# Minimum Flows and Levels for Lake Okeechobee, the Everglades, and the Biscayne Aquifer

## Executive Summary

### *Chapter 1.- Introduction*

This report documents the methods and technical criteria used by staff of the South Florida Water Management District (SFWMD) to develop proposed Minimum Flows and Levels (MFLs) for Lake Okeechobee, the Everglades, and the Biscayne aquifer. Section 373.042 (1), F.S., defines MFLs and directs the SFWMD to use the best available information in establishing a minimum flow or level. Passage of additional MFL legislation in 1997 added the requirements to consider changes and structural alterations, allow exclusions, and require development of a recovery strategy for water bodies that are not expected to meet the proposed criteria.

**Water Resource Functions.** Each surface water body or aquifer serves an array of functions. Water resource functions protected under Chapter 373 are broad and include flood control, water quality protection, water supply and storage, fish and wildlife protection, navigation, and recreation.

**Harm Standards.** Surface water management and consumptive use permitting regulatory programs must prevent **harm** to the water resource. The hydrological criteria include level, duration, and frequency components and are used to define the amount of water that can be allocated from the resource. For purposes of establishing MFLs, **significant harm** is defined as loss of water resource functions that take multiple years to recover, which result from a change in surface water or ground water hydrology. Water shortage declarations are designed to prevent **serious harm,** interpreted as long-term, irreversible, or permanent impacts, from occurring to water resources.

### *Chapter 2 - Description of Water Bodies*

The hydrology of South Florida is strongly affected by its climate, rainfall and seasonal weather patterns. The region has a subtropical climate and average annual rainfall of 53 inches. About 75% of this rainfall occurs during the hot and humid wet season (May through October) and the remainder during the mild dry season (November through April). Construction of the Central and Southern Florida Project for Flood Control and other Purposes (C & SF Project), has significantly altered hydrology, especially from Lake Okeechobee to Florida Bay along Florida's Southeast Coast.

**Lake Okeechobee.** Lake Okeechobee is a large, shallow, eutrophic lake located in south central Florida that serves as a multipurpose reservoir to meet regional water management needs. Development of a minimum level for Lake Okeechobee is based on achieving balanced protection of four water resource functions: a) maintaining levels in coastal canals; b) meeting water storage and supply needs; c) providing fish and wildlife habitat; and d) supporting navigation and recreational use. Lake Okeechobee water depths are controlled by a regulation schedule, while allocations of water from the lake during drought periods are based on a drought management plan.

**Everglades.** The Everglades is an internationally recognized ecosystem and is the largest subtropical wetland in the United States. Today's Everglades is comprised of five Water Conservation Areas (WCAs), the Holeyland and Rotenberger Wildlife Management Areas (WMAs) and Everglades National Park. Minimum level criteria and definition of significant harm for the Everglades were based on protecting six water resource functions: a) providing recharge to protect the Biscayne aquifer; b) supporting Everglades ecosystems c) providing natural biological filtering and nutrient cycling; d) providing refugia for aquatic wildlife e) preventing invasion by undesirable species; and f) maintaining desired salinities in coastal estuaries. Everglades water levels are managed based on regulation schedules in the WCAs and a rainfall based water delivery plan for Everglades National Park

**Biscayne Aquifer.** The Biscayne aquifer provides most of the fresh water for public water supply and agriculture in southeast Florida. Three water resource functions were considered, to provide a primary source of water supply, supply base flow to coastal estuaries, and prevent saltwater intrusion. The principal issue regarding development of minimum level criteria for the Biscayne aquifer is saltwater intrusion. Although the relationships between water levels in coastal canals and chloride levels in the monitoring wells have not been defined, sustained low water levels in canals are an indicator that problems may occur in the future.

**Considerations and Exclusions.** During development of MFL criteria for Lake Okeechobee, the Everglades, and the Biscayne aquifer, a number of structural changes or alterations were considered, along with the constraints such changes have placed on the hydrology of the region. District staff recommend that exclusions, as defined in Chapter 373 F.S., should not be applied to establish MFLs for Lake Okeechobee, the Everglades, and the Biscayne aquifer.

***Chapter 3 - Methods***

**Lake Okeechobee.** Minimum water level criteria for Lake Okeechobee were based on review of drought management plans, historical data, and ecological research Drought management plans indicated that the amount of rainfall that falls in South Florida from year-to-year is highly variable. Historical data showed that when lake levels fall below 11 ft, water levels declined rapidly, affecting the lake's ecology and the ability to deliver water downstream. As water levels fell below 10.5 ft, limitations of outlet structures made it difficult to provide water to protect coastal wellfields against saltwater intrusion. Review of ecological research showed that a decline in lake levels from 12 to 11 ft has significant impact, including a 20% loss of aquatic habitat. These impacts became worse as water levels declined below 11 ft. Relatively little ecological information exists to determine a minimum duration and return frequency, so these components were estimated based on analysis of historical records from 1952 to 1995. Significant harm to navigation and recreation was determined based on water depths needed for safe navigation of the Okeechobee Waterway, bathymetry maps, and discussions with marina operators and boat captains.

**Everglades.** Minimum water level criteria for the Everglades were based on results of a literature review, historical water level and fire data, and data from a mathematical model. Information from the literature described the ranges of water levels that occurred during droughts in the Everglades and other peat and marl based wetlands. Historical water levels were compared with available fire records from the Florida Fish and Wildlife Conservation Commission and published literature. The Natural Systems Model was used as a supplemental means to estimate minimum water depth, duration and return frequency under natural conditions during low rainfall years.

**Biscayne Aquifer.** Literature was compiled and summarized concerning the hydrology and hydrogeology of southeast Florida, the Biscayne aquifer, and saltwater intrusion in unconfined aquifers. Four sources of information were analyzed as follows: water quality and water level data, influence of canals on coastal aquifer water levels using a regional model, influence of canals on location of the saline interface using a two-dimensional solute transport/flow model, and comparison of these data to estimates derived from a theoretical relationship between surface and ground water levels.

***Chapter 4 - Proposed Criteria***

MFL technical criteria for Lake Okeechobee, the Everglades, and the Biscayne aquifer were defined based on the functions provided by the resource and a number of technical relationships.

**Lake Okeechobee.** The significant harm criteria for Lake Okeechobee were based on the relationship between water levels in the lake and the ability to: a) protect the coastal aquifer, b) Supply water to Everglades National Park, c) provide littoral zone habitat for fish and wildlife, and d) ensure navigational and recreational access. In addition, consideration was given to supplying water to adjacent areas such as the Everglades Agricultural Area, the Seminole Indian Tribe, and the Caloosahatchee and St. Lucie basins. Proposed minimum water level criteria for Lake Okeechobee include two components:

Operational MFL Criteria **-** *During most years, water levels in Lake Okeechobee should not fall below 11 ft NGVD. However, in order to make water deliveries from the lake to the LEC Planning Area, the water level in the lake may occasionally fall below 11 ft NGVD from April 15 to July 15, as long as it does not drop below the top of Supply-Side Management Zone C.*

Water Supply Planning MFL Criteria - *The water level in the lake should not fall below 11 ft NGVD for more than 80 days duration, more often than once every six years, on average.*

**Everglades.** Technical relationships for the Everglades included analysis of the effects of water levels on hydric soils, plant and wildlife communities, and frequency and severity of fires. Everglades “no harm” standards will be derived from model simulations for the year 2020 that include implementation of the Comprehensive Everglades Restoration Plan. Impacts associated with significant harm include increased peat oxidation, frequency of severe fires, soil subsidence, loss of aquatic refugia, loss of tree islands; and long-term changes in vegetation or wildlife. The proposed minimum water level criteria for the Everglades considered the two dominant soil types as follows:

*Water levels within wetlands overlying* ***organic peat soils*** *within the WCAs, Rotenberger and Holey Land WMAs, and Shark River Slough (Everglades National Park) should not fall 1.0 feet or more below ground level for more than 30 days, at specific return frequencies for different areas, as identified in the report.*

*Water levels within* ***marl-forming wetlands*** *that are located east and west of Shark River Slough, the Rocky Glades, and Taylor Slough within Everglades National Park should not fall more than 1.5 feet below ground level for more than 90 days, no more frequently than once every 5 years.*

**Biscayne Aquifer.** Technical relationships considered for the Biscayne aquifer included analysis of relationships among ground water levels, canal water levels and saltwater intrusion. Harm occurs when the saltwater interface moves further inland than has occurred historically due to seasonal water level fluctuations, up to and including a 1-in-10 year drought. Significant harm occurs when saline ground water moves inland to an extent that it limits the ability of users to obtain fresh ground water in the amounts specified in their permits and will require several years for the freshwater source to recover. The proposed criteria consist of a minimum canal operational level and duration of the event:

Minimum Canal Operational Level **-** *The minimum water level in a canal, which, if managed for a specific period of time, is sufficient to restrict saltwater intrusion within the coastal aquifer and prevent significant harm from occurring during a period of deficient rainfall.*

Duration **-** *The estimated period of time that canal water levels may remain below the minimum level without causing significant harm to coastal ground water resources.*

Minimum Water Level **-***Water levels in the Biscayne aquifer associated with movement of the saltwater interface landward to the extent that ground water quality at the withdrawal point is insufficient to serve as a water supply source for a period of several years before recovering.*

***Chapter 5- Conclusions and Recommendations***

Research is needed to address technical issues and relationships noted above. Proposed programs for Lake Okeechobee include: development of an updated vegetation map, and field monitoring and experiments to determine factors that influence expansion of torpedo grasses. Research for the Everglades includes studies of: peat accretion in WCA-2A and Everglades National Park, tree islands in WCA-3A and WCA-3B, nutrient thresholds in Everglades ecosystems, vegetation distribution, plant and animal communities in marl-forming wetlands, spatial distribution of soils, wading bird nesting and foraging, distribution and abundance of apple snails, movement and abundance of wading birds, and methods to improve regional models. Additional research is needed in Florida Bay to study sediment cores, the salinity transition zone, seagrass and plankton models and fish communities. Research for the Biscayne aquifer includes development of a solute transport ground water model, improved saltwater intrusion monitoring, and studies of relationships between canal stages and saltwater intrusion, minimum canal level duration, causes of depressed canal and aquifer levels, and potential remedies.

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# Chapter 1
# INTRODUCTION

This report documents the methods and technical criteria used by staff of the South Florida Water Management District (SFWMD or District) to develop proposed Minimum Flows and Levels (MFLs) for Lake Okeechobee, the remaining Everglades, and the Biscayne aquifer. The remaining Everglades include the Water Conservation Areas (WCAs), the Holey Land and Rotenberger wildlife management areas (WMAs), and the freshwater regions of Everglades National Park. The District is also proceeding with efforts to develop MFLs for associated areas, such as the Caloosahatchee River Estuary, by 2000, the Loxahatchee and St. Lucie estuaries by 2001, Florida Bay by 2005, and Biscayne Bay by 2004 (FDEP, 1998).

The *District Water Management Plan* (*DWMP*) *for the SFWMD* (SFWMD, 2000) includes a schedule for establishing MFLs for priority water bodies within the District. Chapter 373.042(2) requires the water management districts to annually review this list and schedule and make any necessary revisions. The SFWMD submitted a revised priority list and schedule to the Florida Department of Environmental Protection (FDEP) in November, 1999. This list indicated that MFLs were to be established by 2000 for the following priority areas: Lake Okeechobee, the Everglades, and the Biscayne aquifer in southeastern Florida and the Caloosahatchee River and Estuary and the aquifer system in southwest Florida. The District also indicated that voluntary peer review would be conducted, pursuant to Section 373.04(4) Florida Statutes (F.S.)

As a first formal step to meet the deadlines to establish MFLs for Lake Okeechobee, the Everglades, and the Biscayne aquifer, this report includes the following:

- A framework for determining MFLs based on the best available information (this approach may be applied to other surface and ground waters within the District).
- Development of a technical basis for establishing MFLs for Lake Okeechobee, the WCAs, Holey Land and Rotenberger WMAs, Everglades National Park, and the Biscayne aquifer.

Restoration goals for the Everglades were established by the Central and Southern Florida Project Comprehensive Review Study (Restudy), which has been developed by the U.S. Army Corps of Engineers (USACE), SFWMD, other agencies and interested parties, at the same time that these MFL criteria were developed. The recommendations made within the Restudy are being refined and implemented in the Comprehensive Everglades Restoration Plan (CERP). A potential for conflict exists in some areas between water levels that are established to achieve restoration and the water levels proposed in this document that are designed to prevent significant harm. As restoration goals for particular areas change over time, proposed MFLs for those areas will also be adjusted if necessary to ensure consistency.

# LEGAL BACKGROUND

The Florida Legislature has mandated that all water management districts establish MFLs for surface waters and aquifers within their jurisdiction. Section 373.042 (1), F.S., defines the minimum level as the "...level of ground water in an aquifer and the level of surface water at which further withdrawals would be significantly harmful to the water resources of the area..." The SFWMD is directed to use the best available information in establishing a minimum flow or minimum level (Section 373.042, F.S.). Each water management district must also consider, the protection of nonconsumptive uses in the establishment of MFLs. Providing protection for nonconsumptive uses is left to the discretion of the water management district.

Passage of the MFLs legislation in 1997 (CS/HB 715, 1249, 321, and 1339 as codified in Section 373.0421, F.S.) added the following requirements to the MFLs statute:

- When establishing a minimum flow or level, the District shall consider changes and structural alterations to watersheds, surface waters, and aquifers and the effect such constraints or alterations have had on the hydrology of the area. Such considerations shall not allow significant harm caused by withdrawals.
- The legislature also recognized that certain water bodies no longer serve their historic hydrologic functions, and that recovery of these areas may not be economically or technically feasible, and could cause adverse environmental or hydrologic impacts. Accordingly, water management districts may determine that setting a minimum flow or level for such a water body based on its historical condition is not appropriate. This exclusion does not apply to the Everglades Protection Area.
- If the existing flow or water level is expected to fall below the established MFL criteria, the District is required to develop and implement a prevention and recovery strategy for those water bodies that are expected to exceed the proposed criteria.

# PROCESS FOR ESTABLISHMENT OF MINIMUM FLOWS AND LEVELS

## Process Steps and Activities

The process for establishing minimum levels for Lake Okeechobee, the WCAs, the Holey Land and Rotenberger WMAs, Everglades National Park, and the Biscayne aquifer can be summarized as follows:

1. An initial draft of the MFL technical criteria document was completed in 1997.

2. A technical workshop was conducted to review this initial draft. The 1997 draft was revised to incorporate comments received from the public and various agencies and a revised the draft was released in July 1998.
3. The District Governing Board gave approval for District staff to conduct voluntary independent scientific peer review of the revised *MFL Technical Criteria* document. District staff responded to the comments provided by the review panel and have incorporated suggested revisions into this final document.
4. Development of a *MFL recovery and prevention strategy for the Biscayne aquifer, Everglades National Park, the WCAs, the Holey Land and Rotenberger WMAs, and Lake Okeechobee* is under way and will be included in the *LEC Regional Water Supply Plan*.
5. As part of the development of the recovery and prevention strategy, appropriate technical analyses are also being conducted to determine the water supply implications of the proposed MFL technical criteria on urban and agricultural users. These results will be integrated into the analysis in the final *LEC Regional Water Supply Plan* with appropriate implementation measures developed consistent with Section 373.0421 Florida Statutes.
6. In conjunction with completion of the *LEC Regional Water Supply Plan* and the *MFL Recovery and Prevention Strategy*, the District will initiate rule development.
7. Field monitoring and laboratory research programs have been initiated, or are currently being developed, to evaluate effects of implementing the MFL technical criteria proposed as part of this plan. These include both short-term and long-term projects to evaluate the effects of the proposed criteria at scales ranging from laboratory studies to field-scale monitoring projects.

## Scientific Peer Review

After the Governing Board authorized District staff to conduct a peer review, the District coordinated the review under Section 373.042, F.S. That section requires an independent scientific peer review [Section 373.019, (9)] of the technical development of MFLs, stating the following:

> Independent scientific peer review means the review of scientific data, theories and methodologies by a panel of independent, recognized experts in the fields of hydrology, hydrogeology, limnology, and other scientific disciplines relevant to the matters being reviewed under Section 373.042.

The document was peer reviewed during July, August, and September 1999. In review of MFLs, the panel acted as a concurrent, interactive group of experts. In essence, the panel's task was to determine if the appropriate scientific models and applications were employed, if all relevant data were used, and if the MFL criteria were a logical consequence of the science and the data. The panel and District staff participated in open public meetings during August and September, 1998.

Once the final data, methods, and models (including all scientific and technical assumptions employed in each model upon which a minimum flow or level is based) have undergone peer review, no additional peer review under the statute will be required. The final report is to be given significant weight when establishing MFLs.

The final report of the peer review panel was completed on September 22, 1998. Overall, the panel found the draft report to be well written, scientifically sound, and adequately referenced. The report made a clear connection between policy foundations and the technical issues. Particularly, the report made clear the issues of significant harm and the point at which such harm occurs. The report also made clear those indicators of significant harm for each of the three hydrologic systems. The report should, however, have made it clearer that MFLs are set to prevent the occurrence of significant harm. Results of the panels evaluation were presented in five major conclusions and 23 recommendations. The conclusions can be summarized as follows:

- The MFL criteria of 11 ft NGVD is appropriate given current information, however, long-term and cumulative effects of levels below 11 feet NGVD on the littoral zone of Lake Okeechobee are uncertain.
- The minimum canal level approach used to establish minimum water levels in the Biscayne aquifer has merit but does not directly address the issue.
- Use of hydric soils as an indicator of MFLs is appropriate, but the MFLs will need to be adapted to fit the diversity of soils present in the region.
- Special consideration should be given to areas with less than one foot of peat soil and less than 1.5 feet of marl soils.
- It is possible to set *initial* MFLs for the three hydrologic systems under consideration prior to setting MFLs for other areas such as Florida and Biscayne bays.

The recommendations addressed the issues raised in the conclusions in greater detail and provided suggestions to improve the final report. A copy of the final report of the peer review panel and responses of District staff to the report recommendations are provided in **Appendix D**.

## Periodic Review of Minimum Flows and Levels

Minimum flows and levels, as well as all water resource protection standards, should be updated on a periodic basis to incorporate newly identified technical information and evolving water management district goals and objectives. For example, the Everglades minimum levels, as proposed, have been identified based on protecting the restored system, as identified in the Restudy, from significant harm. The Comprehensive Everglades Restoration Plan will refine and adapt the recommendations made in the Restudy based on future research results, design changes, and technological advances. Restoration goals and harm standards may change as the system improves over time and in response to new laws and policies of the District's Governing Board and state and federal government. During the next 50 years the Everglades system will be managed to adapt to these conditions. As a part of this effort, minimum levels will also be reviewed on a periodic basis to determine whether the harm and significant harm standards are effectively protecting the resource and fulfilling the legal standards imposed by statute. It is the intent of the District to review the scientific basis of the proposed interim MFL criteria in all future updates of the *LEC Regional Water Supply Plan*. The plan will be updated approximately every five years.

# PRELIMINARY ISSUES

The following preliminary issues must be addressed to establish a minimum flow or level for a specific area:

- What are the priority functions of each water resource and what is the baseline condition for the functions being protected?
- What level of protection for these functions is provided by various harm standards, set forth in Chapter 373, F.S., including *significant harm*?

The following discussion is provided to help understand the legal, policy, and technical implications of these issues in establishing minimum levels for Lake Okeechobee, the Biscayne aquifer, and the remaining Everglades ecosystem.

## Water Resource Functions

Each surface water body or aquifer serves an array of functions. These functions must each be considered when establishing a minimum flow or level as a basis to determine whether or not the water resource is sustainable. The *State Comprehensive Plan*, Section 187.201(8)(b)6., F.S., provides that the water management districts shall do the following:

> Establish minimum seasonal flows and levels for surface watercourses with primary consideration given to the protection of natural resources, especially marine, estuarine, and aquatic ecosystems.

The term, water resource, is used throughout Chapter 373, and is part of the statute title. Water resource functions that are protected under Chapter 373 are broad, as illustrated in Section 373.016, F.S., which includes flood control, water quality protection, water supply and storage, fish and wildlife protection, navigation, and recreation. The need to protect water resources from harm is mentioned in many different places within the statute, including statutory intent (373.016), regulatory implementation (373.219, 373.414), water shortage implementation (373.175, 373.246), enforcement provisions (373.129), and planning requirements (373.026).

Water resources include aquatic and wetland, as well as the abiotic and biotic, components of these systems. The abiotic components include water, its chemical makeup, and soils. Biotic components include the plants and animals that comprise and depend on these systems. Many complex interactions exist among the water and living components that determine the essential nature of water resources.

The State Water Policy, Section 62-40.405, F.A.C, requires that consideration be given to protection of water resources. Consideration was given to natural seasonal changes in water flows or levels, environmental values associated with aquatic and wetland ecology, and water levels in aquifer systems. Specific considerations include the following:

- Fish and wildlife habitat and the passage of fish
- Maintenance of freshwater storage and supply
- Water quality
- Estuarine resources
- Transfer of detrital material
- Filtration and absorption of nutrients and pollutants
- Sediment loads
- Recreation in and on the water
- Navigation
- Aesthetic and scenic attributes

The ultimate policy determination as to which resource functions to consider in establishing MFLs is within the Governing Board's purview. This analysis requires a comprehensive look at sustainability of the resource itself, as well as it’s role in sustaining overall regional water resources.

## Identification of Baseline Conditions for Water Resource Functions

Once the water resource functions to be protected by a specific minimum flow or level have been identified, these functions are then evaluated to determine their applicable baseline or desired condition. These considerations are set forth in Section 373.0421(1)(a), F.S. and allow water management districts, when setting MFLs, to consider changes and structural alterations that have occurred to a water resource. Likewise, Section 373.0421(1)(b), F.S., recognizes that certain water bodies no longer serve their historical function and that recovery of these water bodies to historical conditions may not be feasible. Allowances are provided to account for the loss of historical functions. These provisions are discussed in Chapter 2.

# Level of Protection Provided by Various Harm Standards in Chapter 373

## Definition and Basis of Harm

The overall purpose of Chapter 373 is to ensure the sustainability of water resources of the state (Section 373.016, F.S.) To carry out this responsibility, Chapter 373 provides the District with several tools, with varying levels of resource protection standards. MFLs play one part in this framework. Determination of the role of MFLs and the protection that they offer, versus other water resource tools available to the District, are discussed below.

The scope and context of MFLs protection rests with the definition of significant harm. The following discussion provides some context to the MFLs statute, including the significant harm standard, in relation to other water resource protection statutes.

Sustainability is the umbrella of water resource protection standards (Section 373.016, F.S.). Each water resource protection standard must fit into a statutory niche to achieve this overall goal. Pursuant to Parts II and IV of Chapter 373, surface water management and consumptive use permitting regulatory programs must prevent **harm** to the water resource. Whereas water shortage statutes dictate that permitted water supplies must be restricted from use to prevent **serious harm** to the water resources. Other protection tools include health and safety or reservation of water for fish and wildlife (Section 373.223(3)), and aquifer zoning to prevent undesirable uses of the ground water (Section 373.036). By contrast, MFLs are set at the point at which **significant harm** to the water resources, or ecology, would occur. The levels of harm cited above, harm, significant harm, and serious harm, are relative resource protection terms, each playing a role in the ultimate goal of achieving a sustainable water resource.

## Need for Maximum Levels

Establishing *minimum* levels alone will not be sufficient to maintain a sustainable resource or protect it from significant harm. For both Lake Okeechobee and the Everglades, floods or extended periods of high water, also impact the resource. Setting minimum levels is viewed as a starting point to define water needs for sustainability. The necessary hydrologic regime for restoration of the entire Kissimmee-Lake Okeechobee-Everglades ecosystem must also be defined and implemented through the use of water reservations and other water resource protection tools. Achieving the required water levels throughout this system is an overall, long-term restoration goal. *Maximum* levels for Lake Okeechobee and the WCAs are controlled by regulation schedules for these areas. The overall ability of these schedules to protect the resource is uncertain due to the limited water storage capacity of the regional system, especially during above normal rainfall years. As a result, new or revised maximum water level criteria are being considered for certain areas as part of the Lower East Coast regional water supply planning process. These areas include WCA-3A, WCA-3B and WCA-2A, where existing tree islands require protection. The maximum water level for Lake Okeechobee, as determined by the regulation schedule, is currently being reviewed by the USACE, the District, and other agencies.

### Consumptive Use Permitting Role - Harm Standard

The resource protection criteria used for consumptive use permitting are based on the level of impact that is considered harmful to the water resource. These criteria are applied to varying resource functions, in order to establish the range of hydrologic change that can occur without harm. The hydrological criteria include level, duration, and frequency components and are used to define the amount of water that can be allocated from the resource. According to Chapter 40E-2, F.A.C., saltwater intrusion, wetland drawdown, aquifer mining, and pollution prevention criteria, all define the harm standard for purposes of consumptive use allocation. These harm criteria may be applied using climate conditions that represent an assumed level of certainty. The level of certainty used in the Lower West Coast and Upper East Coast water supply plans is a 1-in-10 year drought frequency, as defined in the District's permitting rules. In addition, the 1-in-10 year drought level of certainty is the water supply planning goal that was established in the 1997 legislative changes (Section 373.0831, F.S.). Another possible standard for harm may be the inability to achieve long-term planning or restoration goals. The standard for harm, as used in the Consumptive Use Permitting process, is considered to be the point at which adverse impacts to water resources that occur during dry conditions are sufficiently severe that they cannot be restored within a period of one to two years of average rainfall conditions. These short-term adverse impacts are addressed under the consumptive use permit program, which calculates allocations to meet demands for use during relatively mild, dry season conditions.

