conditions are dominated by the high light adapted bloom forming species. Although the N:P ratio in the lake provides nutrient conditions that are potentially favorable for dominance by the bloom forming cyanobacteria, their occurrence is often restricted by low light availability (Havens et al. 2003). Therefore, in the shallower, less turbid near shore region N limitation prevails (Aldridge et al. 1995, East and Sharfstein 2006) and the bloom-forming cyanobacteria dominate while in the deeper more turbid pelagic region light is the limiting factor so the non bloom-forming cyanobacteria dominate.

9.4.8.4 Hypothesis 4

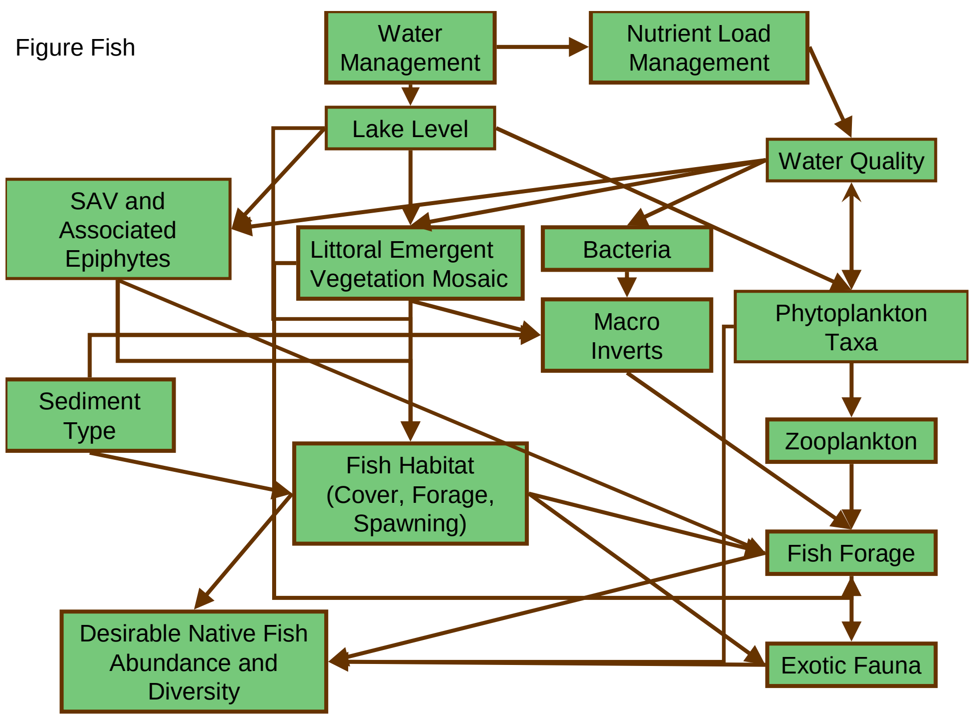
The presence or absence of submerged aquatic vegetation (SAV) and associated epiphytes has an impact on phytoplankton biovolume.

Rationale. SAV and its associated epiphytes have the ability to reduce water column P concentrations by direct uptake or by mediating changes in pH causing coprecipitation of P with calcium, Rooted SAV also stabilizes the sediment preventing the resupension of both sediment and P back into the water column. SAV and epiphytes also compete for nitrogen and other nutrients with phytoplankton. Therefore the presence of submerged plants in the littoral pelagic fringe has the potential to inhibit phytoplankton growth and algal bloom frequency and intensity when nutrient concentrations are high.

9.4.9 Native Fish Species Conceptual Ecological Model

The model below summarizes environmental interactions that are understood to affect native fish abundance and diversity in Lake Okeechobee. A number of these parameters are currently being monitored, and some, such as sport fish abundance and recruitment have been monitored by The Florida Fish and Wildlife Conservation Commission (FFWCC) for decades. Monitoring results will be used in the development of assessment tools based on the hypotheses listed below.

Figure Fish



9.5.1 Native Fish Species Hypotheses

<u>9.5.1.1 Hypothesis 1</u>

Increases in SAV density, biomass, and aerial coverage improve fish habitat and fish foraging opportunities and improve desirable native fish abundance and diversity

Rationale. Havens et al. (2005) observed a significant recruitment of largemouth bass in Lake Okeechobee that coincided with improved diversity and complexity of the SAV and emergent vegetation in 2002, after years of high water and low SAV. Similar results for Lake Okeechobee were reported by Chick and McIvor (1994, 1997) and Furse and Fox (1994). Increasing complexity of the areas for fish forage, fish spawning, and shelter for prey species, will increase fish abundance and diversity.

9.5.1.2 Hypothesis 2

Decreases in nutrient loads and improvements in water quality will result in increased fish diversity and a shift from less desirable rough fish to more desirable game fish

Rationale. Reduced nutrient loads will lead to improved water quality. The improvements in water quality will result in shifts of phytoplankton taxa from cyanobacteria, which are often inedible, toxic or indigestible by zooplankton to diatoms, which are preferred foods. Increases in the Diatoms will change the relative proportion of heterotrophic carbon production to autotrophic carbon production which will lead to an increase in food for forage fish and a shift form planktivorous and benthivorous species to more desirable piscivores.

9.5.1.3 Hypothesis 3

Competition from introduced exotic fauna exerts negative pressure on desirable native fish.

Rationale. Exotic animals in Lake Okeechobee now include fish, amphibians, reptiles, mollusks and macroinvertebrates, as well as avifauna and mammals. Each of these species exerts different impacts on the ecosystem. Many of these species have been accidentally introduced to the lake, and this situation is likely to continue, as new species are introduced to the United States and subsequently spread by boats and other mechanisms into Florida waters. While the specific effects of exotic animals on Lake Okeechobee are for the most part unknown, results from other ecosystems suggest that exotic fauna displace native species, disrupt established trophic relationships and may serve as reservoirs or vectors for disease.

9.5.1.4 Hypothesis 4

Reduction in mud sediment resulting from water management improves macroinvertebrate species diversity resulting in a positive impact on the food web resulting in increases in desirable fish species.

Rationale. The macroinvertebrates surviving in Lake Okeechobee mud sediments are burrowing species (primarily oligochaetes) that are common in polluted and anoxic sediments (Warren et al. 1995). Reducing and or capping mud sediments will shift the taxonomic composition of macroinvertebrate fauna towards more pollution sensitive species that will enhance the available macroinvertebrate food supply.

9.5.1.5 Hypothesis 5

Prolonged low lake stage, particularly during the breeding season, removes large areas of fish foraging and spawning habitat from use and negatively impacts recruitment and ultimately fish abundance.

Rationale. When lake stage declines to 12 feet a majority of the littoral zone is dry. When lake stage is 11 feet the entire littoral zone is dry. At these low lake stages vast areas normally available for use as fish spawning and foraging habitat are gone. At excessively high or prolonged lake stages, littoral pelagic fringe habitat may be removed from use by fish due to negative impacts on submerged and emergent aquatic vegetation. However, high lake stages may open up more upland marsh habitat for potential use by fish, and may therefore not be as damaging as prolonged low lake stages.

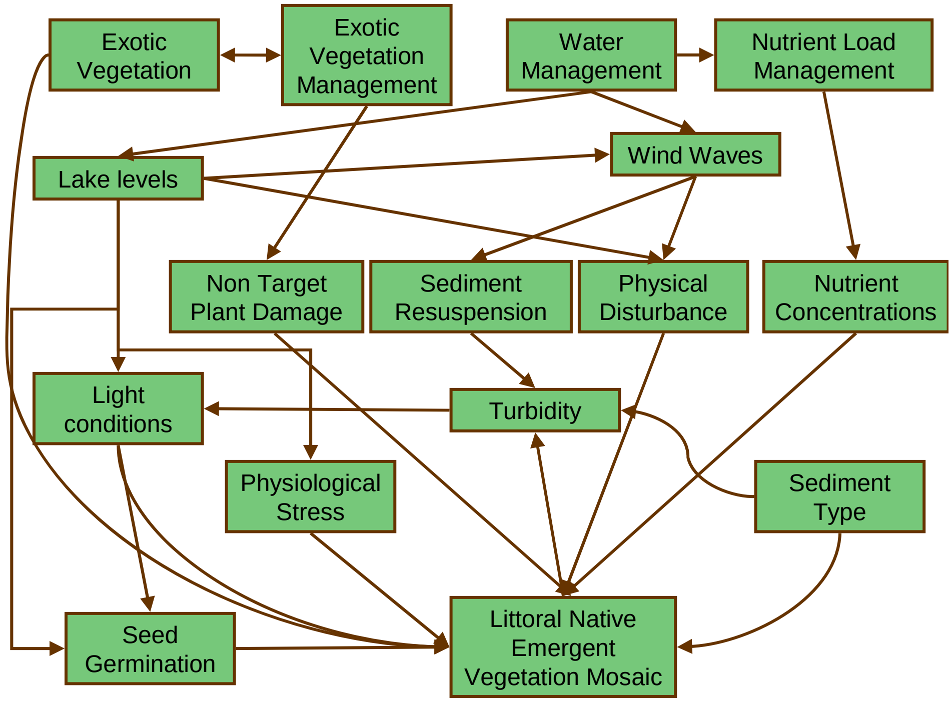
9.5.1.6 Hypothesis 6

Elevated nutrient loads and high water levels favor the development of dense algal blooms which can result in fish kills and negative impacts on other wildlife.