### Water Shortage Role - Serious Harm Standard

Pursuant to Section 373.246, F.S., water shortage declarations are designed to prevent serious harm from occurring to water resources. Serious harm, the ultimate harm to the water resources that was contemplated under Chapter 373, F.S., can be interpreted as long-term, irreversible, or permanent impacts. Declaration of water shortages is another tool that may be used by the Governing Board to prevent serious harm.

When drought conditions exist, water users, typically for irrigation or outside use, increase the amount of withdrawals to supplement water not provided by rainfall. In general, the more severe the drought, the more supplemental water is needed, which increases water shortage restrictions for users. These increased withdrawals increase the potential for serious harm to the water resource.

### Comparison of Significant Harm to Harm and Serious Harm Standards

Where does the significant harm standard lie in comparison to the consumptive use permitting and water shortage standards? The plain language of the standards of harm versus significant harm, although undefined by statute, implies that the minimum flow or level criteria should consider impacts that are more severe than those addressed by the consumptive use permitting harm standard, but less severe than the impacts addressed by the serious harm water shortage standard. The conceptual relationship among the terms harm, significant harm, and serious harm are shown in **Figure 1**.

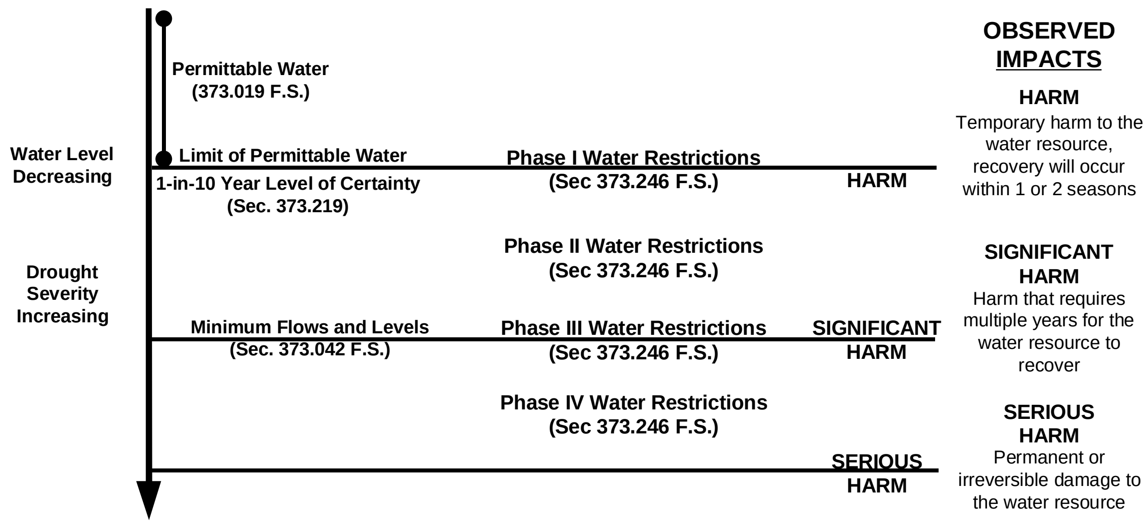


**Figure 1.** Conceptual Relationship Among the Terms Harm, Significant Harm, and Serious Harm.

The technical discussions in Chapter 4 of this report only identify the scale of water resource impacts associated with significant harm that are required to establish minimum water levels for the Everglades, Biscayne aquifer, and Lake Okeechobee. As noted at the beginning of this chapter, conflicts may arise between these MFL criteria and the restoration goals for the Everglades which are presently being refined and developed in the Comprehensive Everglades Restoration Plan. As restoration goals for particular areas change over time, proposed MFLs may also be adjusted, to ensure some degree of consistency with the model described in **Figure 1**.

The District has implemented its water shortage authority by restricting consumptive uses based on the concept of shared adversity between users and the water resources (Chapter 40E-21, F.A.C.). Under this program, different levels or phases of water shortage restrictions are imposed relative to the severity of drought conditions.

Four phases of the current water shortage restrictions are based on the relative levels of risk posed to resource conditions leading up to the serious harm impacts. Under the SFWMD's program, Phase I and II water shortages are primarily designed to prevent harm, such as localized, but recoverable, damage to wetlands or short-term inability to maintain water levels needed for restoration. Actions that may be taken include reducing water use through conservation techniques and minor use restrictions, such as car washing and lawn watering. Phases III and IV, however, require use cutbacks which are associated with some level of economic impact to the users, such as agricultural irrigation restrictions.

The exact actions taken to implement MFLs will be laid out in a recovery and prevention strategy developed through regional water supply planning. Whether a minimum flow or level will be used as a permitting standard or water shortage trigger will depend on whether, and to what extent, the existing permitted uses are causing exceedances and under which level of drought this occurs (e.g., a drought equal or less in severity than the level of certainty or one which is more severe and more appropriately addressed through water shortage cutbacks). In any case, some level of buffer between the MFL and permitting levels must be achieved in order to prevent continuous violations.

### Proposed Definition of Significant Harm to Water Resources

Based on the above considerations, the definition of significant harm for the water resources of an area, as proposed in this document is as follows:

***Significant harm** is defined as a loss of specific water resource functions that take multiple years to recover, which result from a change in surface water or ground water hydrology.*

## MINIMUM FLOW AND LEVELS RECOVERY AND PREVENTION STRATEGY

Section 373.0421, F.S. requires that once the MFL technical criteria have been established, the districts must develop a recovery and prevention strategy for those water bodies that are expected to exceed the proposed criteria. It is possible that the proposed MFL criteria cannot be achieved immediately because of ineffective water distribution infrastructure and/or the lack of adequate regional storage. These storage and infrastructure shortfalls will be resolved through water resource development and water supply development projects, construction of facilities, and improved operational strategies that will increase the region's storage capacity and improve the existing delivery system. Planning and regulatory efforts will, therefore, include a programmed recovery process that will be implemented over time to improve water supply and distribution to protect water resources and functions.

Development of the *Minimum Flows and Levels Recovery And Prevention Plan for Lake Okeechobee, the Everglades and the Biscayne Aquifer* is underway and will be incorporated into the LEC regional water supply planning process. Appropriate technical analysis are also being conducted to determine the water supply implications of the proposed MFL Technical Criteria on urban and agricultural users. These results will be integrated into the final *LEC Regional Water Supply Plan* analysis with appropriate implementation measures developed consistent with Section 373.0421 F.S.

# DOCUMENT STRUCTURE

The following chapter of this report describes the geographic setting, the resources at risk, and functions these resources serve that need to be protected, for Lake Okeechobee, the Everglades, and the Biscayne aquifer. Chapter 3 documents the methods that were used to establish significant harm criteria for the different areas, resources, and functions. Chapter 4 describes the specific hydrologic criteria, with frequency, duration, and depth components, that were developed to indicate the point at which significant harm occurs and includes an analysis of the specific relevant factors and implications of the proposed definition of significant harm. Conclusions and recommendations are presented in Chapter 5 and the literature cited is in the final chapter. Technical Appendices A through F are provided in a separate volume and include more detailed descriptions and analysis of available data, literature, and issues raised during the review process.

# Chapter 2
# DESCRIPTION OF PRIORITY WATER BODIES

## REGIONAL RAINFALL PATTERNS

The hydrology of South Florida is strongly affected by it's climate, rainfall, and seasonal weather patterns. The region has a generally subtropical climate characterized by a long, hot, and humid wet season (May-October) and a relatively mild dry season (November-April). The wet season is characterized by high humidity, intense solar radiation, and unstable atmospheric conditions that result in frequent thunderstorms often accompanied by lighting and intense rainfall of short duration. Severe tropical storms such as hurricanes and tropical depressions also occur during the wet season. These storms can produce large amounts of rainfall over localized areas and cause extensive flooding. In contrast, the dry season is characterized by mild, dry weather. Frontal storms are dominant in the dry season, often bringing cool and occasionally freezing temperatures, and moderate amounts of low intensity rainfall. On average, South Florida receives about 53 inches of rainfall annually, 75 percent of which falls during the wet season (Shih, 1983).

**Figure 2** provides estimates of mean monthly rainfall for Lake Okeechobee, the Everglades, and the Biscayne aquifer for the period of record, 1965-1995 (data from South Florida Water Management Model, version 3.6). Lake Okeechobee receives the lowest total average annual rainfall compared to the Everglades and the Biscayne aquifer with an average of 43.4 inches/year. June, July, August, and September are the wettest months, while November, December, and April are the driest. In contrast, the Everglades (the Water Conservation Areas and Everglades National Park) receive an average of 50.8 inches of rain each year. The wettest month is June and the driest month is December. The lower east coast of Florida (the Biscayne aquifer) receives, on average, the highest amount of rainfall, with an average of 59.2 inches recorded over the 1965-1995 period of record. Again, the wettest month is June and the driest month is December.

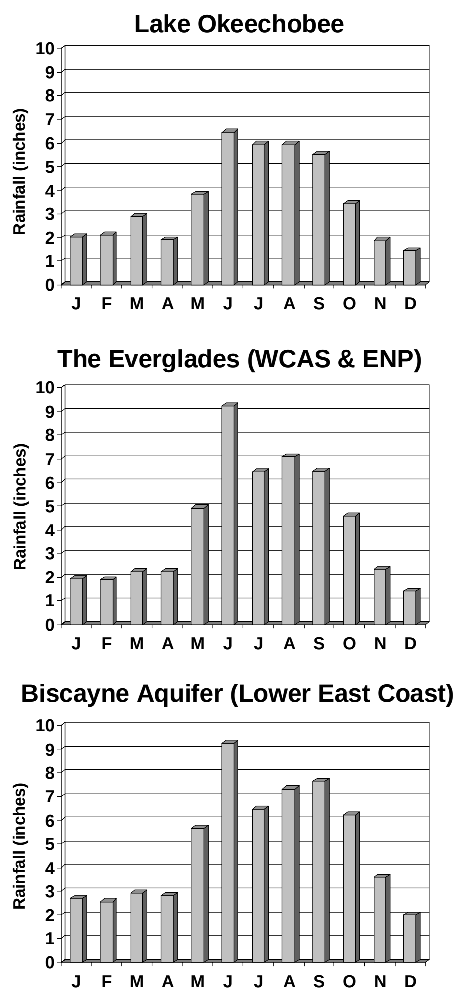


**Figure 2.** Mean Monthly Rainfall for Lake Okeechobee, the Everglades, and the Biscayne Aquifer (1965-1995). Source: Output of SFWMM 1995 Base Case (POR 1965-1995)

# NATURAL VERSUS MANAGED HYDROLOGY

The following is a summary of the regional water budget derived from the 2000 Everglades Consolidated Report (SFWMD, 1999). Average annual water movements and storages in the Everglades from 1965 through 1995 under natural conditions (simulated by Natural Systems Model version 4.5) and under the 1995-base[1] managed conditions (simulated by South Florida Water Management Model version 3.5), are summarized in **Figures 3** and **4**.

Overland flows to the south and west from Lake Okeechobee have been entirely eliminated due to the construction of the levee and water-control structures. If these alterations had not been made, 868,000 acre-feet of water would have flowed overland from Lake Okeechobee to the Everglades and the Caloosahatchee Basin. Instead, 989,000 acre-feet of water is channeled to the south, west, and east for urban and agricultural supply and flood control. In addition, 216,000 acre-feet is discharged back into Lake Okeechobee to prevent regional flooding adjacent to the lake. Also, 149,000 acre-feet of water is discharge from Lake Okeechobee via the St. Lucie Canal.

Historic southerly overland flows from what is now the Everglades Agriculture Area, an area once dense with pond-apple and sawgrass, have also been eliminated. The Natural System Model (NSM) water budget (**Figure 3**) indicates that 157,000 acre-feet of net precipitation plus 900,000 acre-feet of surface water would have combined to form a southerly overland flow from this area into what is now the WCAs. The 1995-base managed condition (**Figure 4**) indicates no overland flow. All flows are now channelized for drainage, flood control, best management practices (BMP) makeup water, and water supply. Some of this water passes through the WCAs and is supplemented by Everglades water to meet urban and agricultural needs in the Lower East Coast Planning Area (172,000 acre-feet) and some WCA water seeps back into the EAA as groundwater (36,000 acre-feet).

Downstream of the EAA and Lake Okeechobee, the three WCAs are currently managed, in part, as large reservoirs for flood control for the Lower East Coast (LEC) Planning Area and the storage of EAA drainage water (**Figure 4**). This storage helps create a large groundwater flow (677,000 acre-feet) to the LEC Planning Area. This flow contributes to the huge movement of canal water lost to tide (2,843,000 acre-feet). This managed system is in sharp contrast to the NSM, which predicted large exchange of surface water, the lack of groundwater movement, and a low amount of freshwater flow to the Atlantic Ocean (**Figure 3**).

Finally, in the NSM water budget, the vast majority of all inflows and outflows in Everglades National Park are overland flows. This is not true for the 1995-base SFWMM water budget. Current inflows from the LEC Planning Area into Taylor Slough are only 32 percent of what was predicted to occur by NSM. The Shark River Slough outflow from Everglades National Park to the southwest, into the Gulf of Mexico, is 48 percent of what was predicted to occur by the NSM.

1. Note that the 1995-base is a fixed Everglades infrastructure, with stationary operational rules (circa 1995) and thus, is not indicative of the amount of actual freshwater delivered to Florida Bay by the C&SF Project from 1965 to 1995 (SFWMD, 1999).

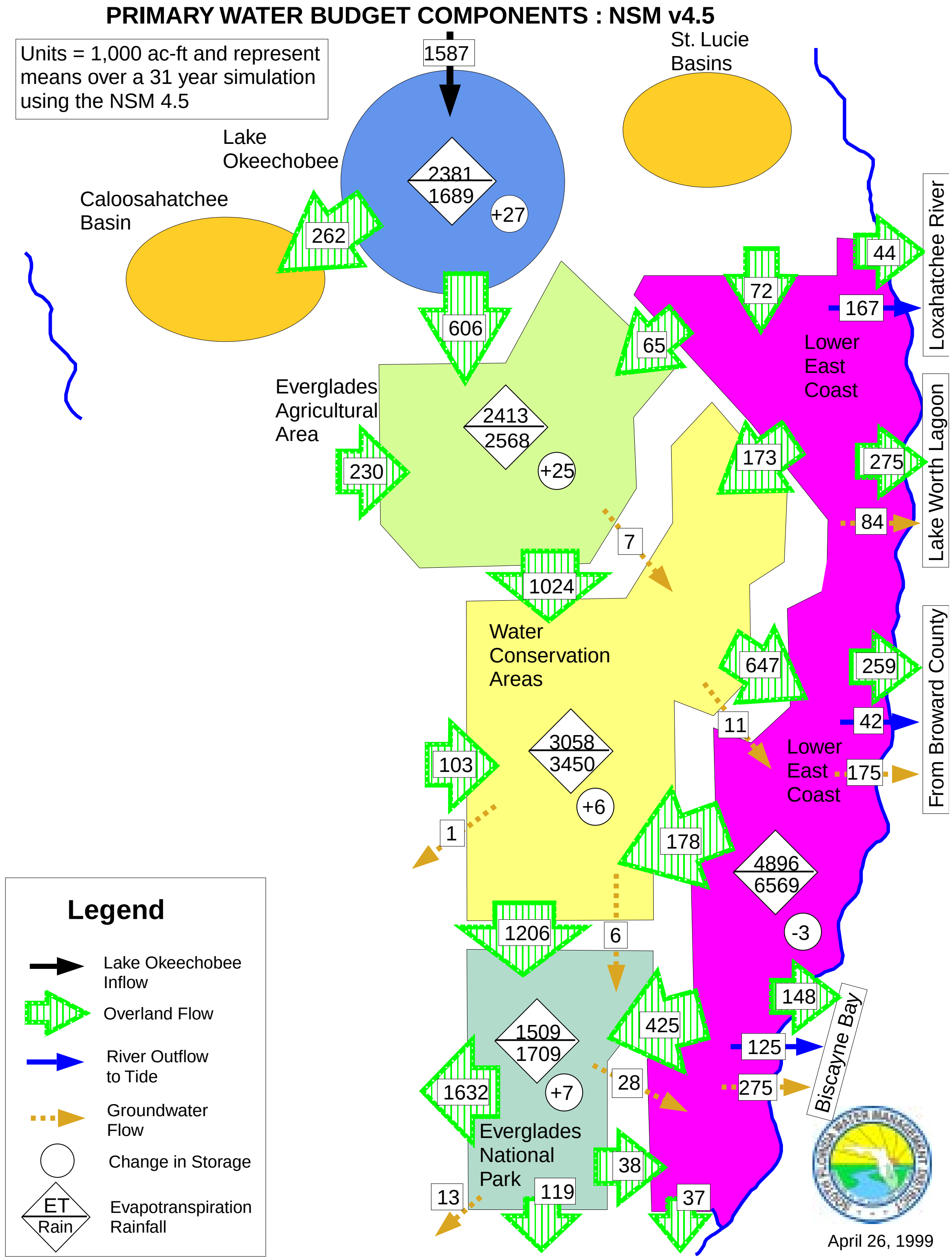


**Figure 3.** Primary Water Budget Components that Resulted from 31-Year Simulations of the Natural Systems Model, version 4.5 (SFWMD, 1999). Data are aggregated by major basins; flow values represent annual averages in thousands of acre-feet.

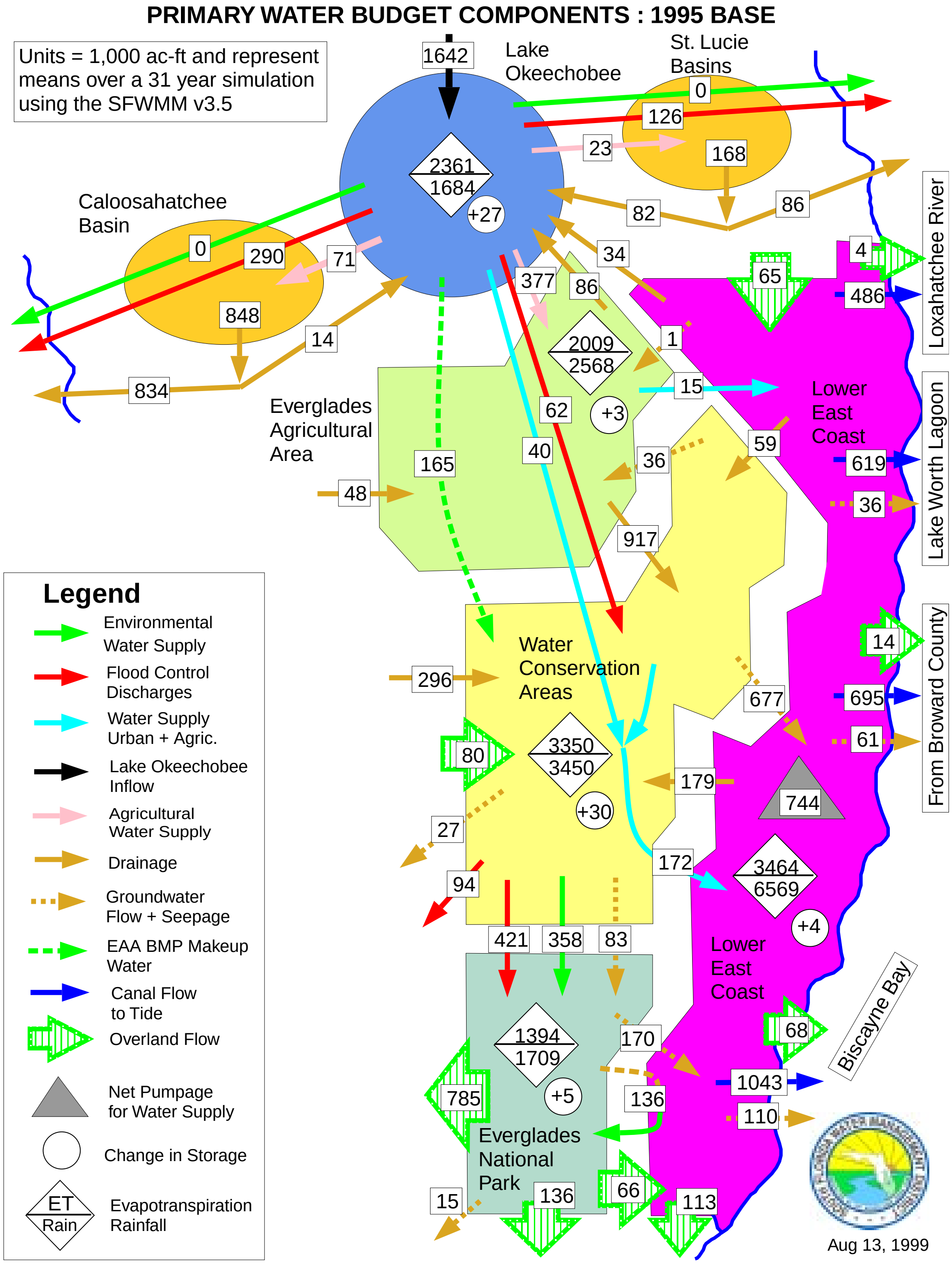


**Figure 4.** Primary Water Budget Components that Resulted from 31-Year Simulations of the South Florida Water Management Model Version 3.5 (SFWMD, 1999). Data are aggregated by major basins; flow values represent annual averages in thousands of acre-feet.

# LAKE OKEECHOBEE

## Major Features

Lake Okeechobee is a large, shallow, eutrophic lake located in south central Florida **(Figure 5**). The lake is often referred to as the "liquid heart" of South Florida's interconnected Kissimmee River-Lake Okeechobee-Everglades ecosystem. With a surface area of more than 730 square miles, Lake Okeechobee represents the third largest lake in the United States. The lake is a multipurpose reservoir developed as part of the Central and Southern Florida Project for Flood Control and other Purposes (C&SF Project). The lake provides the following:

- Water for surrounding lakeside communities
- Supplemental water supply for more than 6.5 million people living within the LEC Planning Area and the Caloosahatchee River Basin
- Supplemental irrigation water for agriculture in the LEC Planning Area (including the EAA), as well as in the Caloosahatchee River and C-44 Canal basins
- Supplemental water that can be delivered via canals to protect the Biscayne aquifer against saltwater intrusion
- A source of water for enhancement of fish and wildlife resources, for navigation and recreation benefits, and for Everglades National Park

The District and the United States Army Corps of Engineers (USACE) have the primary responsibility for management of water levels in the lake, the Florida Department of Environmental Protection (FDEP) and the District are the primary state agencies responsible for water quality protection, and the Florida Fish and Wildlife Conservation Commission (FFWCC) manages fish and wildlife resources.

Lake Okeechobee was formed approximately 6,000 thousand years ago (Hutchinson, 1957). Historic maximum water levels were estimated to range from 19.7 to 21.3 feet (Brooks, 1974). In its original condition, the lake was considerably larger than it is today and consisted of an extensive littoral marsh system extending to the north, west, and south of the lake. Construction of the levee system (Herbert Hoover Dike) around the lake and the lowering of lake levels from a maximum of 20 to 17 ft NGVD effectively isolated thousands of acres of marsh, creating a new littoral zone/marsh community in areas where it had not previously existed. This wetland area now occupies more than 20 percent (98,000 acres) of the total surface area of the lake and provides habitat for a wide variety of plant and animal communities, including a number of rare, threatened, or endangered species such as the snail kite, wood stork, West Indian manatee, and the Okeechobee gourd (SFWMD, 1993a). The littoral zone provides an important nursery ground and habitat for fish and other aquatic organisms. Migratory birds and waterfowl also utilize the littoral zone and open water areas of the lake as a resting area along the Atlantic flyway (Aumen, 1995).

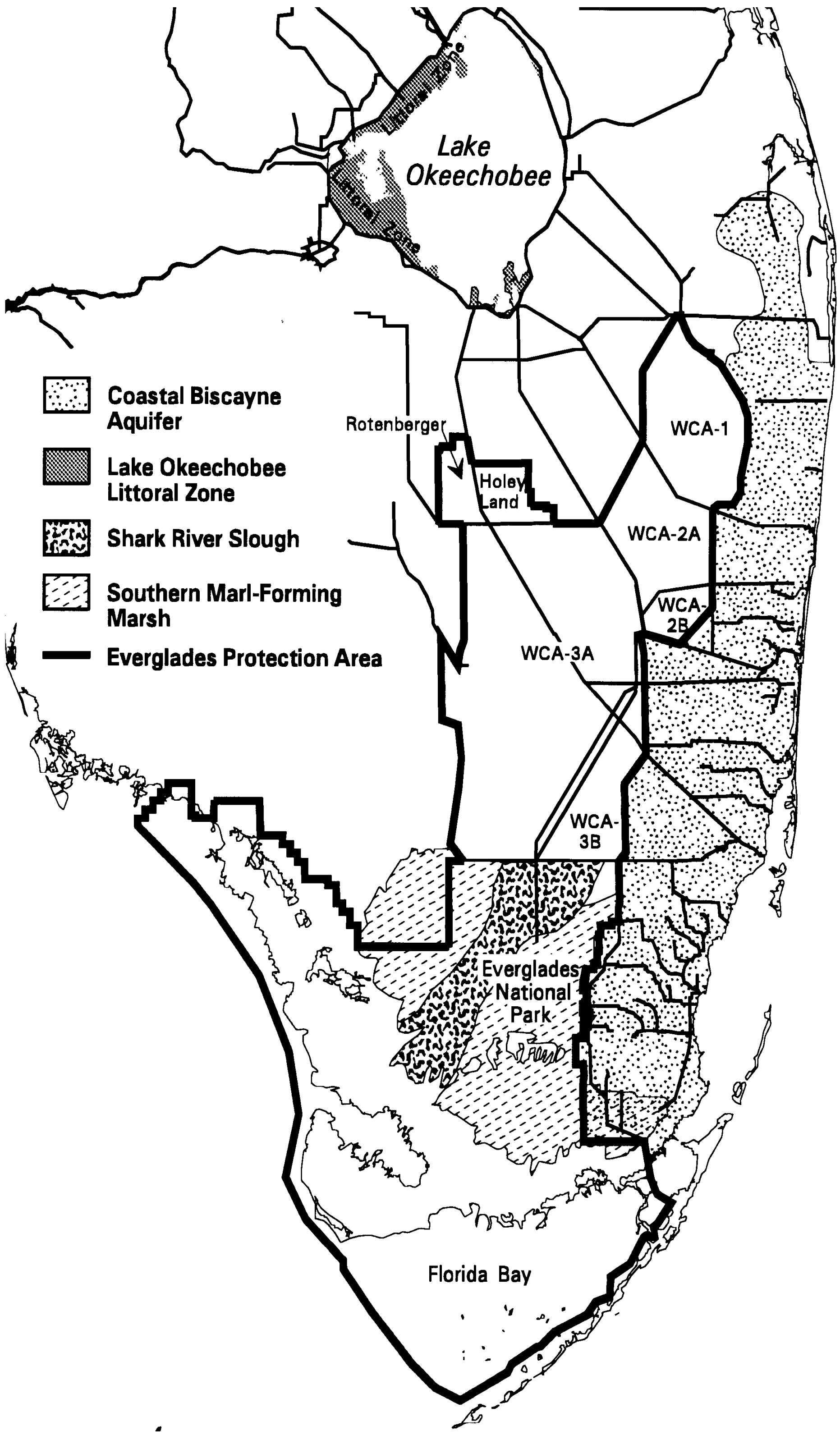


**Figure 5.** Priority Areas for Establishing Minimum Flows and Levels in South Florida.

Lake Okeechobee is also important to navigation and represents a recreational resource of regional importance. The lake is part of the Okeechobee Waterway connecting the east and west coasts of Florida. The lake also supports a nationally renowned sport fishery for largemouth bass, black crappie, bluegill, redear sunfish, and catfish. Recreational and commercial fisheries combined have an estimated value of more than $28 million dollars per year (Bell, 1987). The lake's littoral zone also supports significant wading bird populations and is an important waterfowl hunting area.

## Resource Functions

The development of a minimum level and definition of significant harm for Lake Okeechobee focused on protecting four key water resource functions and achieving a balance among them (not listed in priority order):

- Provide water that can be used to maintain water levels in coastal canals and protect the Biscayne aquifer against saltwater intrusion
- Supply water and provide water storage for the Everglades
- Regionally important ecosystems in the lake littoral zone provide fish and wildlife habitat and support commercial and sport fisheries.
- Provide navigation and recreational use

Several combined hydrological impacts to each water resource function were also considered in defining significant harm for Lake Okeechobee:

- The water supply and storage function of the lake is impacted when water levels in the lake decrease to the extent that water deliveries can no longer be made to the LEC Planning Area to protect the Biscayne aquifer from the threat of saltwater intrusion, while at the same time meeting the demands of lake users who are under severe water shortage restrictions.
- Fish and wildlife habitat is damaged when water levels decrease to levels that impact the lake's littoral zone community and would take multiple years of normal rainfall to recover. Impacts associated with decreased water levels include the following:
    - Complete drying of the littoral zone
    - Loss of food resources and critical habitat for fish and wildlife, including threatened or endangered species
    - Invasion of the littoral zone by terrestrial vegetation and exotic species
    - Navigation and recreation functions of the lake are impacted when lake stages fall to levels that significantly restrict use of the Okeechobee Waterway and restrict

fishermen and boaters from access to the southern and western portions of the lake.

## Water Resource Issues

The major water resource issues associated with management of Lake Okeechobee include the following:

### Water Supply

Much of South Florida depends on Lake Okeechobee as its primary source of water supply during low rainfall periods. Future population growth, land use changes, and competing water supply needs will have significant effect on future water levels and water storage in Lake Okeechobee. Model simulations for 2010 show the increased likelihood of severe water shortages and water supply cutbacks within the Lake Okeechobee and LEC service areas (SFWMD, 1998). This reduced water supply has the potential to increase the problem of saltwater intrusion along Florida's lower east coast during dry periods.

### Flood Protection

During 1997 and 1998, a number of extreme rainfall events increased water depths to levels which exceed the current regulation schedule and threatened the structural integrity of the levee system that surrounds the lake. To maintain an acceptable level of flood protection for communities that surround the lake, water levels during the hurricane season must be maintained at safe levels (<16.5 ft NGVD) that will not threaten the levee system.

### Water Quality

Declining water quality and increased frequency of algal blooms have occurred in the lake as a result of increased nutrient loading from nonpoint sources of pollution originating from agricultural lands located north of the lake (Aumen, 1995; SFWMD, 1997a). This issue has been addressed through adoption and implementation of the *Lake Okeechobee Surface Water Improvement and Management* (*SWIM*) *Plan* (SFWMD, 1989, 1992, 1997a) and was not considered during development of MFLs.

### Impacts to Estuaries

During periods of high rainfall, large regulatory releases of fresh water are made to the St. Lucie and Caloosahatchee estuaries. These discharges cause wide fluctuations in salinity within the inner estuary and impact estuarine biota (Haunert, 1988; Chamberlain et al., 1995)

### Littoral Zone

The plants and animals in the littoral zone of Lake Okeechobee are stressed by extremes in water level, both at the high and low ends. Extreme high water levels flood the littoral zone with nutrient-rich water, may promote the expansion of cattails, and lead to declines in beneficial beds of submerged vegetation. Extreme low water levels render much of the littoral zone unavailable as habitat and appear to promote the expansion of exotic plants including torpedo grass and melaleuca. A primary issue related to defining a minimum water level for the lake is the determination of an appropriate water level regime (hydroperiod) that will maintain the ecological integrity of the littoral zone.

### Exotics

Expansion of undesirable aquatic weeds and exotic plants (torpedo grass, melaleuca, hydrilla, water lettuce, and water hyacinths) have become a threat to the lake ecosystem because of their rapid expansion into areas once occupied by native species. These infestations hinder recreational use of the lake and require expensive chemical treatment (Aumen, 1995).

## Water Management Features

Lake Okeechobee represents South Florida’s most effective surface water storage area. Water levels within Lake Okeechobee are managed using a rule curve, or regulation schedule, while water allocation to downstream users is managed using a combination of the District’s *Water Shortage Plan* (SFWMD, 1989) and *Supply-Side Management Plan for Lake Okeechobee* (Hall, 1991).

### Lake Okeechobee Regulation Schedule

Water levels within Lake Okeechobee are managed according to a regulation schedule developed by the SFWMD and USACE (**Figure 6**). The schedule is designed to protect the integrity of the levees by maintaining a low water level (15.6 ft NGVD) during the wet season, providing storage capacity for excessive rainfall amounts, and preventing flooding in surrounding areas. Water levels are allowed to reach peak stages of 16.5 ft NGVD at the end of the wet season, storing water within the lake for the dry season. The schedule determines the timing and quantity of water that needs to be released from the lake when lake stages exceed certain flood control zones, which vary according to the season (**Figure 6**). The USACE operates the primary structures and navigation locks around the lake and is responsible for maintaining this schedule. The SFWMD operates and maintains the secondary water control structures and pump stations.

Several schedules have been implemented over the past 50 years in response to regional water storage and flood control needs. The lake has been regulated from a minimum of 12.5 to 14.5 ft mean sea level in the late 1940s, up to 15.5 to 17.5 ft NGVD in effect from 1979 to 1990. In 1991, the District proposed a number of modifications to the schedule known as Run 25 that allows for multiple water release zones to better control downstream discharges to the St. Lucie and Caloosahatchee estuaries. Included within the schedule are a series of pulse release zones (Levels I, II, and III) where smaller releases of fresh water are made to downstream estuaries in anticipation of the lake reaching levels that would require large regulatory releases that could damage downstream estuaries. More detailed descriptions of the history and operation of Lake Okeechobee's regulation schedule may be found in Trimble and Marban (1988); the *Lake Okeechobee SWIM Plan Update* (SFWMD, 1997a); and Neidrauer et al. (1997).

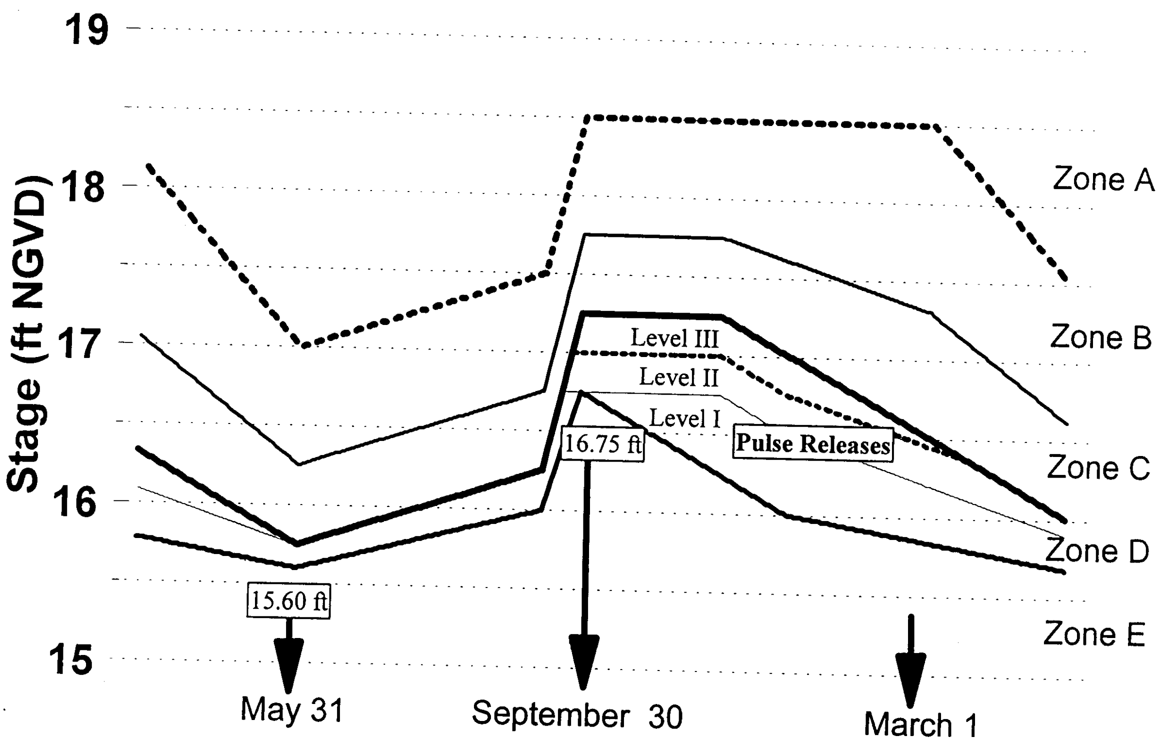


**Figure 6.** Lake Okeechobee Regulation Schedule Run 25.

In early 2000 the District and USACE expect to implement a new regulation schedule called the WSE (Water Supply and Environment) schedule. The WSE schedule uses information about tributary hydrologic conditions and climate forecasting models to guide lake operations. The goal is to minimize harmful effects of high water levels on the lake's littoral zone while not adversely impacting the regional water supply, flood protection, or downstream ecosystems. The decision features of the WSE schedule have been incorporated into the analyses of future scenarios that were conducted for the Central and Southern Florida Project Comprehensive Review Study (Restudy) and the *LEC Regional Water Supply Plan*. Although the effects of the WSE schedule were not evaluated during development of the Minimum Flows and Levels Technical Criteria, they will be incorporated the *Minimum Flows and Levels Recovery and Prevention Plan* as part of the *LEC Regional Water Supply Plan.*

## Drought Management

During years of normal rainfall, the present Lake Okeechobee regulation schedule allows for an ample supply of water to be stored during the wet season for use in the subsequent dry season. Lake Okeechobee receives on average, approximately 43 inches of rainfall each year (period of record 1965-1995). This rainfall amount however, varies widely from year-to-year and from season-to-season. This variability tends to produce erratic and unpredictable rainfall conditions which can result in drought. In addition to this climatic variation, South Florida's rapid growth continually increases demand on the region's available water supply during low rainfall periods. Historical records show that when lake levels fall below 11.0 ft NGVD, water shortage restrictions are imposed by the District along Florida's lower east coast. Once below 11.0 ft NGVD, lake levels decline rapidly affecting the District's ability to deliver water to downstream users, as well as affecting the ecology of the lake. More importantly, as water levels drop below 10.0 ft NGVD, structural limitations of the outlet structures make it increasingly difficult to withdraw water from the lake to send downstream and protect wellfields in Palm Beach, Broward, and Miami-Dade counties against saltwater intrusion.

To avoid extreme drawdowns that impact fish and wildlife communities in the lake, and South Florida's water supply, the District developed a water supply management plan for Lake Okeechobee (SFWMD, 1987; Hall, 1991). The plan was developed in 1982 and serves as the basis for making water management decisions during periods of low rainfall. The primary objective of the plan is to ensure that adequate water remains within the lake for high demand periods, while still allowing the flexibility to respond to short-term needs of users who depend on the lake as their primary water source.

The basis of the plan is an allocation strategy which parcels out lake water based on weekly estimates of water use and demand for various user groups for the remainder of the dry season. Water availability is based on three factors in relation to the amount of water in storage: anticipated rainfall, lake evaporation, and downstream water needs for the balance of the dry season. Each factor used in the computation of weekly water allocations is based on the normal range of values expected to occur over the balance of the dry season. A critical end-of-dry-season (May 31) water level target of 11.0 ft NGVD was established for the lake. This criterion was selected based on the need to provide a backup supply of water within the lake that can be used to maintain freshwater heads in coastal canals which prevent saltwater intrusion of the coastal aquifer, and maintain storage capacity to meet reasonable needs of users. Once critical water levels (within Zones C or D described below) are reached, users have historically been subject to severe water restrictions. Water allotments are computed so that water levels will not fall below the May 31 target water level. The volume of water held in the lake between elevations 11.0 and 10.0 ft NGVD is approximately 327,000 acre-feet and represents the amount of water that is stored in the lake to protect the Biscayne aquifer from saltwater intrusion. The plan is based on six critical lake water level conditions that require various actions to be taken according to the severity of conditions (see **Table 1** below and **Figure 12** in Chapter 4).

**Table 1.** Definitions of Drought Conditions and Actions to be Taken.

<table>
<tr><th>Condition</th><th>Definition</th><th>Actions</th></tr>
<tr><td>Condition 1: Watch</td><td>The lake has roughly enough water supply in the lake to meet the water demands of a 1-in-5 year drought.</td><td>Publicize conditions at Governing Board meetings and in response to press releases</td></tr>
<tr><td rowspan="3">Condition 2: Warning</td><td rowspan="3">Enough water is stored in the lake to meet water use demands of a 1-in-3 year drought.</td><td>Begin mobilization of the District’s Supply-Side Management Task Force; make personnel assignments for appropriate departments</td></tr>
<tr><td>Notify and obtain approval from the USACE to enforce Lake Okeechobee water use restrictions should conditions worsen</td></tr>
<tr><td>Contact key individual water users and organizations</td></tr>
<tr><td rowspan="4">Condition 3: Implementation</td><td rowspan="4">Water levels within this range indicate that, if normal rainfall and average water demands occur for the remainder of the dry season, the lake will fall below the critical 11.0 ft NGVD by May 31.</td><td>Implement Phases 1, 2, 3, and 4 water use restrictions for the LEC Planning Area as water levels fall within Water Supply Management Zones A, B, C, and D of the Lake Okeechobee Water Shortage Management Plan (Figure 12).</td></tr>
<tr><td>All water releases from the lake will be based on the assumptions of average climatic conditions and average water use conditions with a May 31 target lake stage of at least 11.0 ft NGVD maintained.</td></tr>
<tr><td>Mitigation actions approved by the District’s Governing Board may be permitted as outlined in Table 2.</td></tr>
<tr><td>The Executive Director of the District, if appropriate, may conduct public meetings of major Lake Okeechobee users.</td></tr>
</table>

The plan is based on a “live within our means” concept and requires water managers to prudently budget, save, and distribute water according to needs during a water shortage period. The plan provides a balanced water allocation strategy for all users that attempts to avoid severe drawdowns of the lake, and a method for holding a backup water supply in the lake for anticipated high demand periods and prevention of saltwater intrusion of Biscayne aquifer.

Operational decisions on water releases from Lake Okeechobee to downstream users are made jointly by the USACE and the District’s Governing Board after full consideration of local, regional, and environmental water resource issues. Under emergency drought conditions, the Governing Board has the operational flexibility to go below the target minimum level of 11.0 ft NGVD at the end of the dry season (April-June) to make critical water supply deliveries to the LEC Planning Area to protect the Biscayne aquifer from significant or serious harm caused by saltwater intrusion.

The plan also allows users to “borrow” water from their future water supply allocation, This borrowing provision places the risk-based decision on the water users (**Table 2**). Detailed procedures for determining the amount of water available in storage which could be allocated to users to meet dry season demands can be found in the S*upply-Side Management Plan* (Hall, 1991) that was adopted by the District’s Governing Board, has been in operation for seven years and provides an effective means to manage Lake Okeechobee when water supplies are limited.

**Table 2.** Water Supply Actions Available with Governing Board/Executive Director Approval.

| MONTH | ZONE B | ZONE C |
|---|---|---|
| October | Shift[a] 1/3 February Allotment | Shift 2/3 February Allotment |
| November | Shift 1/3 March Allotment | Shift 2/3 March Allotment |
| December | Shift 1/3 April Allotment | Shift 2/3 April Allotment |
| January | Shift 1/3 May Allotment | Shift 2/3 May Allotment |
| February | Lower Target[b] to 10.75 ft NGVD | Lower Target to 10.5 ft NGVD |
| March | Lower Target to 10.5 ft NGVD | Lower Target to 10.25 ft NGVD |
| April | Lower Target to 10.25 ft NGVD | Lower Target to 10.0 ft NGVD |
| May | Lower Target to 10.0 ft NGVD | Lower Target to 9.75 ft NGVD |

a. Shift means to add part of a future month's water allotment to the current month's amount.
b. Lowering the target increases monthly allotments but may result in very low lake levels going into the wet season.

# THE EVERGLADES

## Major Features

The Everglades is an internationally recognized ecosystem that covers approximately two million acres in South Florida and is the largest subtropical wetland in the United States. This area has been described as a vast sawgrass marsh, dotted with tree islands and interspersed with wet prairies and aquatic sloughs that historically covered most of southeastern Florida (Davis, 1943a). Today's remaining Everglades is comprised of the Water Conservation Areas (WCA-1, WCA-2A, WCA-2B, WCA-3A, and WCA-3B), the Holeyland and Rotenberger Wildlife Management Areas (WMAS) and Everglades National Park, which also includes Florida Bay (**Figure 5**). WCA-2 and WCA-3 are also designated as the Everglades (Francis S. Taylor) WMA. WCA-1 is also known as the Arthur R. Marshall Loxahatchee National Wildlife Refuge. Everglades National Park and the WCAs were designated as Outstanding Florida Waters in 1978. They are the surviving remnants of the historical Everglades that once extended over an area approximately 40 miles wide by 100 miles long, from the south shore of Lake Okeechobee to the mangrove estuaries of Florida Bay. This remaining area provides significant ecological, water storage, flood control, and recreational benefits to the region, as well as important habitat for wildlife of national significance.

## Resource Functions

The development of minimum level criteria and a definition of significant harm for the Everglades focus on protection of six key water resource functions of this wetland system (not listed in priority order):

- Provide ground water recharge to prevent saltwater intrusion of the Biscayne aquifer, South Florida's primary drinking water source
- Provide food chains, substrates, and habitats necessary to support healthy Everglades wildlife, including threatened and endangered species
- Provide natural biological filtering and nutrient cycling, to trap suspended solids and metals in sediments, detritus and living tissue, and convert dissolved nutrients derived from rainfall, decomposition, and soil oxidation into biomass
- Provide aquatic refugia for Everglades fish, amphibians, aquatic invertebrates, and other wildlife during droughts
- Provide an Everglades ecosystem that is not degraded due to invasion by terrestrial woody vegetation and introduced exotics such as melaleuca
- Provide water flows that maintain salinity regimes and ensure survival of plant and animal communities in coastal estuaries

Several combined hydrologic impacts to each water resource function were also considered in defining significant harm for the Everglades as follows:

- Relationship between regional ground water levels and Everglades soils
- Everglades water levels and soil-plant community relationships
  - Peat formation and soil loss in the Everglades
  - Marl deposition
- Effects of low water levels on plant communities and wildlife habitat
  - Reduction in primary productivity
  - Changes in distribution and abundance of wetland plant communities
  - Changes in wildlife abundance and distribution
- Effects of water levels on fires
  - Effects of fire in the Everglades
  - Fire history

## Water Resource Issues

A number of structural changes that have occurred to the regional ecosystem were considered during the development of MFL criteria for the remaining Everglades. Construction of the C&SF Project and large-scale urban and agricultural development have isolated large segments of the original Everglades from the natural system by canals and levees. More than half of the original system has been lost to drainage and development (Davis and Ogden, 1994). Today, these developed areas support a variety of land uses, ranging from intensively managed agriculture in the north (EAA) to rapidly spreading urban areas located east of the WCAs. The major water management issues that currently confront the Everglades ecosystem include the following:

### Loss of Dynamic Storage and Spatial Extent

Loss of over 50 percent of the original Everglades wetlands, as a result of land development activities, has greatly reduced the water storage capacity of the ecosystem. Loss of the ability to store large volumes of water that historically moved as sheetflow across the Everglades landscape increases the system's susceptibility to the effects of flood and drought. Reduction in size of the Everglades also limits capacity of this ecosystem to support populations of wading birds, alligators, and panthers that once used the area in much greater numbers (Davis and Ogden, 1994; Science Subgroup, 1994; USACE, 1994).

### Fragmentation of the Everglades

The historical system has been subdivided by construction of canals, levees, roads, and other facilities and has resulted in the loss of connections between the central

Everglades and adjacent transitional wetlands. Everglades wildlife communities and sustainability of the ecosystem may be impaired by this separation and isolation. Construction of canals and levees and impoundment of the WCAs have caused overdrainage of some areas and excessive flooding in other areas (USACE, 1994).

### Changes in Timing, Distribution, and Quantity of Water

Altered timing and volume of discharges into, within, and between freshwater wetlands and estuaries have led to destruction, loss or degradation of native Everglades plant communities and associated wildlife habitat (SFWMD, 1992; Davis et al., 1994; Davis and Ogden, 1994).

### Water Quality

High concentrations of phosphorus in waters that are discharged into the Everglades from the agricultural and urban areas may cause adverse changes in plant communities and wildlife habitat within the WCAs and potentially threaten the ecological integrity of Everglades National Park (SFWMD, 1992; Everglades Forever Act, Chapter 373.4592 F.S., 1994)

### Invasion of Native Plant Communities by Exotic Species

Species such as melaleuca (Bodle et al., 1994), Australian pine, and Brazilian pepper have displaced native plants and degraded or destroyed wildlife habitat within over drained areas of the Everglades.

### Impacts to Estuaries

Adequate quantity, timing, and distribution of water must be discharged from the freshwater areas of Everglades National Park and the WCAs downstream to Florida Bay and Biscayne Bay to maintain the biological integrity of these estuarine ecosystems (Boesch et al., 1993; Bancroft, 1993).

## Water Conservation Areas

The WCAs are an integral component of the Everglades ecosystem and are important sources of water supply for South Florida. The WCAs, located south of Lake Okeechobee and west of the heavily urbanized lower east coast, comprise an area of about 1,350 square miles (**Figure 5**). Although originally part of the larger Everglades ecosystem, these remaining wetlands today serve multiple purposes, and provide the following (not listed in priority order):

- Detention areas for excess water discharged from Lake Okeechobee and flood control discharges from the EAA and portions of the LEC Planning Area

- Sources of water supply for LEC Planning Area agricultural lands and urban areas
- A means to recharge the Biscayne aquifer and retard saltwater intrusion in coastal wellfields
- Sources of water supply for Everglades National Park
- Important habitats for Everglades wildlife
- Public recreational uses
- Tribal uses by Seminole and Miccosukee Indians

## Water Conservation Area 1

### Physical Characteristics

WCA-1, designated as the Arthur R. Marshal Loxahatchee National Wildlife Refuge, is managed by the U.S. Fish and Wildlife Service (USFWS). WCA-1 covers an area of 221 square miles within Palm Beach County. The West Palm Beach Canal discharges agricultural drainage water into the north end of WCA-1 via Pump Station S-5A and the Hillsboro Canal and discharges via Pump Station S-6 into the southwestern portion. The area is enclosed by 58 miles of levees and provides storage for excess rainfall and runoff from the EAA. Ground level elevations range from 16 ft NGVD at the north end to 12 ft NGVD at the south end. The current minimum water level maintained within the perimeter canal is 14 ft NGVD. Below this level, water releases are not permitted unless water is supplied from another source. WCA-1 is an important source of water supply for urban areas in Palm Beach and Broward counties.