Rationale. As algal blooms decline, oxygen is consumed and ammonia released as the mass of algae degrades. Fish exposed to anoxic conditions or high ammonia concentrations will die if there is no escape. In addition, the dominant cyanobacteria in Lake Okeechobee, *Microcystis spp*. is capable of producing toxins that are directly harmful to fish and other wildlife in sufficient concentrations.

9.5.2 Littoral Zone Emergent Vegetation Mosaic Ecological Conceptual Model

The model below summarizes environmental interactions that are known to affect emergent vegetation density, areal distribution and species composition in the littoral zone of Lake Okeechobee. Emergent vegetation mapping using aerial photography has been conducted at approximately annual intervals in the Lake Okeechobee marsh since 1999. Results from this work will be used in the development of assessment tools based on the hypotheses listed below.



9.5.3 Littoral Zone Emergent Vegetation Mosaic Hypotheses

9.5.3.1 Hypothesis 1

Prolonged periods of high lake stage have direct and indirect negative impacts on shoreline and interior marsh vegetation.

Rationale. Desirable native shoreline vegetation including bulrush (*Scirpus californicus*) and SAV are more likely to be uprooted by wind driven waves when lake stage is high. Following a reduction in the spatial extent of rooted macrophytes, turbidity will increase, light availability will be reduced and plant growth will be inhibited due to poor water quality conditions. Additionally, the transport of pelagic water (Total Phosphorus--TP > 100 ppm) into interior regions of the marsh where TP concentrations are often less than 15 ppm occurs most often at high lake stage. An increase in nutrients in the interior marsh will result in the loss of desirable vegetation such as spikerush as cattail and less desirable vegetation expands.

Physically, rooted macrophytes help stabilize bottom sediments thereby reducing sediment resuspension during wind/wave events. During the late 1990s shoreline vegetation was commonly exposed to inundation depths > 2 m. This resulted in the uprooting and elimination of 1000s of acres of emergent macrophytes. The loss of shoreline vegetation also was accompanied by an increase in turbidity and a decrease in light availability (PAR). The negative feed back loop associated with high lake stage, decreases in the spatial coverage of rooted macrophytes, and declines in water quality will further inhibit the growth of desirable rooted vegetation.

Depth and duration of flooding are important in determining the distribution of emergent macrophytes. In deep water, emergent species may not have enough leaf area above the surface of the water to obtain the oxygen needed for respiration and/or the carbon dioxide needed for photosynthesis. Reduced oxygen uptake through the leaves can lead to inadequate supplies of oxygen to the roots and rhizomes that can result in plant death if the water depth exceeds a plants flood tolerance- (Van der Valk 1994).

Seeds of a number of desirable emergent species (Bulrush for example) will not germinate under flooded conditions. Therefore, in the absence of draw downs, recruitment of new plants from the seed bank will not occur. Prolonged high lake stage inhibits/prevents the germination of many desirable plant species in the marsh (Williges and Harris 1995). Without recruitment of new plants from the seed bank, the expansion and persistence of desirable marsh vegetation will occur only from vegetative reproduction.

Operating Lake Okeechobee at lower overall lake stages and providing periodic recession events will reverse these trends and encourage the expansion of desirable native emergent vegetation.

UU9.5.3.2 Hypothesis 2

The occurrence of low water events accelerates the spread of exotic and nuisance invasive vegetation such as torpedograss, *Melaleuca* and cattail and stimulate the germination of desirable native vegetation (e.g., spikerush, beakrush, and bulrush).

Rationale. Exotic and invasive species including torpedograss, *Melaleuca* and cattail grow well in exposed moist soil environments and shallow water habitats. These species commonly form dense monospecific communities that out compete and displace native plant communities. This is due in part to the absence of their native biocontrol organisms that prevent the exotic plants from becoming invasive weeds in their original range. Although low water conditions favor the growth of many non-desirable species, it also promotes seed germination of desirable native plants and allows for natural and controlled fires which can be effectively used with other management tools to control exotic and invasive species. Periodic low water events occurring with a frequency of approximately once per decade are postulated to provide an appropriate balance between the positive and negative effects of low water events.