### Management Issues

Historical data suggests that WCA-1 was originally a much wetter area and was part of the Hillsboro Lakes region of the Everglades (Davis, 1943a; Parker et al., 1955) Canal construction and drainage activities have eliminated overflow that once sustained prolonged hydroperiods within this region. Soils data (Gleason and Spackman, 1974), long-term vegetation studies (Alexander and Crook, 1984), and hydrologic models developed for the Everglades (Fenemma et al., 1994) also suggest that WCA-1 was generally much wetter prior to the construction of drainage canals. Based on this information, the USFWS proposed a change in the WCA-1 regulation schedule to provide deeper water, with longer hydroperiods, in an effort to restore the natural ecosystem functions of the original Hillsboro Lakes marsh system. The new schedule calls for maintaining a minimum water level of 14 ft NGVD and allows a maximum stage of 17.5 ft NGVD. This higher schedule will provide for the following:

- Allow higher water levels during wet years in the northern portion of the refuge
- Increase hydroperiod within the interior marsh to reduce the frequency of annual drying of the marsh

- Improve the timing of the dry season drawdown to benefit nesting wading birds
- Restore snail kite habitat
- Allow for more storage of water within the system during wet and normal rainfall years

## Water Conservation Areas 2A and 2B

WCA-2A is an extensive sawgrass wetland that encompasses 210 square mile area (**Figure 5**) located within southern Palm Beach and northern Broward counties. It is the smallest of the three WCAs. Water levels in WCA-2A are controlled by a system of levees and water control structures which encircle the marsh. WCA-2A provides a variety of functions including the following:

- Aquifer recharge for protection against saltwater intrusion for east coast wellfields
- Flood protection for agricultural and east coast urban areas
- Preservation of Everglades wildlife, including threatened or endangered species
- Recreational opportunities (i.e. hunting, fishing, boating, and wildlife observation) for South Florida residents and visitors.

Management of water levels is the responsibility of the District in accordance with regulation schedules set by the USACE while the FFWCC is responsible for wildlife management. The water regulation schedule ranges from 13 ft NGVD at the end of the wet season (September 15) to 11 ft NGVD from February 1 through June 15 (dry season). The current minimum water level maintained within the L-35B and L-38 borrow canals is 10.5 ft NGVD, below which water releases are not permitted unless water is supplied from another source.

More than half of the surface water entering WCA-2A originates from the EAA (SFWMD, 1992). Canal inflow waters are highly mineralized and contain high concentrations of nitrogen and phosphorus resulting from the oxidation of organic peat soils within the EAA (SFWMD, 1992). The canals also convey water from Lake Okeechobee, which has been enriched by agricultural activities north of the lake. In 1961 the L-35B Levee was constructed across the southern portion of WCA-2 dividing the area into two smaller units, WCA-2A (173 square miles) and WCA-2B (37 square miles), in an effort to reduce water seepage losses to the south and to improve the water storage capabilities of WCA-2A.

This area has been severely affected by stabilized hydroperiods and high regulation schedules that were maintained during the late 1960s and 1970s. Wetlands in the central and southern portions of WCA-2A were flooded for extended periods, resulting in loss of tree islands and conversion of wet prairies to aquatic sloughs (Dineen, 1972; Worth, 1988). Changes have been made to the WCA-2A regulation schedule to mitigate adverse impacts of prior regulation schedules. Many of the ecological losses that occurred in the 1960s and 1970s, however, may take many decades to repair under the improved management of water levels. In the northeastern portion of WCA-2A, long-term discharges of waters with elevated nutrient concentrations through the S-10 structures, in combination with altered hydroperiod and fire, have caused significant changes in existing vegetation communities (Swift and Nicholas, 1987; Davis et al., 1994; Rutchey and Vilchek, 1994; Jensen et al., 1995). This area is currently a major focus of Everglades restoration efforts.

## Water Conservation Areas 3A and 3B

### Physical Characteristics

The largest of the WCAs, WCA-3, covers an area of 915 square miles, and is located in western Broward and Miami0Dade counties (**Figure 5**). The area is predominately a vast sawgrass marsh dotted with tree islands, wet prairies, and aquatic sloughs. A cypress forest fringes its western border along the L-28 Gap and extends south to Tamiami Trail.

In 1962, WCA-3 was divided into WCA-3A and WCA-3B (786 and 128 square miles, respectively) by construction of two interior levees (L-67A and L-67C). The levees were constructed to reduce water losses caused by levee seepage. WCA-3A is the only water conservation area that is not entirely enclosed by levees. The L-28 Gap allows overland flow to enter WCA-3A from the Big Cypress National Preserve and other western basins. WCA-3A is bisected by several major canals including the Miami Canal, which drains the EAA. Water also enters the area via the S-9 Pump Station, which drains urban areas located within western Broward County, and a combination of agricultural and WCA-2A sheetflow from the S-11 structures. Management of water levels within WCA-3A and WCA-3B is the responsibility of the District in accordance with regulation schedules set by the USACE. Wildlife management is delegated to the FFWCC under lease from the SFWMD.

Water levels in WCA-3A are regulated from 9.5 to 10.5 ft NGVD. Water levels in WCA-3A are estimated by averaging data from three gauges: 3A-3, 3A-4 and 3A-28. During droughts, a minimum elevation in the borrow canal of 7.5 ft NGVD is observed. Below this elevation, no further releases are permitted from WCA-3A unless a supply of water from another storage area is transferred to WCA-3A (USACE, 1992).

### Management Issues.

WCA-3A serves a variety of functions including the following (not listed in priority order):

- Aquifer recharge and protection against saltwater intrusion for east coast urban areas
- Flood protection for agriculture and east coast urban areas

- Habitat for the preservation of Everglades wildlife, including threatened or endangered species
- Recreational opportunities (i.e. hunting, fishing, boating, and wildlife observation) for South Florida residents and visitors
- A source of high quality inflow water for Everglades National Park

The initial WCA-3A operating schedule and configuration of water management structures has caused the overdrainage of northern WCA-3A, resulting in loss of organic soils, tree islands, and wet prairies due to soil subsidence and peat fires (Zaffke, 1983; Schortemeyer, 1980). Satellite map imagery shows that much of northern WCA-3A is in transition from wetlands to brush vegetation (primarily wax myrtle and willow) and large areas of eastern WCA-3A are being invaded by cattails.

Construction of Alligator Alley, and the associated borrow canal, have restricted sheetflow to the south. The location and design of the Miami Canal have contributed to the overdrainage of the northern end of WCA-3A. Water discharged through the S-8 Pump Station moves south in the canal at a greater rate than historic sheetflow. Additional environmental enhancement structures have been added in the Miami Canal, such as S-339 and S-340 in the Miami Canal, to induce more sheetflow through the marsh, but the addition of these structures has not solved the problem. Sheetflow within WCA-3A must be restored, especially in critically impacted northern areas, to protect the natural resources. Water levels in the northern portion should be raised during dry periods to reduce the incidence of severe muck fires. In contrast, construction of the L-29 Levee across the southern end of WCA-3 in 1962 interrupted the southerly flow of water to Everglades National Park causing water ponding and extended hydroperiods at the south end of WCA-3A. Both of these conditions are considered harmful to Everglades plant communities and wildlife habitat (Zaffke, 1983).

## Holey Land and Rotenberger Wildlife Management Areas

### Physical Characteristics

Together, the Holey Land and Rotenberger WMAs comprise approximately 59,000 acres consisting of sawgrass, sawgrass/brush, and tree islands (**Figure 5**). These areas are state owned and are managed by the Florida Fish and Wildlife Conservation Commission (FFWCC) for deer, hog, and waterfowl hunting. Wading birds and a host of other nongame species of Everglades wildlife also utilize the area.

### Major Issues

The Holey Land and Rotenberger WMAs have been identified as areas in need of hydrologic restoration. Similar to northern WCA-3A, the Holey Land and Rotenberger WMAs have experienced excessive drying, repeated muck fires, soil subsidence, and severe damage to tree islands resulting from lower water levels, soil oxidation, and wildfires. Drier conditions have allowed Everglades wetland communities to be replaced by woody terrestrial species such as salt bush and wax myrtle. Diversion of nutrient-enriched canal water has also allowed cattails to replace native vegetation. In 1983, a Memorandum of Understanding was entered into by the FDEP, the Board of Trustees of the Internal Improvement Trust Fund, the FFWCC, and the SFWMD to establish a process for the implementation of a plan to restore Everglades values associated with the Holey Land and Rotenberger WMAs and provide for the establishment of water regulation schedules that will simulate more natural hydroperiods. In June 1990, the District and the FFWCC entered into an agreement detailing the initial operational schedule for the Holey Land WMA that will improve hydroperiods for both the Holey Land WMA and WCA-3A (SFWMD, 1992).

## Everglades National Park

### Physical Characteristics

Everglades National Park encompasses 2,150 square miles of freshwater sloughs, sawgrass prairies, marl-forming wet prairies, mangrove forests, and saline tidal areas located at the southern end of the Florida peninsula (**Figure 5**). The topography is extremely low and flat, with most of the area below 4 ft NGVD, while highest elevations (6 to 7 ft NGVD) occur in the northeastern portion of the park. Schomer and Drew (1982) recognized five hydrologic/physiographic subzones located within Everglades National Park (**Figure 7**). These include the following areas:

- Shark River Slough
- Rocky Glades
- Broad River/Lostman's River
- Coastal mangrove swamps and lagoons
- Cape Sable area

Everglades National Park was formally established by Congress in 1934 to preserve the unique ecology of the Everglades. It was designated by the United Nations as a World Heritage Site in 1979. It has also been named as a Federal Wilderness Area, an International Biosphere Reserve, and a Wetland of International Significance. Today Everglades National Park represents the second largest national park in the United States and is also considered one of the nation's ten most endangered parks.

### Major Issues

The quantity, quality, distribution, and timing of water flows into the Everglades National Park must be sufficient to maintain and restore the full abundance and diversity of the native floral and faunal communities throughout the Everglades National Park. Water supply is critical to the continued survival and function of Everglades National Park and Florida Bay. Changes in the distribution, timing, and volume of water inflows to Everglades National Park and subsequent changes in hydroperiod have been linked to the decline of the Everglades National Park’s biological resources.

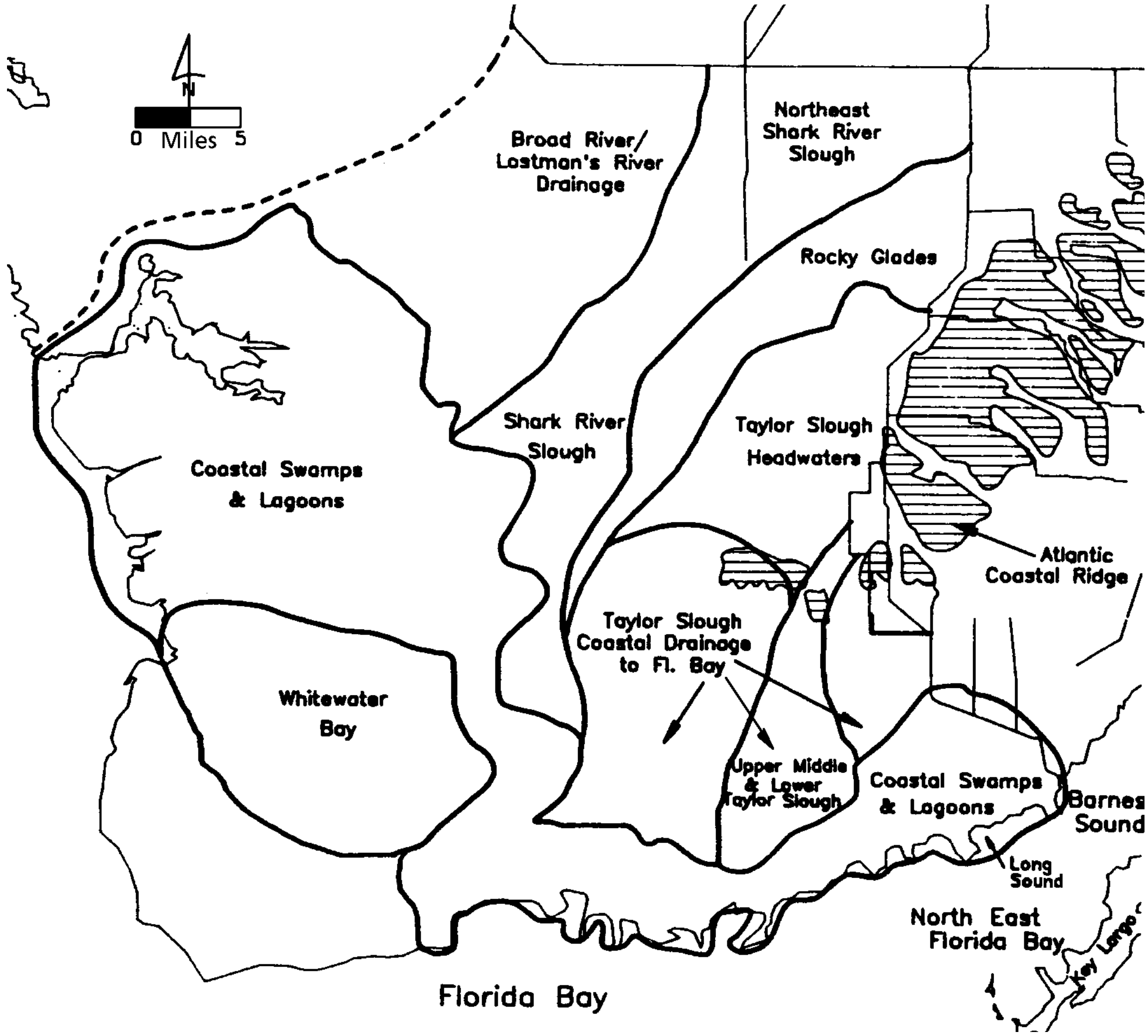


**Figure 7.** Hydrologic and Physiographic Provinces of the Everglades National Park Study Area. (Modified from Schomer and Drew, 1982; Davis, 1943a; White, 1970; Puri and Vernon, 1964.)

## Shark River Slough

### Physical Characteristics

This area of Everglades National Park consists of a broad southwesterly arc of continuous wetlands, interspersed with sawgrass strands, open water sloughs, wet prairies, and tree islands extending from Tamiami Trial to the mangrove estuaries of Florida Bay (**Figure 7**). Underlying soils are moderate to shallow depth Loxahatchee peat. Shark River Slough occupies the center of the Everglades trough and has been described as a wide, slightly concave depression in the underlying limestone (White, 1970). The slough represents the principle watershed for Everglades National Park and provides the primary source of freshwater inflow for downstream Florida Bay estuaries.

### Management Issues

Uncontrolled flow to Shark River Slough was impeded by construction of the first east-west road (Tamiami Trial) and the borrow canal built across the Everglades in 1928. Construction of the eastern perimeter levee and impoundment of the upstream WCAs as part of the C&SF Project essentially eliminated natural sheetflow to Shark River Slough by the mid 1950s.

Current flow patterns to Everglades National Park are highly influenced by upstream management of the WCAs and pumping of agricultural and urban drainage canals to the north and east. Water level declines have occurred throughout the park, with major declines occurring along the eastern boundary of the park in northeast Shark River Slough, the Rocky Glades, and northern Taylor Slough. During wet years, western Shark River Slough receives large regulatory releases from the upstream WCAs. These high flows substantially alter natural water patterns and transform the area from a transitional marl-forming wetland to the main flowway. A rainfall-based plan for water deliveries to Everglades National Park will allow reintroduction of sheetflow and restoration of more natural water depths and hydroperiods within eastern and western Shark River Slough.

## Southern Marl-Forming Marshes

### Physical Characteristics

These wetlands are characterized by the formation of marl soils (also known as calcitic mud). Marl is formed by the precipitation of calcite by blue-green algae in submerged algal mats (periphyton) under shallow water/short hydroperiod conditions. Marl-forming marshes occur on the eastern and western margins of Shark River Slough, as well as in Taylor Slough and the Rocky Glades (**Figure 7**). These wetlands occur at a slightly higher elevation than Shark River Slough and exhibit corresponding shallow water depths and shorter hydroperiods. These communities have also been called the southern coastal marsh prairies (Davis, 1943a), southeast saline Everglades (Egler, 1952), marl Everglades, marl prairies (Harper, 1927; Werner, 1976; Olmsted and Loope, 1984), *Muhlenbergia* prairies (Olmsted et al., 1980), and southern marl marshes (Davis et al., 1994). The dominant vegetation is muhly grass and sawgrass.

### Management Issues

Agricultural and urban development in the east Everglades has resulted in a direct loss of marl-forming wet prairies through conversion of marshes to farmland and housing projects. Construction of the C&SF Project and the South Dade Conveyance System has resulted in compartmentalization of the remaining marl prairie/Rocky Glades wetland system through a network of levees and canals designed to drain the area during wet periods. This water management system has altered hydropatterns and lowered water tables throughout the eastern portion of Everglades National Park and reduced flows to Florida Bay.

Presently, large areas of the Rocky Glades and adjacent marl prairies remain dry under average rainfall conditions, as compared to 7 to 10 months inundation under natural conditions. Shortened hydroperiods reduce wetland aquatic productivity. They reduce fish and invertebrate populations, which in turn limit foraging opportunities for wading birds and other Everglades wildlife. Lowered water levels and shortened hydroperiods also alter Everglades fire regimes and allow invasion by woody plants, exotics, and other terrestrial species.

# COASTAL BISCAYNE AQUIFER

## Major Features

The principal ground water resources for the LEC Planning Area are the surficial aquifer and the Biscayne aquifer. These two ground water systems provide most of the fresh water for public water supply and agriculture within the study area. The Biscayne aquifer is an unconfined aquifer and a component of the Surficial Aquifer System underlying most of southeast Florida as shown in **Figure 8**. These ground water systems provide the following:

- A major source of drinking water for more than 6.5 million people living in urban areas along Florida's east coast
- A source of water for local wells, canals, and lakes
- A major source of irrigation water for agriculture
- A source of water to replenish regional wetlands and provide base flow to estuaries such as Biscayne Bay and Florida Bay

The Biscayne aquifer is composed of units and formations principally deposited during the Pleistocene epoch, or Great Ice Age. This interval of geologic time was a period of climatic instability where great glaciers advanced and retreated across the continents. As the glaciers advanced, sea level declined and large areas of South Florida became exposed as dry land. Deposition during this time occurred due to dune building and formation of freshwater limestones. As the glaciers melted, sea levels increased and eventually submerged the southern peninsula, creating a highly productive, shallow marine environment. During this time period, marine deposits dominated the composition of the Biscayne aquifer. Typical marine deposits from these high sea level stands occur throughout South Florida and include the coral limestones on Key Largo and the oolitic ridge along the coast (Hoffmeister, 1974).

The major geologic deposits that comprise the Biscayne aquifer include: the Miami Limestone, the Fort Thompson Formation, the Anastasia Formation, and the Key Largo Formation. The base of the Biscayne aquifer is generally the contact between the Fort Thompson Formation and the underlying Tamiami Formation of Plio-Miocene age. However, in places where the upper unit of the Tamiami Formation contains highly permeable limestones and sandstones, these zones would also be considered part of the Biscayne aquifer if the thickness exceeds 10 feet (Fish and Stewart, 1991).

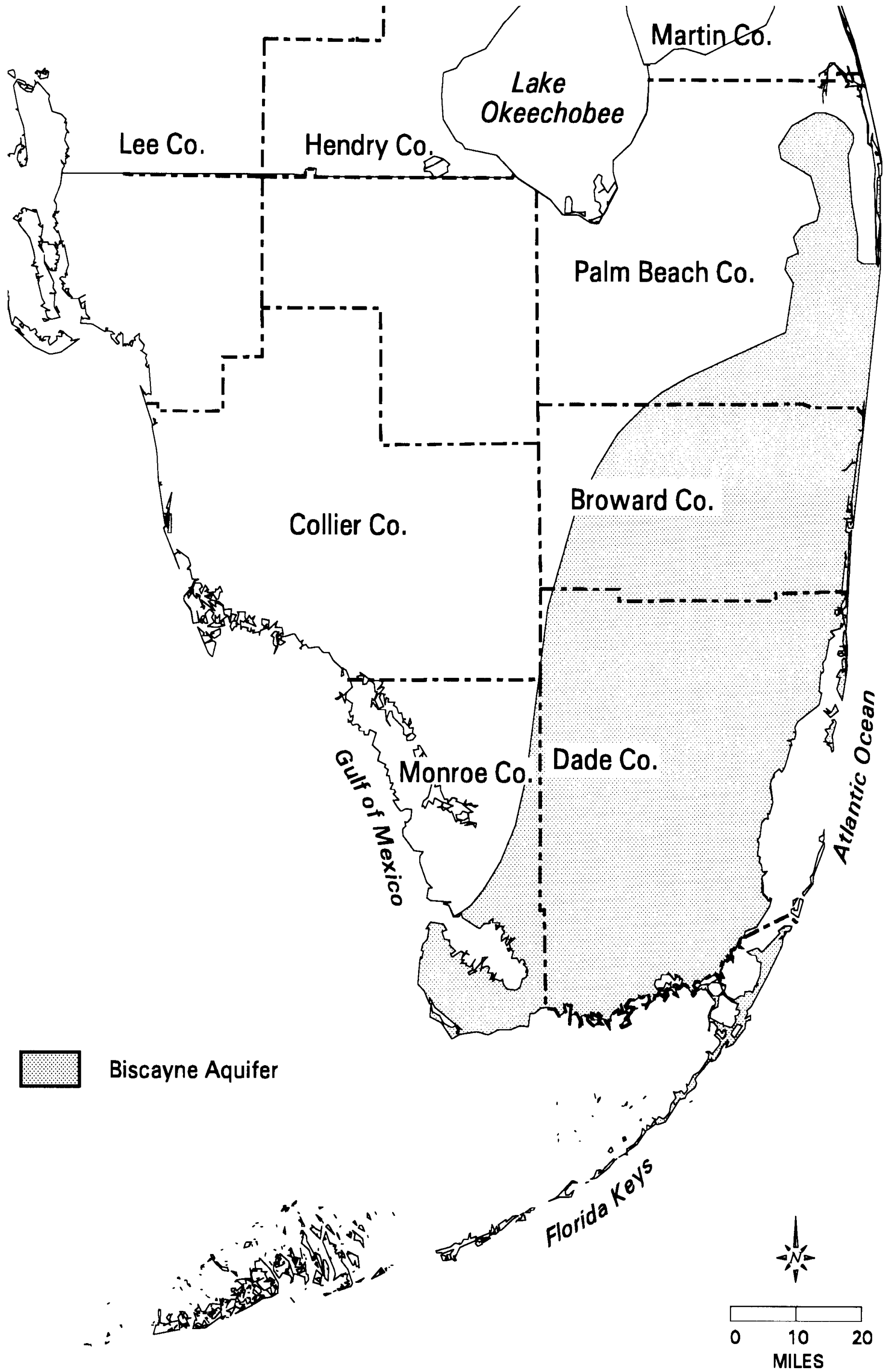


**Figure 8.** Location of the Biscayne Aquifer System in South Florida.

The Biscayne aquifer is composed of interbedded, unconsolidated sands and shell units with varying thicknesses of consolidated, highly solutioned limestones and sandstones (Shine et al., 1989). In general, the Biscayne aquifer contains less amounts of sand and a greater percentage of solution cavities in the limestone than the Surficial Aquifer System. The Biscayne aquifer is one of the most permeable aquifers in the world and has transmissivities in excess of 7 million gallons per day, per foot of drawdown (Parker et al,. 1955). Due to its regional importance, it has been designated as a sole source aquifer by the U.S. Environmental Protection Agency (USEPA) under the Safe Drinking Water Act and is, therefore, afforded stringent protection.

## Resource Functions

The following water resource functions were considered in the development of minimum water level criteria for the Biscayne aquifer:

- It represents the primary source of water supply for urban and agricultural users within the LEC Planning Area.
- It provides base flow to important estuaries such as Biscayne Bay and Florida Bay during low rainfall years.
- Maintenance of appropriate ground water levels within the Biscayne aquifer prevents saltwater intrusion.

The hydrological impacts to these water resource functions that were considered in defining significant harm for the Biscayne aquifer were as follows:

- When ground water levels decline, saltwater intrusion begins to occur within the aquifer.
- The head of ground water that is needed to halt the further advance of saltwater intrusion can be determined using a number of different approaches based on theoretical analyses, and results of field investigations and modeling studies.
- Ground water levels in the Biscayne aquifer can be regulated by controlling water levels in coastal canals.

The definition of significant harm for the Biscayne Aquifer system could be based on consideration of many possible sources of damage. In developing MFLs criteria for the Biscayne aquifer, emphasis was placed on factors that are within the jurisdictional authority of the District, can be controlled and monitored on a regional scale, and can be controlled and tracked using existing District permitting capabilities, structural features, and extensive monitoring network.

Saltwater intrusion was chosen as the primary criterion of interest for defining significant harm to the Biscayne aquifer for the following reasons:

- Saltwater intrusion represents a major threat to South Florida's regional water supply system.

- The District has the responsibility to protect the resource from saltwater intrusion through operation and maintenance of the structures, pump stations, and canals that comprise the C&SF Project.
- Saltwater intrusion is most likely to be directly influenced by changes in aquifer levels.

On a regional scale, it is the responsibility of the District to regulate canal levels and salinity structures along the lower east coast to prevent saltwater intrusion. Saltwater intrusion is often a regional phenomenon that can occur over many miles of coastline and impact numerous users across multiple political boundaries. On a local scale, consumptive uses and drainage systems are regulated by the District in a manner that restricts the net annual inland movement of the saltwater–freshwater interface. This movement is influenced by a number of factors including individual or cumulative impacts of drainage projects and/or withdrawals from wellfields. Surface water management systems are issued permits to ensure that postdevelopment peak runoff rates do not exceed predevelopment rates.

## Major Issues

The principal issue regarding development of minimum level criteria for the Biscayne aquifer is saltwater intrusion, which is the contamination of the aquifer by a westward-moving front of salt water. Along the eastern edge of the Biscayne aquifer, both fresh water and salt water are in contact as shown in **Figure 9**. When ground water levels are lowered inland adjacent to this saltwater–freshwater interface, salt water potentially

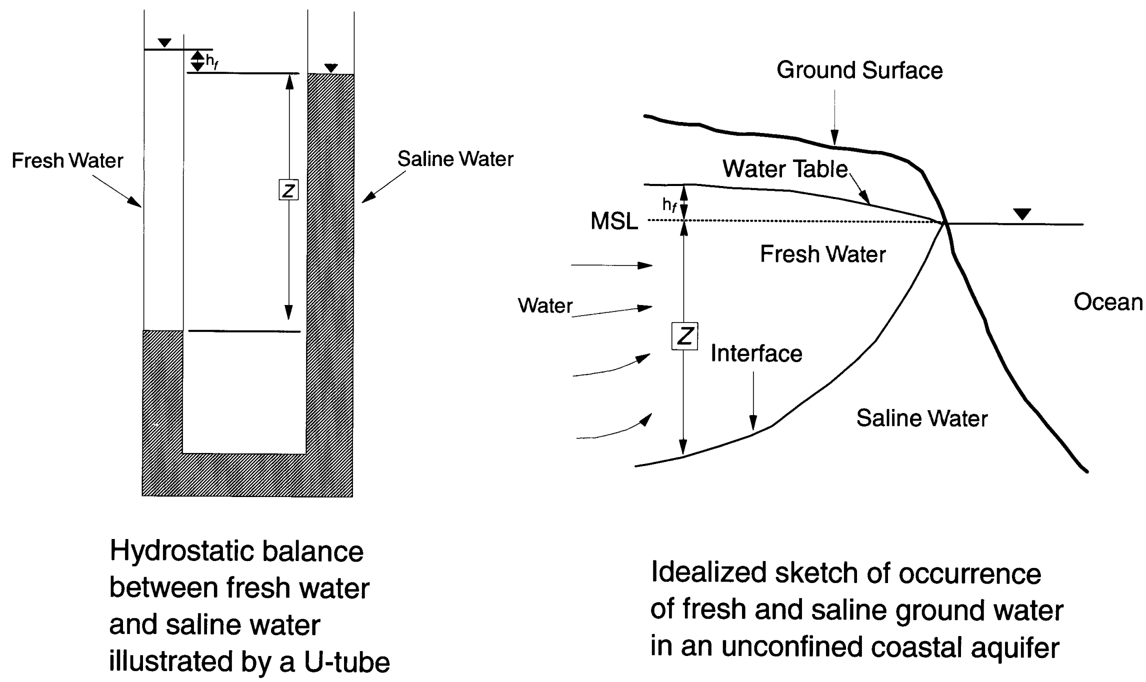


**Figure 9.** Gyphen-Hertzberg Relationship Showing Freshwater/Saltwater Interface Along the Lower East Coast of Florida.

can move inland, replacing fresh water with saline water. Once the higher density saline water has migrated inland, it remains there for long periods of time and may cause a long-term, or perhaps permanent loss, of that portion of the aquifer as a source of fresh water. Along the lower east coast, lowering of the ground water table due to overdrainage and increased wellfield withdrawals has allowed salt water to invade and contaminate the Biscayne aquifer during periods of drought (Parker et al., 1955). Saltwater intrusion of the Biscayne aquifer is considered as one of the most serious threats to South Florida's coastal water supply.

In conjunction with the District’s Consumptive Use Permitting program, saltwater intrusion is monitored along the lower east coast by collecting samples from a series of monitoring wells located along the saltwater–freshwater boundary near the coast. When analysis of samples from one or more of these wells indicates that chloride levels have increased beyond an established threshold, appropriate management actions are taken, based on the District’s *Water Shortage Policy*, to reduce withdrawals or increase the amount of water delivered from the regional system in the vicinity of those wells. Water levels in coastal canals are a direct indicator of water levels in the adjacent aquifer and the potential that saltwater intrusion may occur. Although there is not an exact relationship between water levels in the canals and chloride levels in the monitoring wells, low water levels in canals are an indicator of future problems. Historical data indicate that some areas that have had low water levels in the adjacent canals for extended periods (more than six months) have later experienced significant saltwater intrusion.

# IDENTIFICATION OF BASELINE CONDITIONS FOR WATER RESOURCE FUNCTIONS

## Definitions

Once the water resource functions to be protected by a specific minimum flow or level have been identified, these functions are then evaluated to determine their applicable baseline or desired condition. These considerations are set forth in Section 373.0421(1)(a), F.S. They allow water management districts, when setting MFLs, to consider changes and structural alterations that have occurred to a water resource. Likewise, Section 373.0421(1)(b), F.S., recognizes that certain water bodies no longer serve their historical function and that recovery of these water bodies to historical conditions may not be feasible. Allowances are provided to account for loss of historical functions. These provisions are discussed below to determine if they apply to minimum levels that are proposed for the Everglades, Biscayne aquifer, and Lake Okeechobee.

### Considerations

Section 373.0421(1)(a), F.S. requires the consideration of changes and structural alterations to watersheds, surface waters, and aquifers and the effect such constraints or alterations have had on the hydrology of the area. The important qualifier to this consideration is it *cannot* be used to allow significant harm to be caused by withdrawals.

This consideration, which relates to the level of protection that is provided by the minimum flow or level, requires the Governing Board to consider that, due to human activities, some water resources are not performing their historic or natural functions.

In establishing a minimum flow or level for an affected area under this consideration, the Governing Board may therefore decide not to protect the resource for a purpose it served in the past or to the extent it once functioned. The statute limits, however, the consideration of changes in functions caused by withdrawals. Likewise, the Governing Board may choose to define significant harm based on reference to unimpacted systems.

### Exclusions

Section 373.0421(1)(b) also provides exclusions for setting MFLs. These statutory exclusions explicitly do not apply to the Everglades Protection Area. The Everglades Protection Area is defined in Section 373.4592(2)(h) F.S., as “Water Conservation Areas 1, 2A, 2B, 3A and 3B, the Arthur R. Marshall Loxahatchee National Wildlife Refuge, and Everglades National Park.” As a result of this prohibition, District staff only utilized the considerations in Section 373.0421(1)(a) F.S., in developing minimum levels for these areas. The first exclusion in subsection 373.0421(1)(b)1 F.S. recognizes that certain water bodies no longer serve their historic hydrologic functions, and that recovery of these areas may not be economically or technically feasible and could cause adverse environmental or hydrologic impacts. In conclusion, the exclusion provides that water management districts may determine that setting a minimum flow or level for such a water body based on its historical conditions is not appropriate.

District staff recognizes that the exclusion in 373.0421(1)(b)1, regarding historic functions, could be considered in establishment of minimum levels for Lake Okeechobee, the Holey Land and Rotenberger WMAs, and the coastal Biscayne aquifer. All of these areas have been greatly altered by development and require flood protection. Recovery of levels in Lake Okeechobee and the coastal Biscayne aquifer to historic levels, on a regional scale, would be technically and economically infeasible, due to the current level of flood protection and development which exist in these two areas. In addition, adverse hydrologic impacts to urban areas in Miami-Dade, Broward, and Palm Beach counties and agricultural areas surrounding Lake Okeechobee may also prohibit the recovery of these areas to historic conditions.

Although it appears that the exclusion may be applicable, District staff have determined that the considerations in Section 373.0421(1)(a) F.S. adequately address the changes and alterations in water resource functions applicable to these areas. As a result, there appears to be no basis to invoke the exclusion in subsection (1)(b)1 or to document the economic and technical feasibility of recovery.

The remaining exclusions in subsections 373.0421(1)(b)2 through 3, F.S., are not applicable to Lake Okeechobee, the Holey Land and Rotenberger WMAs, and the Biscayne aquifer, since these exclusions only pertain to water bodies less than 25 acres in size or constructed water bodies. As stated above, these exclusions cannot statutorily be applied to the Everglades Protection Area.

## Water Resource Considerations

During the development of MFLs criteria for Lake Okeechobee, the Everglades, and the Biscayne aquifer, District staff considered a number of structural changes or alterations that have occurred within these priority water bodies, as well as the constraints such changes have placed on the hydrology of the region. Since the considerations in Section 373.0421(1)(a), F.S., adequately address baseline conditions of the Biscayne aquifer and Lake Okeechobee, District staff do not recommend that the exclusions established in subsection (1)(b) of Section 373.0421, F.S. be applied. Changes, alterations, and constraints on these resources, as covered by statute, are listed below by area.

### Lake Okeechobee

- Historic water levels for the lake were estimated to range between 16 and 21 ft NGVD. Early drainage efforts lowered the lake connecting it to the Caloosahatchee River. Catastrophic hurricanes of the 1920s and 1940s prompted the federal government to improve flood protection for the region. In 1948, Congress authorized construction of the C&SF Project which included impoundment of the lake with the 38 ft NGVD Herbert Hoover Dike. This structure was completed in the 1960s, resulting in the regulation of all lake inflows and outflows with the exception of Fisheating Creek.
- The C&SF Project recognizes that the lake is a multipurpose, regional resource. Authorized project purposes included flood control, irrigation, municipal and industrial water supply, enhancement of fish and wildlife, navigation, and recreation.
- To maintain an acceptable level of flood protection for communities that surround the lake, water levels during the hurricane season must be maintained at safe levels (less than 16.5 ft NGVD) that will not threaten the structural integrity of the levee system, as determined by USACE regulations.
- Another constraint placed on the lake is the amount of water that can be stored for water supply. When lake levels fall below 10.5 ft NGVD, structural limits of the outlet structures make it increasingly difficult to withdraw water to send to downstream users and protect the coastal aquifer from the threat of saltwater intrusion. Theoretically, 9.5 ft NGVD represents the level below which water can no longer be withdrawn from the lake to send to the LEC Planning Area.
- In its original condition, the lake was considerably larger than it is today and consisted of an extensive littoral marsh system extending to the north, west, and south of the lake. Construction of the Herbert Hoover Dike and the lowering of lake levels from a maximum of 20 to

17 ft NGVD effectively isolated thousands of acres of marsh, creating a new littoral zone/marsh community in areas where it had not previously existed.

- A variety of regulation schedules have been implemented on the lake to meet management objectives. In 1978, the maximum regulation stage was raised from 15.5 to 17.5 ft NGVD to obtain increased water storage capacity. In 1991, an interim regulation schedule (Run 25) was developed to better protect downstream estuaries from harmful lake regulation schedule discharges. Future changes are anticipated to address water supply and environmental issues.

## Water Conservation Areas

- Construction of the C&SF Project coupled with large-scale urban and agricultural development of the LEC Planning Area have isolated large segments of original Everglades from the natural system by canals and levees. More than half of the original system has been lost to drainage and development (Davis and Ogden, 1994). Today, these developed areas support a variety of land uses, ranging from intensively managed agriculture in the north (EAA) to rapidly spreading urban areas located east of the WCAs.
- Loss of more than half of the original Everglades system to drainage and development has placed a fundamental limitation on the system's capacity to support populations of Everglades wildlife (i.e. wading birds, alligators, panthers) that once inhabited the area in much larger numbers.
- The three WCAs are now managed as surface water impoundments. As part of the C&SF Project, these areas serve multipurpose functions as follows:
    - Flood control for excess water discharged from Lake Okeechobee, the EAA, and coastal urban areas
    - Recharge for coastal ground water levels to prevent saltwater intrusion
    - Supplemental water supply for agriculture, municipal, and industrial use
    - Water supply for Everglades National Park
    - Fish and wildlife habitat
    - Public recreational use
- The WCAs no longer receive overland flow derived from upstream rainfall or overflow from Lake Okeechobee. These areas now depend primarily on direct rainfall, EAA runoff, and flood releases from Lake Okeechobee. These discharges have significantly altered the volume, timing, distribution, and quality of water in the WCAs. Altered flow

regimes and degraded water quality have also resulted in loss or degradation of native plant communities and associated wildlife habitat.

- Construction of levees and canals have impounded large areas of the WCA marshes resulting in the loss of natural overland flow, overdrainage of some areas and excessive flooding in other areas (USACE, 1994). Overdrainage has allowed terrestrial woody vegetation and introduced exotics such as melaleuca, Australian pine, and Brazilian pepper to replace native plant communities.
- Construction of the four major canals (North New River, Miami, Hillsboro, and West Palm Beach canals) through the central portion of the Everglades has resulted in over drainage of large areas (e.g., northern WCA-3A). These canals have reduced water depths and altered hydroperiods, reduced soil elevations, and formed subsidence valleys along the axis of the major canals. Construction of major roads such as Tamiami Trail (U.S. 41) and Alligator Alley (I-75) has impeded water flow south to the southern WCA-3A and Everglades National Park.
- WCA-2 and WCA-3 were originally constructed over portions of the Biscayne aquifer. Hydrologic studies indicate that these areas were too porous to hold water. Partitions WCA-2B and WCA-3B were created to reduce seepage losses.
- Water levels in the WCAs are now operated by regulation schedules which dictate when water management structures open and close. These schedules are driven primarily by two objectives: minimize flood risks during the hurricane season and maximize water storage during the dry season. As such, the WCAs function as surge tanks, which attempt to modulate the wide swings in flood and drought that are common to the region and attempt to maintain water levels and hydroperiods that will support sawgrass marshes, sloughs, and tree island communities that are indigenous to the region (Light and Dineen, 1994).

### Holey Land and Rotenberger Wildlife Management Areas

- Construction of the Miami Canal and impoundment of the Holey Land and Rotenberger WMAs by a levee system has cut off historical sheetflow and altered the hydrology of both WMAs (much drier than historical conditions).
- By the late 1960s these hydrological changes in combination with conversion of some portions of the marsh to farmland has significantly lowered water levels and altered hydroperiod. These hydrologic changes have resulted in severe muck fires, loss of tree islands, loss of peat soils, and conversion of native sawgrass communities to terrestrial brush vegetation.

- Numerous artificial muck islands were constructed by the FFWCC in the 1970s in an attempt to help mitigate the loss of tree islands and wildlife impacted by muck fires (Schortemeyer, 1980).

### Everglades National Park

- In Everglades National Park, uncontrolled flows to Shark River Slough have been impeded by construction of Tamiami Trial (U.S. 41) across the Everglades in 1928. Construction of the eastern perimeter levee and impoundment of the upstream WCAs, as part of the C&SF Project, essentially eliminated natural sheetflow to Shark River Slough by the mid 1950s. Current flow patterns to Everglades National Park are highly influenced by upstream management of the WCAs and pumping of agricultural and urban drainage canals to the north and east.
- Construction of the L-67A Canal now diverts much more water into western Shark River Slough as compared to historical conditions. East of L-67A, historical flows into Everglades National Park via northeast Shark River Slough have been significantly altered as a result of construction of L-29, WCA-3B, and the eastern perimeter levee. This area now has significantly less flow as compared to predrainage conditions and exhibits shorter hydroperiods, shallower water depths, and more frequent drawdowns as compared to predrainage conditions.
- Agricultural and urban development in the east Everglades has resulted in the loss of marl-forming wet prairies through conversion of marshes to farmland and housing projects. Construction of the South Dade Conveyance System (L-31N and L-31W) caused compartmentalization and overdrainage of remaining marl prairies in the Rocky Glades and northern Taylor Slough headwaters. This water management system has altered hydropatterns and lowered water tables throughout eastern Everglades National Park and has reduced flows to Florida Bay.

### Biscayne Aquifer

- The Biscayne aquifer provides most of the fresh water for public water supply and agriculture within the LEC Planning Area.
- Construction of the north-south perimeter levee and subsequent lowering of water levels in coastal canals east of the Everglades to provide flood protection for development, have resulted in an overall lowering of the ground water table four to five feet below historical levels.
- The Biscayne aquifer is one of the most permeable aquifers in the world and is highly susceptible to saltwater intrusion.
- Lowering of the ground water table to provide drainage, increased water withdrawals from wellfields, and construction of the major coastal canals has allowed salt water to invade and contaminate large areas of the Biscayne aquifer during periods of drought.

- Water levels in coastal canals provide a direct indication of water levels in the adjacent aquifer and are indirectly related to chloride concentrations in monitoring wells. Historical data indicate that when water levels in the canals and aquifer remain low for more than six months, significant inland migration of the freshwater/saltwater interface may occur.

# Chapter 3
# METHODS

## LAKE OKEECHOBEE

Minimum water level criteria for Lake Okeechobee were based on three sources of information: review of the District's current drought management and water supply plans for Lake Okeechobee, results from recent ecological research on Lake Okeechobee, and the relationship between lake stage and navigation and recreational use of the lake.

### Review of Drought Management Plans

The amount of rainfall that falls in South Florida from year-to-year is highly variable and, in some years, can result in drought conditions. Historical records show that when lake levels fall below 11 ft NGVD, severe water shortage restrictions occur along Florida's lower east coast. Once below 11 ft NGVD, these levels decline rapidly, affecting the District's ability to deliver water to downstream users, as well as affecting the ecology of the lake. As water levels drop below 10.5 ft NGVD, structural limitations of the lake's outlet structures makes it increasingly difficult to withdraw water from the lake to send downstream to protect lower east coast wellfields against saltwater intrusion. In 1982, the District adopted a water management strategy designed to avoid extreme drawdowns of the lake that impact South Florida's backup water supply. This plan provides a balanced water allocation strategy for all users to avoid severe drawdowns of the lake, a method for holding water in reserve for later high demand periods, and a defined minimum level for holding water in reserve to protect coastal wellfields from the threat of saltwater intrusion. District staff reviewed the *Staff Manual for the Management of Water Shortages* (SFWMD, 1987) and the *Supply-Side Management Plan for Lake Okeechobee* (Hall, 1991) to identify how water is currently managed in the system to ensure that adequate water is stored in the lake to prevent significant harm to the water resources of Lake Okeechobee and the Biscayne aquifer (See **Figure 15** in Chapter 4).

### Ecological Research

#### Minimum Level

Minimum water level criteria were developed to prevent significant harm to the following:

- The lake's commercial and recreational fishery
- The nesting and foraging habitat of wading birds, migratory water fowl, and the federally-designated endangered snail kite
- Ecotourism, including bird watching, hiking, and other related activities

Significant harm, from an ecological perspective, is considered to be an adverse change in one or more of these values that takes multiple years to recover under normal rainfall conditions. The ecological criteria proposed here are consistent with a conceptual ecosystem model developed by a multiagency panel of experts (Havens and Rosen, 1997), and with the low lake level criterion developed as part of the C&SF Project Comprehensive Review Study (Restudy). The recommendations made in the Restudy are being implemented in the Comprehensive Everglades Restoration Plan (CERP).

The focus of this section is on Lake Okeechobee's littoral zone, the geographic region that provides the ecological values listed above. Quantitative relationships between the values and low lake levels were determined from the following:

- Information regarding fish and wildlife use of different regions of the lake's littoral zone
- Output from a GIS model regarding flooding and drying of the littoral zone as a function of lake surface elevation
- Direct observations of changes that have occurred in the littoral community during and after major drought events
- Results of experimental and observational research relating plant growth rates to water levels

The spike rush (*Eleocharis*) community of Moonshine Bay and the bulrush (*Scirpus*) community at the littoral fringe are particularly important as habitats for wildlife populations (including largemouth bass, black crappie, and the federally-designated endangered snail kite), and as such were considered to be most intimately linked to the lake's ecological and societal values. Review of GIS maps developed as part of this study indicated the critical level at which these habitats are no longer submerged (11 ft NGVD). A matrix of the various aspects of significant harm that have been observed under such low lake conditions was compiled (**Table F-1,** Appendix F). Finally, experimental and observational results regarding the expansion of exotic and nuisance plants (e.g., torpedo grass, melaleuca, and cattail) under various water level regimes were considered, to predict how much their spread would be accelerated under low lake level conditions.

Lake Okeechobee has experienced seven low lake stage events (< 11 ft NGVD) since the lake was encircled by a dike, regulated according to a flood-control schedule, and utilized as a source of water for regional water supply needs. The cumulative impact of these low water events is uncertain, owing to a lack of long-term ecological monitoring of the ecosystem. There is evidence from a littoral plant survey in the 1970s (Pesnell and Brown, 1973) that a diverse wetland plant community persisted in the littoral zone following three droughts during the preceding 20 years when the lake reached 10.1 ft NGVD in 1956, 10.2 ft NGVD in 1962, and 10.3 ft NGVD in 1971. However, impacts of these events on fish and wildlife are not well documented.

In contrast, today's littoral zone has a dramatically different vegetation community, including thousands of acres of the exotic plants melaleuca (*Melaleuca quinquenervia*) and torpedograss (*Panicum repens*). These plants offer relatively poor habitat for fish and wildlife due to their dense growth form, and in the case of torpedograss, the presence of low levels of oxygen within the water column. Results of both observational and experimental research indicate that their expansion into native plant communities may be facilitated by low lake stages (less than 11 ft. NGVD) which dry out the marsh.

Field surveys and GIS maps indicate that torpedograss presently is restricted to more upland areas of the littoral zone, at elevations greater than 13 ft NGVD. However, during a brief period of reduced water levels in 1997, torpedograss expanded into lower elevations of the marsh (Moonshine Bay area) previously dominated by spike rush. Small colonies of torpedograss now occur throughout much of this area. Moonshine Bay is a pristine central region of the littoral zone that provides nesting habitat for game fish (including the largemouth bass), and foraging habitat for wading birds, migratory waterfowl, and the federally-endangered Everglades snail kite (Bennetts and Kitchens, 1997).

Researchers have speculated that if Moonshine Bay should become dry (lake stages less than 11 ft NGVD for an extended period of time), these conditions will allow for the rapid expansion of torpedograss throughout the area. Experimental research conducted by the US Army Corps of Engineers Waterways Experiment Station (Lewisville, Texas) has now confirmed this view. Torpedograss spreads primarily by fragmentation. Small pieces of existing plants are carried to new locations by water currents, and when they become rooted, new colonies form. In controlled experiments, the following was documented:

- Torpedograss fragments cannot successfully become rooted unless they make contact with the sediments
- Fragments generally will not sink to the sediments when there is standing water because they are highly buoyant
- Fragments that are placed in contact with sediments can develop roots, but they cannot successfully produce aboveground leaves and shoots when water depths are greater than 25 cm
- At water depths less than 25 cm, rooting and production of lateral rhizomes occurs quickly (in less than a month)
- Once these plants become established, they can tolerate higher water levels (up to 100 cm) by drawing on reserve energy and nutrients contained in their roots

The relevance of these research results for Lake Okeechobee are (a) torpedograss is unlikely to spread into regions of the littoral zone where water depths exceed 25 cm, (b) in Moonshine Bay, average depths within the bay are below 25 cm when lake stage falls to 11 ft NGVD, and (c) when lake stages fall from 12 to 11 ft NGVD, another critical habitat, the nearshore bulrush (*Scirpus californicus*) community, becomes exposed. The bulrush represents a prime habitat for sportfish nesting and foraging along the lake's western shoreline.

To prevent significant ecological harm from occurring to littoral zone and nearshore communities, it is recommended that lake levels not drop below 11 ft NGVD for extended periods of time to prevent further expansion of torpedograss within Lake Okeechobee.

### Minimum Duration and Return Frequency

Recent research results indicate that lake stages below 11 ft NGVD have the potential to increase torpedograss expansion within the littoral zone. Ideally, the minimum level should also include a duration target (number of days the lake can remain below 11 ft NGVD without causing significant harm), and an allowable return frequency (number of years between events). To date, however, our understanding of the ecosystem is not at a level that permits establishment of science-based criteria for these two attributes. Current research efforts are focused on determining ecological risk versus duration of exposure for various littoral zone plant communities. Results of these ongoing research efforts are not currently available. Until more complete ecological information becomes available, District staff used the lake's current historical period of record (1952-1995) to provide an initial nonecological estimate of the number of successive days and number of years between events that lake levels could be allowed to recede below 11 feet NGVD (see **Figure 18**, Chapter 4). These historical data were used because the present littoral zone plant communities, and hence the hydrologic conditions that have preceded formation of these communities, are considered to be acceptable. However, it is recognized that these conditions merely provide a very simplistic "place holder" in this process, to indicate whether future consumptive withdrawals cause more frequent or prolonged lows than occurred in the past.