9.5.3.3 Hypothesis 3

Floating exotic vegetation can have a negative impact on bulrush and other native plants which is further exacerbated under high lake stage conditions.

Rationale. High lake stage enhances the wind driven transport of floating exotics (water hyacinth and water lettuce) from previously isolated locations (interior areas of Torry and Kreamer Islands) and from the watershed into open shoreline regions of the marsh. These exotics, especially water hyacinth, commonly form large floating mats that exceed 50 m in length. The floating mats of hyacinth can cause extensive physical damage through uprooting and/or breaking emergent plant stems (e.g., bulrush) as they are pushed around the lake by wind and waves.

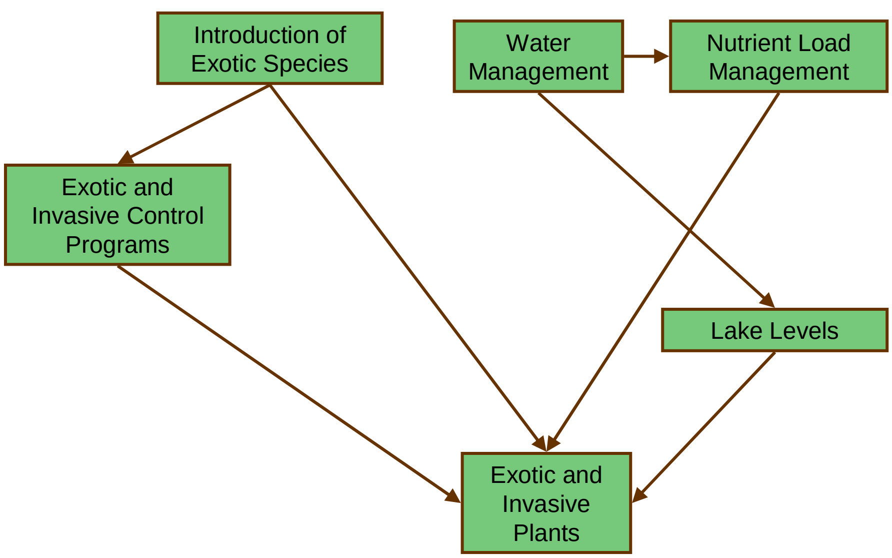
9.5.3.4 Hypothesis 4

Exotic vegetation management activities can have a negative impact on bulrush and other native non-target species.

Rationale. Floating mats of water hyacinth and water lettuce commonly occur along the littoral/pelagic interface (shoreline). To reduce the areal coverage of these exotic species and maintain navigational access to the lake, these mats are often sprayed with herbicide. Because the mats are commonly entangled in stands of bulrush and other native vegetation, some non-target plant damage is likely to occur during treatment. While it is recognized that chemical control of exotics is an unavoidable necessity on Lake Okeechobee at times, the non-target damage can be extensive.

9.5.4 Exotic Vegetation Ecological Conceptual Model

The model below summarizes our current understanding regarding control of exotic and/or invasive vegetation in the littoral zone of Lake Okeechobee. Despite the environmental changes that will eventually be brought about by CERP projects, it seems clear that ongoing vegetation management activities will nevertheless continue to be an essential component of lake management activities for the foreseeable future.



9.5.5 Exotic Vegetation Hypotheses

UUUUUUUUUUUUUUUUUUUUUUUU9.5.5.1 Hypothesis 1

Vegetation management activities can effectively control exotic and invasive plant species in Lake Okeechobee. When exotic vegetation is removed from the landscape, native plants are likely to become reestablish in previously impacted areas

Rationale. Floating mats of water hyacinth and water lettuce and monodominant stands of torpedograss, *Melaleuca*, and Brazilian Pepper trees have effectively been controlled with herbicides. Both aerial and ground based treatments have been effective. However, in some areas non-target damage to native vegetation may be a serious concern. Spikerush and other native plants have become established in many areas previously impacted by torpedograss.

9.5.5.2 Hypothesis 2

The transport of pelagic water (TP > 100 ppm) into interior regions of the marsh where TP concentrations are often less than 15 ppm occurs most often at high lake stage. Eutrophication of the interior marsh will result in the loss of desirable vegetation such as spikerush and sawgrass and lead to the expansion of cattail and other non-desirable vegetation.

Rationale. The expansion of cattail into Moonshine Bay in the 1980s first occurred along open airboat trails and in Cochran's pass. These areas were connected to the littoral/pelagic interface and likely received periodic inputs of P rich water during periods of high lake stage. Since the 1990s, hundred's of acres of fragrant water lily also have become established along the lake's shoreline and at interior marsh sites including Moonshine Bay.

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