### Lake Stage for Navigation and Recreational Use

Information used to determine the lower limit at which significant harm occurs to navigation and recreation access to the lake was based on the following information:

- Review of the document, *Central and Southern Florida Project, Water Control Plan for Lake Okeechobee and the Everglades Agricultural Area* (USACE, 1991), which identified the water depths needed for safe navigation of the Okeechobee Waterway
- A bathymetry map of Lake Okeechobee showing one foot contours of the lake bottom (**Figure F-1,** Appendix F)
- Discussions with local marina operators and boat captains who provided insight regarding their navigation experiences on the lake during low lake stages.

## EVERGLADES

Development of minimum water level criteria for the remaining Everglades was based on three primary sources of information: a review of the literature, results obtained from output of the Natural System Model version 4.5 F (NSM v 4.5 Final), and a review of historical water levels and fire records. The processes used to review and integrate this body of information are described below.

## Literature Review

A review of scientific and technical literature was conducted to compile and summarize available information that describes the ranges of water levels that occur during drought conditions within the Everglades and within other peat and marl based wetland systems. The search was limited primarily to include studies conducted within South Florida to document minimum water levels recorded during low rainfall periods and their subsequent impact on wetlands. These data were synthesized into tables to show ranges of minimum water levels, the duration of each event, and return frequency. A computer bibliographic search (Dialog Information Service) was also conducted using the following key words: hydric soils, peat and marls, soil subsidence, Everglades water levels, Everglades hydroperiod, changes in Everglades plant communities, fire in the Everglades, effects of drought in the Everglades, and minimum water levels. Results of this search are included in the list of references provided in **Appendix E** of this report. Technical publications produced by the SFWMD and the South Florida Research Center at Everglades National Park were also reviewed. The final product includes a list of technical publications that discuss low water periods observed in the Everglades as well as documented events where environmental impacts have been documented as a result of overdrainage of the system.

## Review of Historical Water Levels and Fire Records

Fire is a natural force that has shaped the Everglades ecosystem. Periodic fires prevent the natural succession of fire-adapted species such as sawgrass or maidencane to woody or bush vegetation. Communities maintained by fire are called fire subclimax communities. Conversely, severe fires that consume peat and damage wetland plant communities can result in ecological impacts that last from 3 to 10 decades (DeAngelis, 1994). Therefore, a potential increase in the frequency of severe fires, due to lowered water levels or shortened hydroperiods relative to historic conditions, represents an impact to the water resource functions of the Everglades and should be considered when establishing MFLs. In this study, District staff reviewed historical hydrologic conditions at key water management locations located within the WCAs, the Holey Land and Rotenberger WMAs, and within the freshwater regions of Everglades National Park. These data were compared with available fire records provided to the District by the FGFWFC, as well as those obtained from published literature (e.g., Loveless, 1959; Robertson, 1953; Craighead, 1971; Gleason and Stone, 1974; Schortemeyer, 1980; Wade et al., 1980; Taylor, 1981; Zaffke, 1983; Alexander and Crook, 1984; Gunderson and Synder, 1994).

## Modeling

The Natural Systems Model (NSM) has been used as a means to estimate and compare water depths, duration, and return frequencies for low water conditions in the remaining Everglades system under natural conditions. The NSM provides a means to simulate the hydrologic response of the predrainage Everglades, using recent (1965-1996) records of rainfall and other climatic inputs, and determine how the unaltered system would have responded to recent climatic (rainfall) conditions. The NSM was first developed in 1989 by District staff (Perkins and MacVicar, 1991) and has been revised and updated. Version 4.1 of the NSM was adopted by the Scientific Working Group (1995) as the best available tool to simulate the hydrologic response of the natural Everglades. Further refinements have been made to the model and the current release is version 4.5 Final.

Use of the NSM was of limited value in the analysis to determine MFLs for the Everglades, because this system has been extensively modified from its historic condition. The nature and effects of these modifications were described previously in the Water Resources Considerations section of Chapter 2. Although the Everglades cannot be restored to its predrainage condition, other efforts, such as the Comprehensive Everglades Restoration Plan, are underway to determine the best means to achieve as much restoration as possible.

The NSM modeling approach was used help estimate certain aspects of the Everglades MFL criteria because predrainage hydrologic data do not exist for these areas. Use of recent historical rainfall data allows comparisons to be made between the response of the natural system and that of the current managed system under identical climatic conditions. In this sense, the NSM is a useful planning tool to understand how the natural system originally worked and native ecosystems may have responded, without the canals, levees, and water management structures in place.

In the NSM, the canals, structures, and levees are replaced with the rivers, creeks, and channels that discharge water from the interior of the peninsula toward the coast through a simulated version of the transverse glades, which extended along the coast in Broward and Miami-Dade counties. Historical sheetflow characteristics, which were present prior to development of South Florida, are used to convey water through the marshes. The vegetation and topography used by the NSM are based on estimates of predrainage conditions. Historical vegetation is based on a map originally developed by Davis (1943a) and later updated and modified by Costanza (1975). Historical topography is based on current knowledge of ground elevations in the Everglades and is updated using best available historical data (e.g., ground levels recorded during construction of the primary canal system through the Everglades). In areas where the historical topography is higher than current conditions, surface water ponding depths are presented as adjusted, or normalized, to ground level for both the current managed system and the NSM.

In this study, the NSM was used as one of several sources of information that District staff reviewed to examine how low, for how long, and how often water depths declined under natural conditions during low rainfall years. Review of the available literature identified information that could be used to estimate the minimum water depth (how low) and the duration that water levels remained at low levels (how long). The literature however did not provide information of the frequency with which such events could be expected to occur (how often).

For example, descriptions of Everglades National Park, prior to construction of regional drainage facilities, showed that areas such as Shark River Slough were flooded for long periods of time. Occasional regional drought events occurred under natural conditions that lowered water levels in the slough to one foot or more below ground, but there is no direct observational evidence to document how often such events occurred. The NSM provides a means to translate what is known of historical topography, landscape ecology, and rainfall patterns to estimate this frequency. NSM results indicated that some areas in the slough dry out once every 10 to 15 years, while other areas apparently remain permanently flooded or dry out less than once every 30 years.

Under natural conditions in the northern Everglades, portions of the sawgrass plain located south of Lake Okeechobee dried out more frequently and experienced periodic low water levels of a foot or more below ground and occasional fires, perhaps once every 4 to 5 years.

Analyses using the NSM to determine frequency of drought conditions focused on locations that represent present day water management gauges within the WCAs and Everglades National Park. Key gauges selected for this analysis are shown in **Figure 18** (in Chapter 4), and include the following:

- The 1-7 gauge located in the central portion of WCA-1
- The 2A-17 gauge in the central portion of WCA-2A
- The 2B-21 gauge at the south end of WCA-2B
- The 3A-2 (deer gauge), 3A-3, 3A-NE, and 3A-NW gauges in northern WCA-3A
- The 3A-4 and 3A-28 gauges in central and southern WCA-3A
- The 3B-SE gauge in the southeast portion of WCA-3B
- The NP-201, G-620, NESRS-2, NP-33, NP-36, NP-38, G-1502, and NP-67 gauges located in Everglades National Park

# BISCAYNE AQUIFER

Development of minimum water level criteria for the Biscayne aquifer were determined from three primary sources of information: a review of the available literature; a review and evaluation of historical water levels and water quality data from area monitoring wells; and a review of various ground water models to determine the relationships among ground water levels, aquifer characteristics, and the degree of saltwater intrusion that could be expected during a major drought.

## Literature Review

A review of the available literature was conducted to compile and summarize existing information on the hydrology and hydrogeology of southeastern Florida, the Biscayne aquifer, and saltwater intrusion within an unconfined aquifer system. Scientific literature was obtained using an online computer search and manual location of information. This review was generally limited to references specific to southeastern Florida; however, more general literature on the mechanics of saltwater intrusion was also reviewed. A summary of the key information obtained from the review are cited below and are included in the literature cited section of this report. In addition to the literature cited in the text, many other references may be found within the cited works themselves. The primary focus of this review was to understand the mechanics of saltwater intrusion within the Biscayne aquifer and to determine if a scientifically defensible relationship exists among ground water levels, aquifer characteristics, and the degree of saltwater intrusion. In addition to the literature review, water level and water quality data were also analyzed for more than 500 monitoring wells located throughout the study area. Sources of information included U. S. Geological Survey (USGS) data, the SFWMD SALT data base, and various consulting reports and articles.

A thorough description of the stratigraphy and geologic history of the deposits comprising the Biscayne aquifer is provided in Parker et al. (1955) and elaborated on by Hoffmeister (1974) and White (1970). Information concerning the delineation and extent of the Biscayne aquifer is presented in Fish (1988), Klein and Hull (1978), and Shine et al. (1989). These sources base the definition of the Biscayne aquifer on hydraulic properties rather than on geologic formation boundaries.

A number of sources provide information on the lithology and hydraulic characteristics of the Biscayne aquifer, including Fish (1988), Fish and Stewart (1991), Shine et al. (1989), and Restrepo et al. (1922). The bulk of the aquifer material consists of highly permeable, cavity-riddled limestones and sandstones of the Pamlico Sand, Miami Limestone, Anastasia Formation, Key Largo Limestone, Fort Thompson Formation, and part of the Tamiami Formation. Descriptions of these formations are provided by Parker et al. (1955). Hydraulic conductivity of the Biscayne aquifer ranges from 500 to 4,000 feet per day in Palm Beach County (Shine et al., 1989), to more than 10,000 feet per day in Broward and Miami-Dade counties (Restrepo, 1992; Fish, 1988; Fish and Stewart, 1991).

General information on the mechanics of saltwater intrusion was found in Freeze and Cherry (1979), Bear and Todd (1960), and Domenico and Schwartz (1990). These references also describe the Ghyben-Herzberg relationship as discussed in this report. Wirojanagud and Charbeneau (1985) describe the phenomenon of saltwater upconing around pumping wells. The cyclic flow of saltwater in the Biscayne aquifer was discussed in Kohout (1960) and Merritt (1996).

The work of both Kohout (1960) and Merritt (1996) suggest that salt water under tidal influence can move greater distances and be more easily incorporated in seaward discharge of fresh water in heterogeneous aquifers with high hydraulic conductivity, like the Biscayne aquifer, than in less permeable, more lithologically uniform aquifers. Merritt (1996) also points out that when diminished rainfall and lowered ground water stages decrease freshwater inputs to tidal canals, sea water can circulate inland close to the land surface rather than at depth during high tides. Bear and Todd (1960) show that tidal fluctuations cause the transition zone between salt and fresh water to be larger closer to the coast, and suggest that aquifer heterogeneity may also encourage a wider transition zone.

All of these references combine to illustrate the complex interaction between hydraulic properties of the aquifer, tidal action, rainfall and runoff, pumping in coastal wellfields, ground water levels, and coastal stages.

Information on the location of the saltwater interface in the Biscayne aquifer during various years was obtained from reports prepared by J.M. Montgomery, Inc. (1986), Sonenshein and Koszalka (1995), and Merritt (1996). Water level and chloride data from USGS, SFWMD, and consultant reports were analyzed to determine average and seasonal water levels and to help determine the position and movement of the saltwater interface.

Insight into the influence of rainfall on ground water elevations and flow patterns was obtained from Sonenshein (1994) and Merritt (1996), and also through comparison of rainfall and water level data. Merritt (1996) includes a discussion of the effects of water management controls on seasonal average water elevations and on the movement of the saltwater interface in response to short- and long-term low water periods. Merritt concluded that it is average annual or long-term ground water levels, rather than seasonal variations, which significantly affect the position of the saltwater interface.

## Data Analyses and Modeling Approaches

To determine a minimum level that should be established for the Biscayne aquifer, the following four separate approaches were used:

- An evaluation of water quality and water level data from LEC Planning Area monitoring wells and canal stage data from coastal water management structures was performed.
- An evaluation of the influence of the maintained canal levels on coastal aquifer water levels using the South Florida Water Management Model (SFWMM).
- An evaluation of various canal stages and their influence on the position of the saline interface using a two-dimensional solute transport/flow model (SWICHA) was performed (Andersen et al., 1986).
- These data were compared to the well known Ghyben-Hertzberg relationship as a method for determining the minimum level that should be maintained to prevent saltwater intrusion of the Biscayne aquifer. It should be noted that the Ghyben-Hertzberg relationship was not used in the study to establish any minimum level proposed in this report. It is used here for comparison purposes only.

### Evaluation of Monitoring Well Data

Water level and water quality data from 500 monitoring wells within the study area were evaluated. Average dry and wet season water levels were determined for each well. In addition, initial, mean, and final chloride concentrations were noted for each monitoring well to determine if the saltwater front had reached that monitoring well, if the front was stable, if the front was still moving, and long-term trends. The depth of each well was also noted. Stage duration curves were developed for each coastal control structure. The mean and 84th percentile stages were calculated and the data were then analyzed to determine if there was a relationship between water levels and chloride concentration. Analyses of these data found coastal canal stages maintained near the 84th percentile (one deviation from the mean) as the best fit for protecting the aquifer against further saltwater intrusion. Statistical analyses were also completed for 49 selected wells to determine the correlation between well water levels and chloride concentration. Correlation coefficients, covariance, standard deviation, mean, and variance statistics were performed to assist this evaluation.

### SFWMM Modeling

The SFWMD maintains over 1,400 miles of canals, levees, and water management structures designed primarily to provide drainage for developed areas along Florida's lower east coast. This extensive canal system (**Figure 10**) also plays an important role in preventing further inland migration of salt water into the Biscayne aquifer. During times of drought, water is maintained in coastal canals by transporting water from the WCAs or from Lake Okeechobee eastward into coastal basins.

Development of MFLs for the Biscayne aquifer required an understanding of how the canal network influences coastal water level conditions within specific geographic areas. The South Florida Water Management Model (SFWMM) was used to analyze the interaction between the coastal canals and aquifer water levels during times of drought. The SFWMM is a two-dimensional, regional-scale, integrated surface-ground water flow model that simulates the hydrology and water management of southeastern Florida. The model covers an area of approximately 7,600 square miles, and includes the remaining Everglades ecosystem, the urbanized east coast, and agricultural areas located south and east of Lake Okeechobee. The model performs a continuous daily simulation over 31 years (1965-1995) of historical data, including operation of the canal network.

In setting MFLs to prevent saltwater intrusion, it was necessary to evaluate what influence these canals have on water levels within the Biscayne aquifer. To increase the understanding of the relationship between the canal network and aquifer water levels, two separate model runs were simulated using the SFWMM:

- The first simulation consisted of operation of the system under present conditions. That is, coastal canals, which are currently maintained by the regional system during drought periods, continue to receive water from the WCA system and Lake Okeechobee during low rainfall years.
- The second simulation evaluated another option in which coastal canals were not maintained for water supply purposes during drought years.

Each scenario used daily climate data for the period of record (1965-1995). A water shortage trigger module, developed as part of the LEC regional water supply planning process was used to record water levels at key monitoring locations along the

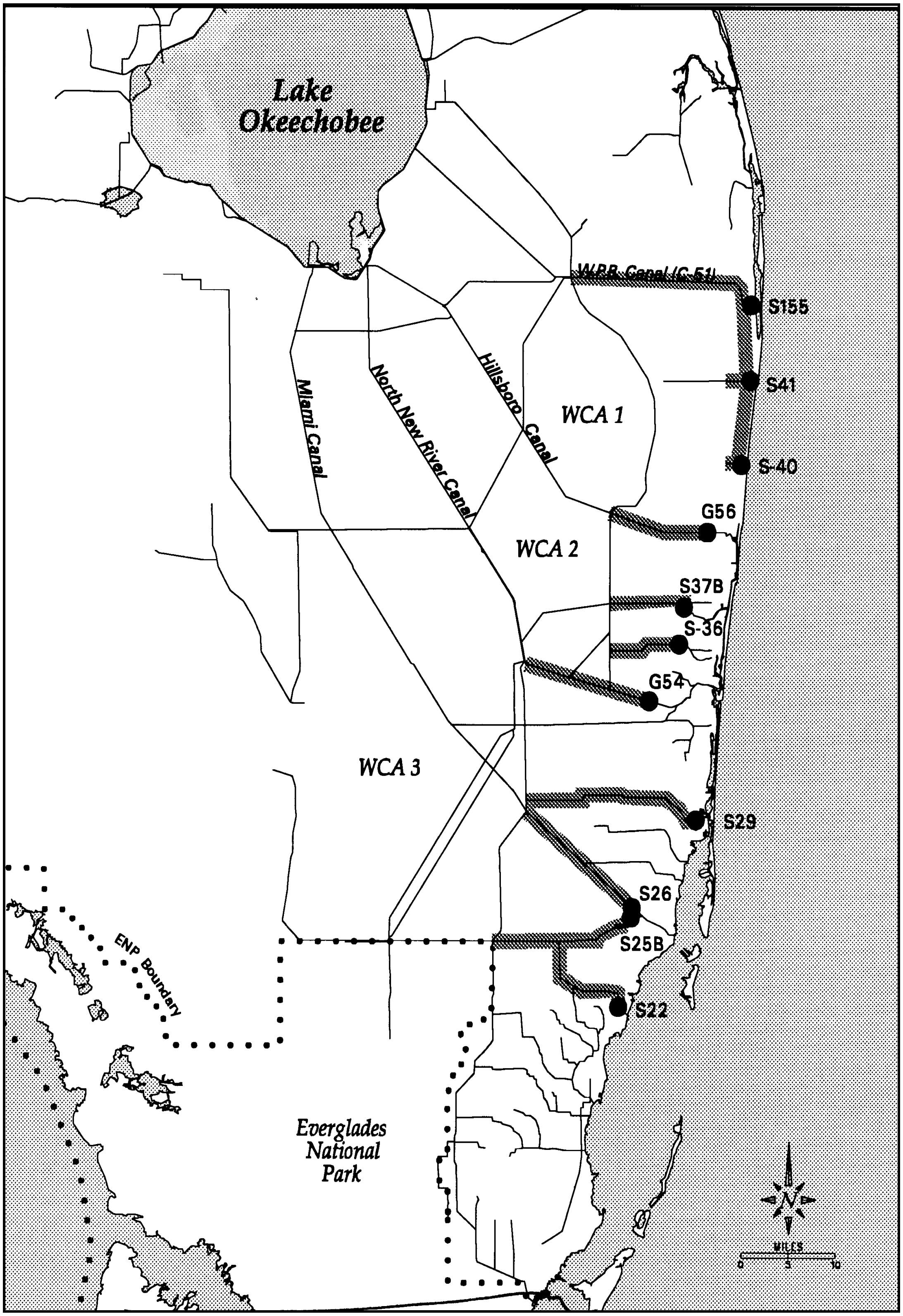


**Figure 10.** SFWMD Coastal Canal Network Indicating Key Water Management Canals and Structures for Maintenance of Minimum Levels in the Biscayne Aquifer.

coast. The water shortage module predicts when water shortage restrictions should be evoked based on water levels near the saltwater interface. In general terms, a Phase 1 water shortage is anticipated when coastal water levels fall below 1 ft NGVD. Data from 20 key monitoring locations were recorded along the lower east coast of Florida. Results of the maintained canal simulation were compared with results of the nonmaintained canal simulation at key monitoring locations to determine the role that the regional canal system played in preventing saltwater intrusion within the Biscayne aquifer.

### Saltwater Intrusion Modeling

Another method used to determine minimum levels for the Biscayne aquifer was to estimate the position of the saltwater interface from the results of various local-scale modeling scenarios. Preliminary results were based upon two-dimensional, cross-sectional modeling of the Biscayne aquifer at various transects along the southeast coast of Florida. Variations of inland water levels and impacts of canal water level changes were analyzed and evaluated. The model used to gain a general understanding of local-scale saltwater intrusion within the Biscayne aquifer was SWICHA, a three-dimensional, finite element code developed by Huyakorn, Mercer, and Andersen (1986) for analyzing seawater intrusion in coastal aquifers. The SWICHA model allows both two-dimensional, cross-sectional analysis of saltwater intrusion and more elaborate three-dimensional evaluations. In this study, five separate two-dimensional cross-sectional models were developed and modified from the work of Andersen et al. (1986) to evaluate various MFL scenarios.

### Evaluation of the Ghyben-Herzberg Relationship

For comparison purposes, the theoretical Ghyben-Herzberg relationship (Todd, 1980) was also evaluated to determine the minimum level that should be maintained to prevent saltwater intrusion of the Biscayne aquifer. **Figure 9** in Chapter 2 shows the idealized Ghyben-Herzberg relationship model for the freshwater/saltwater interface along a coastal aquifer. The Ghyben-Herzberg relationship assumes that the interface exists in a static equilibrium, with a hydrostatic pressure distribution in the freshwater region of the aquifer and stationary salt water (Bear, 1972). The equation developed by Ghyben and Herzberg to simulate their observations is:

$$Z = hf \times 40$$

*where:*
*Z = Depth to saltwater interface (feet below sea level)*
*hf = Freshwater head (ft NGVD)*

In evaluating the applicability of this method to South Florida conditions, several variables are known. These include historical water level and chloride concentrations from a number of monitoring wells along the coast, the depth of each monitoring well, and the depth to the base of the Biscayne aquifer. The theoretical freshwater head necessary to prevent saltwater intrusion is based on calculation of the Ghyben-Herzberg relationship for each selected monitoring well. The depth of the monitoring well was divided by 40 to obtain the theoretical freshwater head as the slope of the saltwater interface is 40 times greater than the slope of the water table. The theoretical freshwater head was then compared to actual wet and dry season average water levels recorded for each well. If the actual recorded water level was greater than the theoretical freshwater head, then it was assumed that saltwater intrusion would not occur. If the value was less than the theoretical head, it was assumed that salt water could potentially contaminate the monitoring well. Average and recent chloride concentration data from each well were then used to determine the percentage of wells that could remain as fresh water producing wells and those that might be affected by salt water, as predicted by the Ghyben-Herzberg relationship.

It should be emphasized here that District staff did not use the Ghyben-Herzberg relationship to establish any minimum level recommended in this report. Its use here is **for comparison purposes only**.

# Chapter 4
# PROPOSED MINIMUM FLOWS AND LEVELS CRITERIA

The following sections present the Minimum Flows and Levels (MFL) criteria as required in Chapter 373, Florida Statutes for Lake Okeechobee, the three Water Conservation Areas (WCAs), the Holey Land and Rotenberger WMAs, the freshwater regions of Everglades National Park, and the Biscayne aquifer. Each section provides a summary of the technical relationships which were considered in defining significant harm for each water body and a detailed presentation of the proposed MFL criteria with supporting documentation.

For the purposes of this study, significant harm is defined as a loss of specific water resource functions resulting from a change in surface water or ground water hydrology that takes multiple years to recover from (see Chapter 1 for further discussion of the definition of significant harm).

## LAKE OKEECHOBEE

### Resource Functions

The following water resource functions were considered in the development of the proposed minimum water level criteria for Lake Okeechobee:

- Provide water that can be used to maintain water levels in coastal canals, meet human needs and protect the Biscayne aquifer against saltwater intrusion
- Supply water and provide water storage for the Everglades
- The lake is a regionally important ecosystem that provides fish and wildlife habitat and supports commercial and sport fisheries.
- Maintain navigation and recreational use

Additional factors that were considered included the need to supply water to areas other than the Everglades and the Biscayne aquifer, including the Caloosahatchee River, St. Lucie Canal, the Seminole Indian Tribe, and the Everglades Agricultural Area.

### Technical Relationships Considered in Defining Significant Harm

#### Protection of the Coastal Aquifer

As part of the Central and Southern Florida (C&SF) Project, Lake Okeechobee plays a critical role as a source of fresh water to maintain coastal ground water levels which prevent saltwater intrusion of the Biscayne aquifer. During dry periods when freshwater supplies are depleted along the lower east coast of Florida, fresh water is discharged from interior storage areas such as Lake Okeechobee and, when available, the WCAs, to the coastal canal system. These water releases help maintain a freshwater head within the coastal ground water aquifer that prevents inland movement of the saltwater front. Saltwater intrusion can occur whenever water levels within local canals or the aquifer drop below the elevation needed to stabilize the adjacent saltwater front.

Historical records show that when lake levels fall below 11 ft NGVD, water shortage restrictions have been imposed along Florida's lower east coast (Hall, 1991). **Figure 11** provides a summary of the relationship between lake stage and the amount of water that can be stored in the lake for delivery to lower east coast canals during dry periods. Historical data shows that when lake water levels reach 11 ft NGVD, these levels typically continue to decline rapidly, affecting the District's ability to deliver water to coastal canals. Once water levels fall below 10.5 ft NGVD, the physical limitations of the lake's primary outlet structures make it increasingly difficult to convey water from the lake to coastal canals. The 10.5 ft NGVD elevation generally represents the bottom of the conservation pool for water supply planning purposes. The District has established a water conservation policy (i.e., Supply-Side Management Plan) which applies a percentage reduction to water withdrawals below the seasonally varying water supply schedule.

### Water Supply for Everglades National Park.

Shortly after Everglades National Park was created, it became apparent that it was not receiving sufficient freshwater flows during dry periods to maintain viable aquatic ecosystems and protect vegetation and wildlife from damaging fires. In 1970, Congress adopted Public Law 91-282, which provided a minimum water delivery schedule for Everglades National Park based on minimum monthly flow requirements. Later, it became apparent that this schedule resulted in unnatural volumes and timing of water flows discharged from the WCAs to western Shark River Slough. This altered flow regime caused failure of alligator nests, abandonment of wading bird rookeries, and alteration of wetland communities (NPS-SFRC, 1989). In 1984, this delivery schedule was replaced with a water delivery model called the Rainfall Plan, to provide a more natural timing of water deliveries to Everglades National Park (MacVicar, 1985; Neidrauer and Cooper, 1989). Using this approach, water is discharged into Everglades National Park during periods when rain falls within the upstream watershed. If no rainfall occurs, then no water is provided. This management method has helped maintain more natural cycles of wet and dry season flows to Everglades National Park and meet it's water needs during regional droughts. The Rainfall Plan has also helped to reestablish more natural hydroperiods and better overland flow to Shark River Slough (Light and Dineen, 1994). This plan is in effect today while other additional improvements are being evaluated, such as the Modified Water Deliveries to Everglades National Park Plan, and the C-111 South Dade Project.

Water deliveries from Lake Okeechobee to the Everglades are made pursuant to the District's Best Management Practice (BMP) Make-Up Water rule, Part II of Chapter 40E-63, F.A.C. Deliveries under this rule are made consistent with a model that quantifies the amount of water to be replaced due to reduction of flow to the Everglades Protection

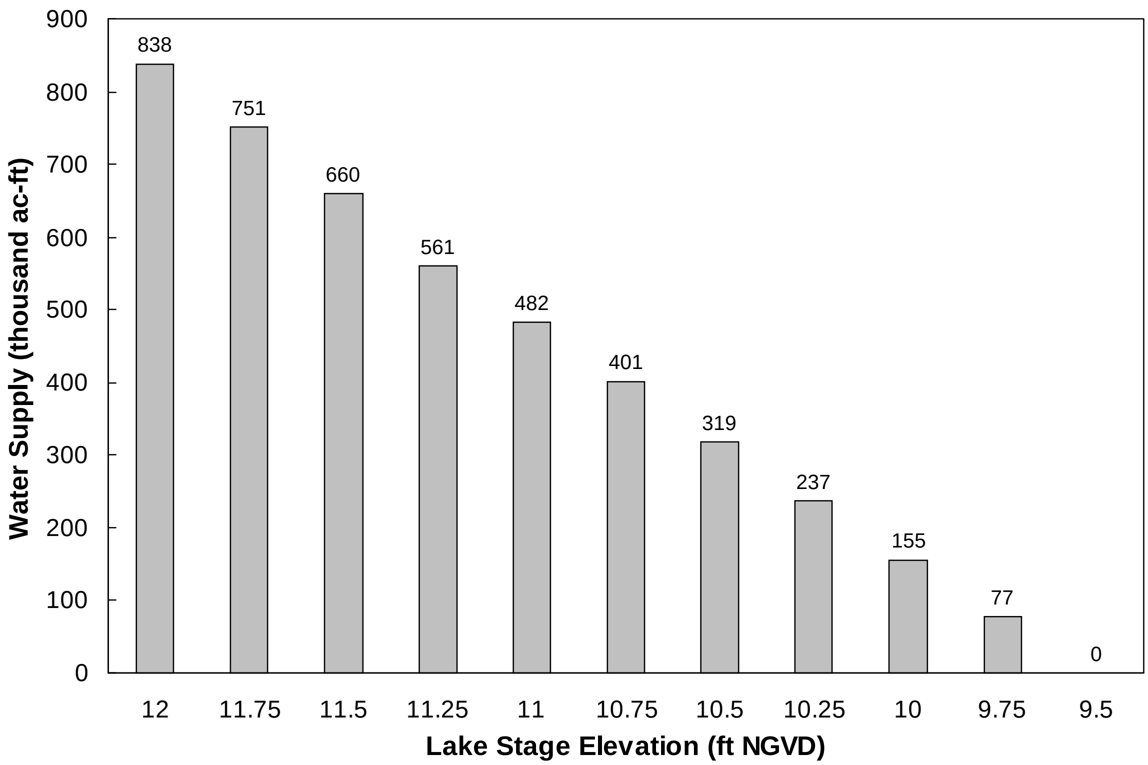


**Figure 11.** Amount of Water Available in Lake Okeechobee for Delivery to LEC Planning Area Canals at Various Stage Levels. Source: SFWMD data. Graph based on lake stage/ volume relationship.

Area resulting from implementation of BMPs within the EAA. Under extreme hydrologic conditions, such as when Lake Okeechobee levels are at the warning stage or lower, pursuant to the Supply-Side Management Plan, the rule provides the Governing Board with the authority to deviate from the delivery schedule. At this time, no approved plan for Everglades National Park deliveries during water shortage has been incorporated into the Supply-Side Management Plan. Such delivery options may need to be developed and evaluated in the LEC regional water supply planning process to modify the current Supply-Side Management Plan. District staff does not consider this concern to be influential to establishing minimum level technical criteria for Lake Okeechobee.

### Lake Okeechobee Littoral Zone and Associated Fish and Wildlife Values

The following fish and wildlife values for Lake Okeechobee were identified in a multiagency workshop held in March, 1997 (Havens and Rosen, 1997):

- A commercial and recreational fishery valued at over $480 million dollars (Furse and Fox, 1994)

- A rich avifauna community that includes wading birds, migratory waterfowl, and federally-designated endangered snail kite and wood stork (Richardson and Harris, 1995; Smith et al., 1995)
- Ecotourism and recreation, including fishing, hunting, and bird and wildlife observation

These values depend on the diverse mosaic of natural vegetation that characterizes the lake's littoral zone (Richardson and Harris, 1995; Smith et al., 1995). The integrity of the littoral zone depends an maintaining a favorable hydrologic regime that avoids "drowning" plant and animal communities through maintenance of water levels that are too high, or excessive drying of the littoral zone substrate that will destroy or modify existing wetland communities.

### Navigation/Recreation

When lake levels fall below 12.56 ft NGVD, navigation of the Okeechobee Waterway becomes impaired. At levels below 11 ft NGVD, access to the lake for fishermen and other recreational boaters becomes limited to maintained channels and boat trails, especially in the southern and western portions of the lake. Once water levels drop near 10 ft NGVD, recreational access to the lake becomes significantly restricted, since much of the littoral zone is exposed as dry land or contains only a few inches of water.

### Other Considerations

Other factors to consider include the need to provide water supply to the Everglades Agricultural Area, the Seminole Indian Tribe, and the Caloosahatchee and St. Lucie Basins. During drought conditions, agricultural water needs within these basins are estimated on the basis of weather, soil, and crop conditions. Using Supply-Side Management (Hall, 1991), the amount of water in storage and the proportion that is available for allocation are calculated. Based on this calculation, water is allocated as a percentage of the flow volume that would be needed to meet normal dry season irrigation demands in each basin. The allocation is adjusted on a monthly or weekly basis to allow for changes in regional and local conditions. The Governing Board has the authority to adjust these allocations based on local conditions (**Table 2**). Special conditions may apply in the St. Lucie Canal Basin during periods when water levels in coastal canals are higher than the stage in Lake Okeechobee. During such periods, no additional water can be supplied from the lake, and water from the basin may in fact, flow back into the lake to enhance regional supplies. Also, in the Caloosahatchee Basin, water releases from the lake may periodically be required to improve water quality conditions in the canal, when algae blooms or saltwater contamination occur at the S-79 Structure (USACE, 1991).

## Water Resource Functions and Significant Harm

### Water Supply and Water Storage

During years of normal rainfall, the lake's regulation schedule allows for an ample supply of water to be stored in the lake for later use during the dry season. The amount of rainfall that falls in South Florida is highly variable and in some years can result in drought conditions. Review of historical records shows that when lake levels fall below 11 ft NGVD, these levels continue to fall rapidly causing water shortage restrictions to be imposed for the LEC and Lake Okeechobee service areas. When lake stages fall below 10.5 ft NGVD, the structural limits of the lake's outfall structures and regional water conveyance system make it increasingly difficult to discharge water from the lake to the LEC. These discharges are necessary to protect the coastal aquifer against saltwater intrusion.

To examine the water supply and water storage functions of the lake, staff reviewed the District's existing drought management plan known as the *Supply-Side Management Plan for Lake Okeechobee* (Hall, 1991), which was developed to avoid extreme drawdowns that impact South Florida's regional water supply. This plan currently serves the District as the basis for making water management decisions during periods of low rainfall. Supply-side management has been in operation since 1982 and provides (a) water allocation strategy for all users to conserve water and avoid severe drawdowns of the lake, (b) a method for holding enough water in the lake for anticipated high demand periods, and (c) a defined low water level stage that provides enough water in the lake to protect the coastal aquifer from the threat of saltwater intrusion. For a more detailed discussion of how these management zones are operated during low rainfall periods to maintain coastal ground water levels and provide water to the EAA and the Caloosahatchee River and St. Lucie Canal basins, see SFWMD (1987) and Hall (1991).

In general, under the current lake regulation schedule and normal rainfall conditions, water levels in Lake Okeechobee will not fall below 11.0 ft NGVD. Exceptions occur when there is a regional drought. Under drought conditions, the District implements the Supply-Side Management Plan designed to protect the water resource functions listed in **Table 3** and keep sufficient water in the lake to maintain levels above 11 ft NGVD by the end of the dry season. However, when drought conditions are severe and water levels are predicted to drop below 11 ft NGVD by the end of the dry season, the District Governing Board has the authority and responsibility to review water conditions and determine the amount that can and should be released from the lake to downstream users.

The District's water allocation strategy is based on six critical lake water management zones that require specific actions to be taken once water levels fall within each designated zone. These include six water shortage zones: management zones A through D, a warning zone, and a watch zone (**Figure 12**).

The top of Zone A, as shown in **Figure 12**, represents a sufficient amount of water stored in the lake to meet expected dry season demands when normal rainfall, evapotranspiration, and water use demands prevail within all basins. If water levels fall below Zone A, Phase 1 and Phase 2 water use restrictions may be imposed by the

**Table 3.** Key Water Resource Functions of Lake Okeechobee and Proposed Minimum Level Criteria.

| Water Resource Function | Proposed Minimum Level | Comment |
|---|---|---|
| **Protect Biscayne Aquifer Water Quality** | The top of Supply-Side Management Zone C (**Figure 12**) from April 15 through July 15 represents the proposed significant harm limit to protect Lake Okeechobee's water supply. | When water levels fall below the top of Zone C, there is a significant risk that not enough water is available in the lake to maintain freshwater heads in LEC canals necessary to protect the Biscayne aquifer from migration of the freshwater/ saltwater interface. Resulting damage will take multiple years to recover. |
| **Provide Fish and Wildlife Habitat** | Measurable harm occurs to the littoral community and it's associated ecological values when lake levels remain below 11 ft NGVD. | Existing scientific information is not currently sufficient to establish a minimum duration or return frequency for the proposed minimum level. Research over the next several years will better define ecologically-based duration and return frequency criteria. |
| **Maintain Navigation and Recreation Access** | Drawdowns below 10 ft NGVD results in significant harm to navigation and recreational use of the lake. | Drawdowns below 10 ft NGVD significantly impact navigation along the Okeechobee Waterway, restricting navigation and recreational use by the public and causing significant economic loss to local businesses |

District's Governing Board for the LEC, the EAA, and the Caloosahatchee and St. Lucie basins. The top of Zone A sets a minimum lake stage of 11 ft NGVD at the end of the dry season (May 31), and a minimum lake stage of 13.5 ft NGVD on October 1 in order to avoid water shortage restrictions for lake users. However, once water levels fall within Zone C, there is increased risk that not enough water is stored in the lake to protect the Biscayne aquifer from saltwater intrusion. For this reason, Phase 3 and Phase 4 water restrictions could be imposed when water levels fall below Zone C. Thus, the top of Zone C as shown in **Figure 12** represents the minimum level, or significant harm limit, for Lake Okeechobee's water supply.

### Protection of Fish and Wildlife Habitat

The littoral zone of Lake Okeechobee developed in its present location after construction of the Herbert Hoover Dike in the mid 1950s and the adoption of a water regulation schedule that lowered the lake and exposed an area of lake sediments that was once overlain by deep water (Havens et al., 1996). Today this littoral zone covers 22 percent of the lake's surface area and supports a diverse mosaic of native plants and animals. To fully understand the ecological impact that each of these water level regimes have had on the lake, it is important to consider how dike construction and water management have changed the relationship between lake stage and littoral zone flooding and drying (**Figure 13**)

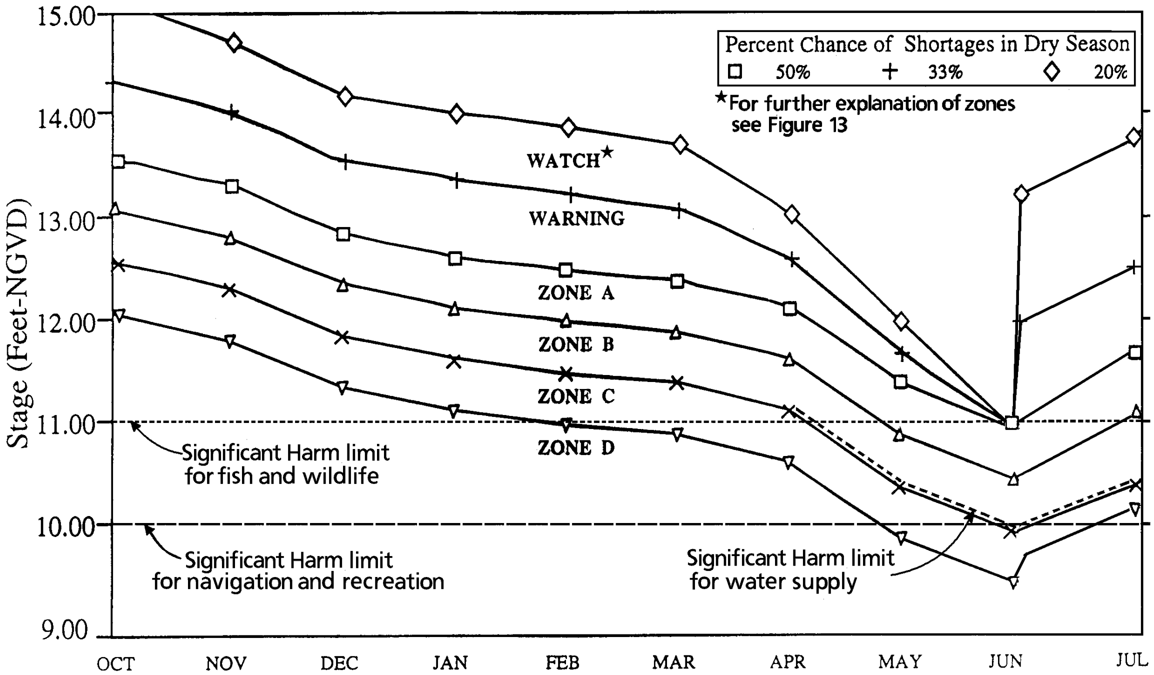


**Figure 12.** Lake Okeechobee Water Supply Management Zones (Hall, 1991).

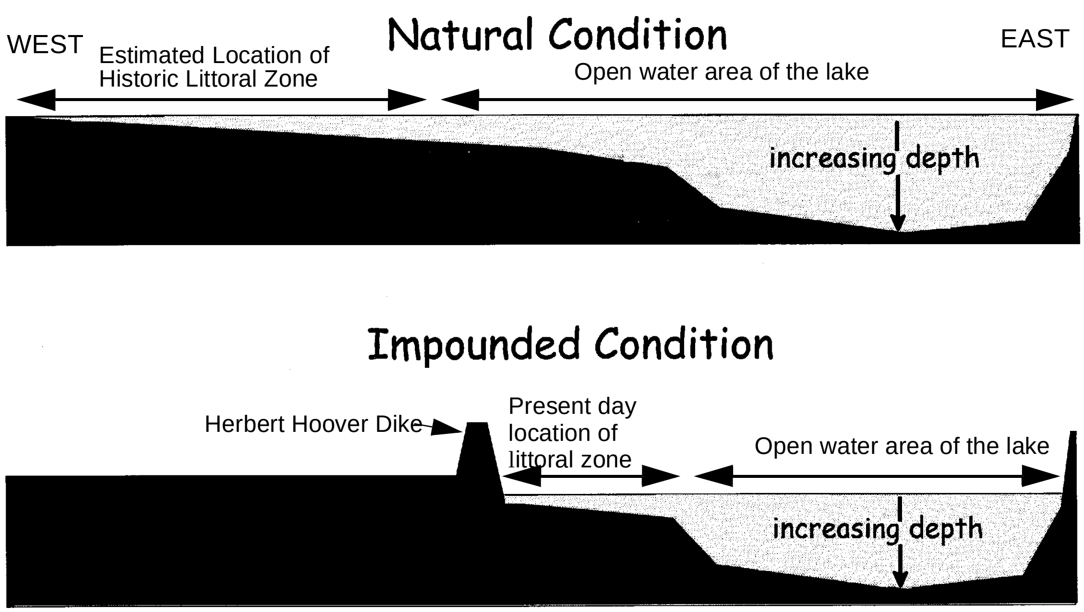


**Figure 13.** Cross-Section of the Littoral Zone and Open Water Areas of Lake Okeechobee under Natural Conditions versus the Current Impounded Condition (conceptual diagram - not to scale).

Predevelopment Lake Okeechobee was considerably larger in surface area, with a littoral zone that extended over a wide expanse of low-gradient land to the north, west, and south of the lake's open water region (Havens et al., 1996). To the south, the littoral zone was contiguous with the Florida Everglades. Seasonal variations in lake levels according to historic accounts (Brooks, 1974) and output of the Natural Systems Model (version 4.5) indicate the lake ranged between 16 and 22 ft NGVD under natural, predrainage conditions, and periodically flooded and dried out the larger historic littoral zone region. Today the smaller impounded littoral zone is constrained between the Herbert Hoover Dike and a relatively steep shelf at the eastern littoral edge, where it meets the open water area of the lake (**Figure 13**). As a result of construction of the dike, when lake stage reaches 15 ft NGVD, the entire littoral zone is flooded. Further increases in stage simply result in deeper flooding of the littoral region, with no opportunity for outward expansion of the lake across shallow wetland habitat. Due to the rather steep slope of the eastern littoral zone shelf, when lake stages remain at 11 ft NGVD or less, most of the littoral zone is dry, and there is little opportunity for expansion of shallow wetland habitat into the lake. The only exception is at the south end of the lake, where a more gradual depth gradient occurs. At low water levels, submerged plant growth in this region may actually benefit from increased light penetration. However, such benefits also occur when lake stages are between 12 and 13 ft NGVD.

**Distribution of Littoral Zone Vegetation.** The current distribution of plants in the littoral zone has been quantitatively linked to localized variations in hydroperiod (Richardson et al., 1995). Particular plant assemblages support certain kinds of fish and wildlife (Aumen and Wetzel, 1995). The two examples below illustrate this point.

In the Moonshine Bay region, deep within the western littoral marsh, there is a large expanse of spike rush (*Eleocharis*), a native sedge that provides primary foraging habitat for the endangered snail kite (Bennett and Kitchens, 1997). This pristine, nutrient poor community is characterized by two to three feet of standing water during the wet season, a hydroperiod of greater than 95 percent, interspersed emergent plants, and an associated periphyton community (Steinman et al., 1997). In many respects, the Moonshine Bay vegetation community closely resembles pristine interior areas of the Everglades (McCormick et al., 1997). The periphyton community in this region of the lake supports a large population of native apple snails, which are the primary food resource of the endangered snail kite. The spike rush community is also important spawning habitat for largemouth bass and other important sport fish.

At the interface between the littoral zone and the open water region of the lake, there exists another important community, dominated by giant bulrush (*Scirpus*). This community is critical habitat for both largemouth bass and black crappie, two of the most important sport fish in the lake (Fox et al., 1995). In a recent analysis, Furse and Fox (1994) calculated that the economic value of this habitat is $48,828 per acre, for a total value of $174 million for the entire 3,576-acre habitat.

In addition to native plants, the littoral zone now contains 15 invasive exotic species, including melaleuca (*Melaleuca quinquenervia*) and torpedo grass (*Panicum repens*). Melaleuca was introduced by the USACE to stabilize soils on the newly constructed Herbert Hoover Dike and torpedo grass was introduced into the watershed north of Lake Okeechobee as a forage crop for beef cattle. Both plants have expanded over thousands of acres in the marsh, displacing native vegetation. The District has been conducting a multimillion dollar program to eradicate melaleuca, and it remains to be seen whether native plants will recolonize treated areas.

In the case of torpedo grass, there is no proven method for control, short of applying a general-action herbicide that kills all vegetation. Research is being conducted by District and University of Florida scientists assessing the application of general action herbicides, along with controlled fires, as methods for controlling torpedo grass. Results to date are mixed; in some cases, there has been nearly total control in herbicide-treated experimental plots, while in other cases, control has been less than 20 percent. It also remains unclear whether native plant communities can consistently recolonize sites that were formerly occupied by torpedo grass.

There are two important features associated with the vast expanses of torpedo grass that now occur in the littoral zone of Lake Okeechobee. First, they are poor habitat for fish and other aquatic animals. The growth form of torpedo grass is much like a hay field with little or no open water area for aquatic organisms to move about, feed, or capture prey. Nighttime dissolved oxygen levels in torpedo grass stands have been observed to fall to zero. Such conditions are not suitable for most aquatic animals. Secondly, torpedo grass has continued to expand in the marsh over the last decade, and it now encircles Moonshine Bay, one of the deepest regions of the marsh that still is dominated by native spike rush. Within this community, there also are islands of torpedo grass on higher elevation sites (K. Havens, personal communication). Expansion outward from these isolated islands is a constant threat to the native plant community, and may occur rapidly if low lake levels frequently occur.

Results from a recent study of the lake’s vegetation communities support this view. Richardson et al. (1995) noted that hydroperiod within native spike rush communities averages 96 percent, while hydroperiod within torpedo grass and melaleuca communities averaged near 80 percent and 78 percent, respectively. Hydroperiod is defined as the percent of time water inundates a wetland on an annual basis. Richardson et al. (1995) concluded that (a) hydrologic variables appear to be the major determining factor in the vegetative patterns seen in the Lake Okeechobee marsh; and (b) higher elevation areas of the marsh that now contain melaleuca and torpedo grass may expand if hydroperiods are shortened due to lower lake levels.

**Lake Okeechobee Research Findings.** A principal finding from wading bird and fisheries research, conducted during the five-year Lake Okeechobee Ecosystem Study (Aumen and Wetzel, 1995) was that some variation in lake levels are necessary for maintaining a healthy littoral community. Smith et al. (1995) recommended spring lake level recessions from above 15 ft NGVD to below 13 ft NGVD, in order to concentrate prey resources (macro invertebrates and small forage fish) and promote wading bird nesting on the lake. Periodic (every several years) declines in lake level to below 12 ft NGVD also were considered beneficial, because they can invigorate willow stands, allow limited fires to burn away cattail wrack, recycle nutrients, and encourage establishment of successional vegetation complexes. These moderate or periodic water level recessions will not cause significant harm to the community, unless they occur for long durations. In fact, the hydrologic restoration goal for the lake in the Comprehensive Everglades Restoration

Plan (USACE, 1999) is for fluctuations of lake levels between 12 and 15 ft NGVD, in as many years as possible (Havens, Manners, and Pace, 1998).

Results of recent observational and experimental research conducted by staff at the District and wetland ecologists at the US Army Corps of Engineers Waterways Experiment Station (USACE-WES) indicate that low water levels (<25 cm above the sediment surface) allow for rapid invasion of torpedograss. In the critical Moonshine Bay region of the Lake Okeechobee littoral zone, these low water levels occur when lake stage falls to 11 ft NGVD.

**Relationship between Lake Stage and Impacts to Fish and Wildlife.** Quantitative relationships between lake levels and significant harm impacts were evaluated in this study based on (a) output from a GIS model that relates flooding and drying of the littoral zone to lake stage, (b) information regarding fish and wildlife usage of different regions of the littoral zone and open water areas of the lake, (c) direct observations of changes in the littoral community during and after major drought events and (d) results of experimental research that relates exotic plant growth rates to water levels.

When lake levels drop to 11 ft NGVD, GIS models indicate that 94 percent of the littoral marsh is dry and no longer functions as aquatic habitat for fish and other aquatic-dependent wildlife, because water levels are at, or below ground surface (**Figure 14**). Certainly there is a loss of wetland habitat as lake levels decline over a wider range of depths, starting at 15 ft NGVD, when the entire marsh is submerged. However, it is when lake levels fall from 12 to 11 ft NGVD that critical spike rush and giant bulrush habitats become dry, and can no longer provide habitat for fish and other aquatic animals. When lake levels drop to 11 ft NGVD, the bulrush community also experiences competition with the nuisance plant cattail (C. Hanlon, personal communication), further affecting habitat quality for fish and other aquatic dependent species of wildlife.

Lake Okeechobee, the WCAs, and Everglades National Park represent important habitat for the federally-designated endangered snail kite. These areas are hydrologically interconnected by the C&SF Project and their water levels are strongly correlated (Bennetts and Kitchens, 1997). During a regional drought, loss of food resources (apple snails) due to drying of multiple habitats could represent a serious threat to the survival of the snail kite. Under these conditions the littoral zone of Lake Okeechobee, especially Moonshine Bay, may function as a habitat of last resort if water levels can be maintained above 11 ft NGVD.

When lake levels drop to 11 ft NGVD, the spike rush habitat of Moonshine Bay is exposed and becomes more susceptible to invasion by torpedo grass. Controlled experiments conducted at the University of Florida have shown that torpedo grass growth rates are significantly reduced by 30 cm. (1 foot) of standing water (Thayer and Haller, 1990). Growth is rapid when standing water occurs at the soil surface. In contrast, the native plant spike rush is a marsh species that thrives in Moonshine Bay with water depths up to 3 foot NGVD deep (K. Havens, communication).

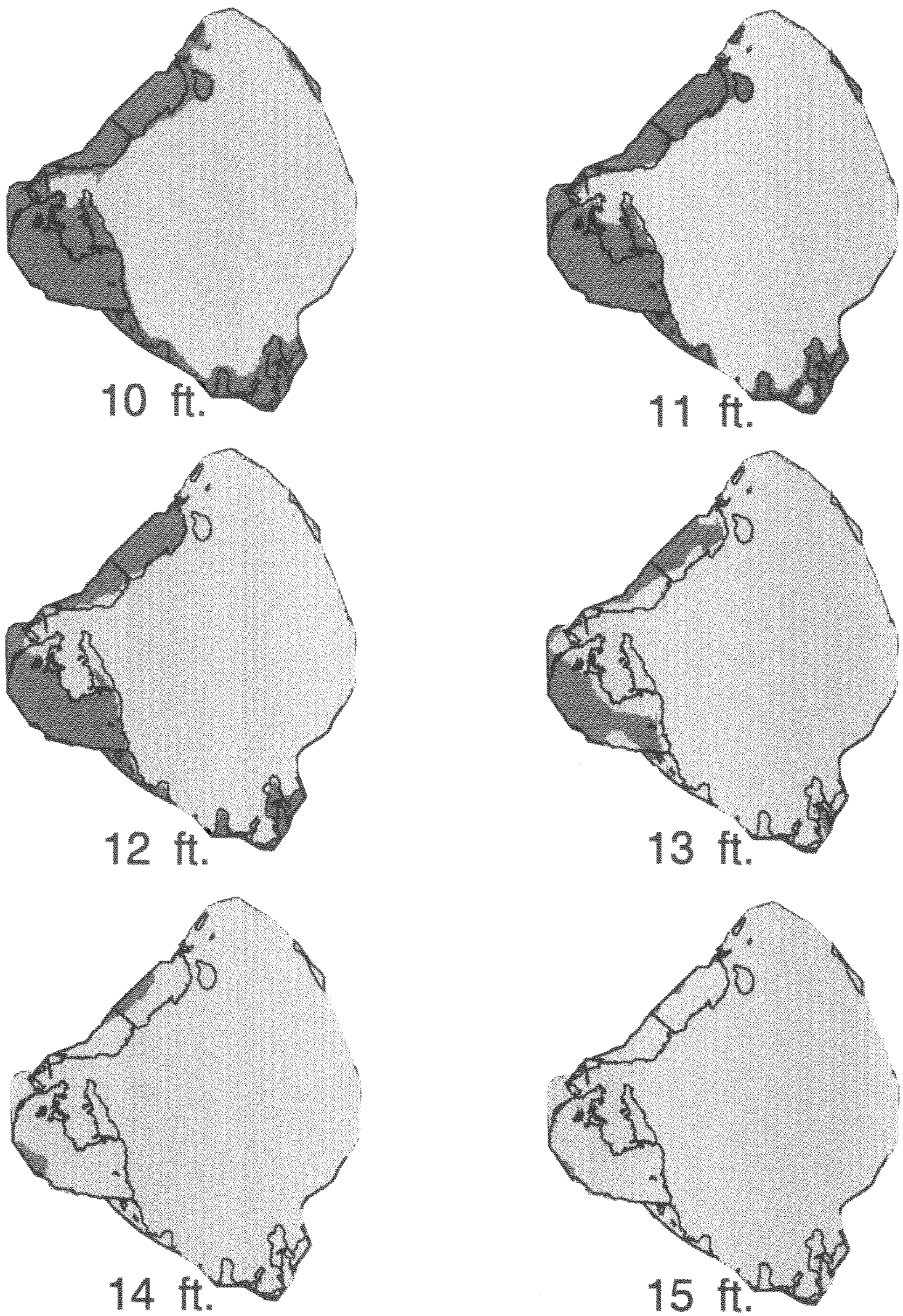


**Figure 14.** Exposed Land (indicated by dark gray areas) in Marsh Zones and Percentage of Total Marsh Zone Exposed for Six Water Level Conditions in Lake Okeechobee. At water levels below 10 ft NGVD and above 15 ft NGVD, there is 100 percent and 0 percent exposure, respectively.

Recent research conducted by the USACE-WES wetland ecology group supports the view that maintaining lake levels above 11 ft NGVD helps prevent the expansion of torpedograss within the littoral zone. That research also helped defined a water depth below which the risk of expansion is high. For the Moonshine Bay region of the lake's littoral zone that depth corresponds to a lake stage of 11 ft NGVD.

Changes in plant community structure in a nearby region of the marsh between 1997 and 1998 provide some evidence of how the Moonshine Bay community might be affected by several months of drying. In summer of 1997, low lake levels resulted in the drying of a large region of the southwestern corner of the littoral zone dominated by spike rush. This area was dry for approximately two months, during which time the soils became desiccated and devoid of living plants. Reflooding occurred in the fall of 1997. In summer 1998, District biologists noticed this region had developed a mixture of spikerush and torpedo grass. In contrast, torpedo grass did not appear to expand substantially in Moonshine Bay, which remained flooded with approximately one foot of water during the summer of 1997 (K. Havens and C. Hanlon, personal communications).

When lake levels drop to 11 ft NGVD, large areas of the marsh become available for colonization by melaleuca. After the 1989/90 drought, District scientists and aquatic plant managers observed a large increase in the density and areal extent of new melaleuca seedlings in the marsh, despite extensive management efforts to eradicate this exotic plant. Maintenance of standing water over the marsh may play an important role in limiting the expansion of this exotic plant within the littoral zone. This reflects the fact that melaleuca seedlings display little or no germination while submerged (Lockhart, 1995; C. Hanlon and D. Thayer, personal communications). Once the plants germinate, however, they are able to continue growth even if the soil is reflooded.

Based on the information presented above, Lake Okeechobee's littoral zone and associated fish and wildlife habitats are impacted when lake levels drop to 11 ft NGVD. Existing ecological information concerning the lake and its response to low water levels are not currently sufficient to establish a minimum duration and return frequency for the lake. A number of research projects have been proposed over the next several years to determine the response of littoral zone vegetation to various lake levels and hydroperiods. This research should provide the District with better information to define a biologically-based duration criterion. However a science-based criterion for return frequency will likely remain elusive, given the long-term (decades) nature of data that would be required to support that attribute.

**Relationship between Lake Stage and Navigation and Recreation Access.** The Okeechobee Waterway crosses South Florida from the Atlantic coast to the Gulf of Mexico via the St. Lucie Canal, Lake Okeechobee, and the Caloosahatchee River. The authorized project channel depth across Lake Okeechobee from Moorehaven to Port Mayaca is 8 feet deep when the water level in the lake is at 12.56 ft NGVD. Another channel, which follows the south rim canal from Clewiston to the St. Lucie canal, is 6 feet in depth when water levels are at 12.56 ft NGVD. When water levels fall to 11 ft NGVD, boat traffic along the Lake Okeechobee waterway is restricted to boats with drafts of four feet or less. This limits most sailboats more than 30 feet in length and most powerboats of more than 40 feet in length. At a lake elevation of 10 ft NGVD, the Lake Okeechobee Waterway is impassible to most fixed keeled sailboats. Recreational access within the lake is also limited, with virtually no access to the littoral areas.

# Proposed MFL Criteria for Lake Okeechobee

## Criteria Development

In an effort to address the often competing water resource functions of the lake (listed below) the following dual minimum water level criteria were developed for Lake Okeechobee. These criteria were developed based on a review of available scientific data summarized in this report, including the following:

- Review of the District's Supply-Side Management Plan for Lake Okeechobee (Hall, 1991)
- Ecological results of a five-year study of the lake (Aumen, 1995) and its response to changing water levels
- Results from a GIS model of the lake that was used to estimate the percent of the littoral zone that is dry or flooded at various lake stages
- Hydroperiod requirements of native wetland vegetation based on historic records of plant community structure and water level fluctuations in the lake
- Controlled experiments conducted by the USACE-WES that indicate rapid torpedograss expansion can be expected if the littoral zone becomes dry
- Navigation and boat access requirements

The following dual MFL criteria for Lake Okeechobee focus on achieving a balance among, and preventing significant harm to, four key water resources functions of the lake (not listed in priority order):

- Protect ecosystems that provide fish and wildlife habitat within the littoral zone,
- Provide water supply and storage for the LEC Planning Area,
- Protect the Biscayne aquifer against saltwater intrusion
- Providing navigation and recreational access to the lake during dry periods

**Table 3** provides a comparison of proposed minimum levels presented in this report for each of the above key water resource functions. Review of this information shows that significant harm, defined for each water resource function, occurs within the range from 11 to 10 ft NGVD. The top of Supply-Side Management Zone C as shown in **Figure 12**, from April 15 through July 15, represents the significant harm limit for protecting water supply during dry periods. The rationale for utilizing Supply-Side

Management is that when water levels fall below the top of Zone C, there is serious risk that not enough water can be stored in the lake to maintain a freshwater head within coastal canals to protect the Biscayne aquifer from the threat of saltwater intrusion (i.e., significant harm). In contrast, significant harm occurs to fish and wildlife habitat (i.e., the littoral zone) when lake stages recede below 11 ft NGVD anytime of the year. Finally, drawdowns of the lake below 10 ft NGVD result in significant restrictions to navigation and recreational use of the lake.

District staff reviewed the minimum water level criteria proposed for each of the four water resource functions presented above and integrated them into dual minimum water level criteria for Lake Okeechobee to manage water levels during periods of low rainfall. The dual criteria consist of an operational component and a longer term water supply planning component as presented below.

## Description of Criteria

Minimum water level criteria proposed for Lake Okeechobee consist of two components: operational and water supply planning criteria. Operational criteria are used to identify when the MFL has been exceeded on a day-to-day basis. Water Supply Planning Criteria provides water managers with information as to how often, and for what duration, the MFL may be exceeded based on the expected frequency of natural drought events. These criteria are defined as follows:

- Operational MFL Criteria - During most years, water levels in Lake Okeechobee should not fall below 11 ft NGVD. However, in order to make water deliveries from the lake to the LEC Planning Area, the water level in the lake may occasionally fall below 11 ft NGVD from April 15 to July 15 as long as it does not drop below the top of Supply-Side Management Zone C, as shown in **Figure 15**.
- Water Supply Planning MFL Criteria - The water level in the lake should not fall below 11 ft NGVD for more than 80 days duration, more often than once every six years, on average (This criterion was developed based on historical data because sufficient ecological data are not available--see discussions of *Minimum Duration and Return*

*Frequency* in the Lake Okeechobee Section of **Chapter 2** and *Operational* and *Water Supply Planning* MFL criteria below).

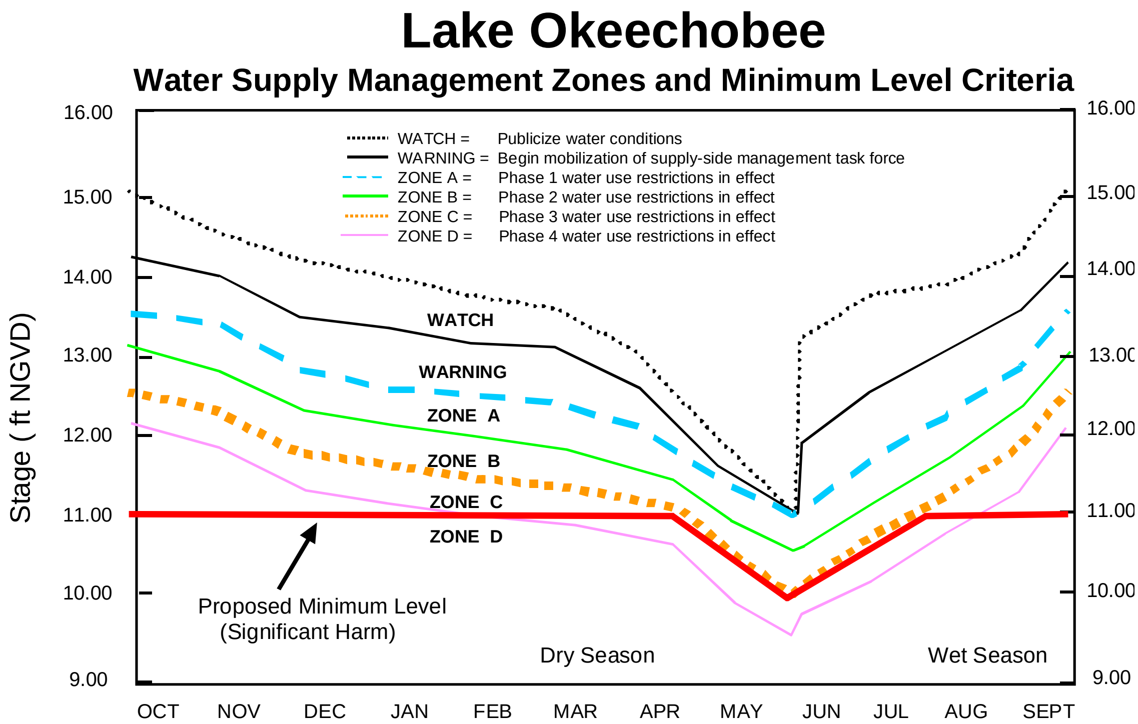


**Figure 15.** Proposed Minimum Level for Lake Okeechobee in Relation to Supply-Side Management Zones A through D.

### Operational MFL Criteria

From an operational standpoint, the proposed minimum level for Lake Okeechobee is 11 ft NGVD, except for the period of April 15 to July 15. During this 90-day period, the proposed minimum level for the lake is the top of Supply-Side Management Zone C, which is 11 ft NGVD on April 15, and may reach a minimum of 10 ft NGVD on May 31, and returns to 11 ft. on July 15 **(Figure 15**). The 11 ft. criterion was selected, in part, based on the need to provide a backup supply of water within the lake to protect the Biscayne aquifer from the threat of salt-water intrusion. This backup supply of water represents approximately one foot of water off the lake, between lake stages of 11 and 10 ft NGVD, or 327,000 ac-ft. of water as shown in **Figure 12**. During actual drought periods, the Governing Board has the flexibility to deliver Lake Okeechobee water as necessary to optimize protection of South Florida's water resources.

Review of historical data (see below) shows that water levels in Lake Okeechobee have generally remained above 11 ft NGVD (with two exceptions) from mid-July through the first two weeks of April. It should also be understood that, under current water shortage management practices, that if water levels begin to decline during drought conditions and fall below the top of Zone C or into Zone D, Phase 3 and Phase 4 water restrictions would be contemplated for users well before the minimum water level is reached. These restrictions are designed to keep the lake from reaching the designated level that may cause significant harm to the region's water supply or the ecological resources of the lake.

### Water Supply Planning MFL Criteria

The above operational criteria were developed to help water managers identify when the minimum lake level has been exceeded on a day-to-day basis. However, in the development of these criteria it was also recognized that if the lake fell below 11 ft NGVD every year, or once every several years, this would clearly have a major impact on both the ecology of the lake and its ability to function as a regional water storage facility. Therefore, for water supply planning purposes, the MFL must also include some kind of acceptable duration and return frequency criteria that account for regional drought cycles during which the lake may recede below 11 ft NGVD due to natural conditions.

Duration is defined as the number of consecutive days that water levels remain below 11 ft NGVD without causing significant harm to the water resource functions of the lake. Return frequency is defined as the acceptable number of years between these low water events (water levels falling below 11 ft NGVD). This information is needed by the District in its water supply planning process to account for the effects of natural drought cycles on lake water levels versus those caused by water supply withdrawals. These criteria will be incorporated into the District's ongoing water supply planning computer simulations to predict how well or poorly a specific water supply alternative performs over the long-term. Ideally, the duration and return frequency criteria should be based on scientific information obtained from ecological research on the lake.

Unfortunately, our current understanding of the ecosystem in not at a level that permits establishment of science-based criteria for these attributes. Until better scientific information is available, the District proposes to use the 1952-1995 historical period of record (period of time following construction of the Herbert Hoover Dike) to calculate an interim duration and return frequency component for the Lake Okeechobee MFL. The historical record (**Table 4** and **Figure 16**) shows that water levels fell below 11 ft NGVD a total of seven times over the 43-year period of record (once every 6.1 years) in response to low rainfall periods with an average duration of 82 days. Based on these data, the interim water supply planning criteria for Lake Okeechobee is water levels should not fall below 11.0 ft NGVD more often than once every 6 years (on average) with a duration no greater than 80 consecutive days.

# EVERGLADES

## Resource Functions

Minimum water level limits need to be established within the Everglades (the WCAs, Holey Land and Rotenberger WMAs, and Everglades National Park) to prevent the occurrence of extreme low water events that impact the sustainability of the

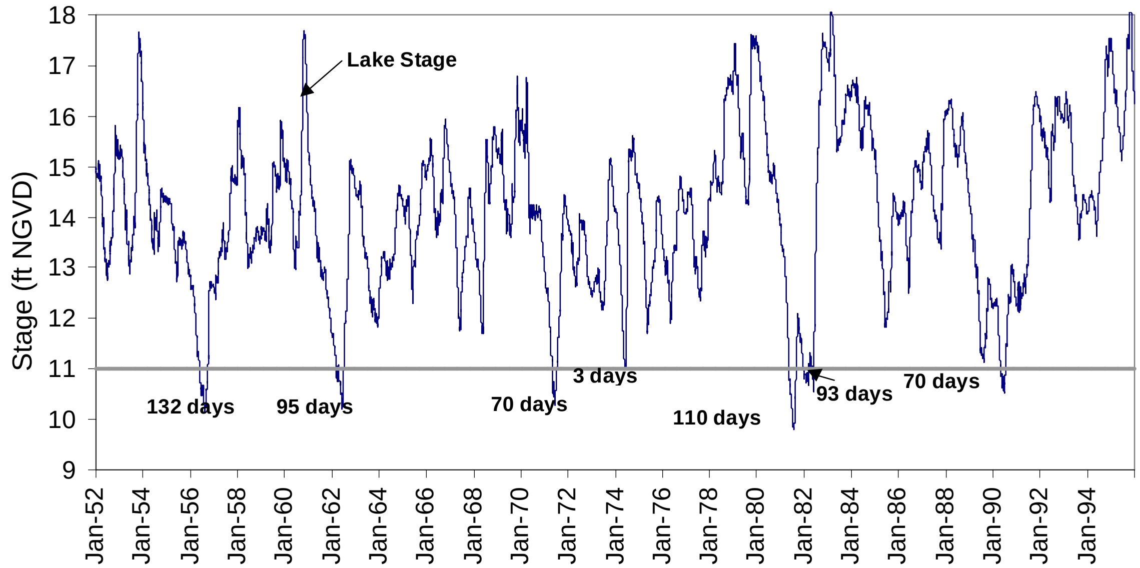


**Figure 16.** Hydrograph Showing Historical Lake Stage (1952-1995) and the Number of Times and Duration that Lake Stages Fell Below 11 ft NGVD

**Table 4.** Occurrences of Water Levels Below 11.0 ft NGVD, Based on the 1952-1995 Historical Period of Record

| No. Times Water Levels Below 11 ft NGVD | Return Frequency (years) | Average Duration Below 11 ft NGVD | Dates Criteria Were Exceeded |
|---|---|---|---|
| 7 | once every 6.1 years | 82 days | 1) May 26 - Oct. 5, 1956 (132 days)<br>2) April 4 - June 29, 1962 (95 days)<br>3) April 30 - July 8, 1971 (70 days)<br>4) May 31 - June 2, 1974 (3 days)<br>5) May 13 - Aug. 30, 1981 (110 days)<br>6) Jan. 2 - May 26, 1982 (93 days)<br>7) May 4 - July 12, 1990 (70 days) |

ecosystem. The following six water resource functions were considered in the development of minimum water level criteria for the Everglades:

- Provide ground water recharge to prevent saltwater intrusion of the Biscayne aquifer, South Florida's primary drinking water source
- Provide hydropatterns that will support Everglades food chains, substrates and habitats necessary to support wildlife, including threatened and endangered species
- Provide natural biological filtering and nutrient cycling -- trapping suspended solids and metals in sediments, detritus and living tissue,

and converting dissolved nutrients derived from rainfall, decomposition and soil oxidation into biomass.

- Provide aquatic refugia for Everglades fish, amphibians, aquatic invertebrates, and other wildlife during droughts
- Provide an Everglades ecosystem that is not degraded due to invasion by terrestrial woody vegetation and introduced exotics such as melaleuca
- Provide water flows that maintain salinity regimes and ensure survival of plant and animal communities in coastal estuaries

As noted previously, overall restoration goals for the Everglades are presently being established by the Comprehensive Everglades Restoration Plan, because this is an ongoing process. There is a potential for conflict in some areas between water levels that are established to achieve restoration and the water levels proposed in this document that are designed to prevent significant harm. As restoration goals for particular areas change or are modified over time, proposed MFLs may also be adjusted to ensure consistency.

## Technical Relationships Considered in Defining Significant Harm

### Importance of Hydric Soils

Protection of hydric soils (organic peat and marl) was selected as a criterion for Everglades ecosystems because of the following:

- More than 90 percent of the soils of the Everglades are comprised of either peat or marl.
- Almost all of the plants and animals that inhabit the Everglades region depend, at least in part, on the hydrologic regime that produces hydric soils. Therefore, maintenance of a hydrologic regime which protects hydric soils will also help protect other water resource functions of the Everglades such as providing fish and wildlife habitat.
- Establishment of minimum water levels will help protect the resource from overdrainage which results in soil oxidation, and fires which consume peat, lower ground elevations, impact wetlands, tree islands and wildlife communities.
- Preservation of hydric soils helps to maintain the freshwater head in the Everglades and therefore is important for maintaining ground water flows to the east (to help prevent saltwater intrusion of the coastal aquifer) and to the south to help maintain ground water base flows to South Florida's estuaries.

Based on technical information provided in this document, District staff have concluded that excessive drying of hydric soils (marl and organic peat), which leads to soil oxidation and subsidence, impacts Everglades plant and animal communities and constitutes harm to the resource that could require many years (decades or perhaps centuries) to recover. Water level reductions below those that would normally occur, may allow organic peat soils to dry out, oxidize, and burn more often, or more severely than would occur during normal dry season conditions. Continual destruction of soils disrupts or destroys the overlying plant communities that provide food, shelter, and habitats for Everglades fish and wildlife. Continual loss of these soils threatens both the integrity and sustainability of the Everglades ecosystem. Although the exact conditions that make it possible for peat soils to oxidize at a significant rate or burn excessively are not completely known throughout the region, the proposed criteria are based on best available data from a number of different sources. The attempt has been made to define conditions where increased soil losses are more likely to occur. Whereas one or more inches of peat may oxidize during a very dry year and many inches or feet of peat may be lost during a severe fire, even under ideal condition, peat soils accrete at a very slow rate of about 0.04 to 0.06 inches per year.

## Relationship Between Protected Functions and Everglades Soils

In its original condition, the Florida Everglades represented the largest single body of organic soils in the world, covering over 3,100 square miles (Stephens, 1984). Formed under anaerobic, waterlogged conditions, these soils began to subside as wetlands were drained and developed. Subsidence is caused primarily by drainage, biochemical oxidation, compaction, and burning of organic soils. Agricultural development south of Lake Okeechobee has substantially reduced ground water levels within the EAA. Some areas have recorded peat losses of up to 5 to 6 feet (Stephens, 1984). Significant lowering of ground level elevations has also occurred in the Everglades, primarily along major drainage canals (**Figure 17**). In the natural system, Everglades peat functioned as a regional freshwater sponge, absorbing rainfall and creating a hydrostatic head higher than what is currently maintained in the system today (Stephens, 1984). Prior to development, ground water flows to the coast occurred from recharge areas located behind the coastal ridge (Parker et al., 1955). Once areas behind the ridge were drained for development, regional ground water flows to the east coast became governed by ground water heads maintained in the Everglades. These flows move primarily eastward from the Everglades to the LEC Planning Area via ground water or the regional canal network and help stabilize the freshwater-saltwater interface (Fish and Stewart, 1991). The continued loss of peat resources in the Everglades, and associated loss of freshwater head, has the potential to further reduce ground water flows to the east and thus increase the threat of saltwater intrusion during drought periods. Saltwater intrusion into coastal wellfields has been the chief threat to South Florida's water supply since drainage activities began in the early 1900s (Stephens, 1984). Providing adequate minimum water levels in the Everglades during low rainfall years is important to preserve peat resources and future water supplies.

## Everglades Water Levels and Soil-Plant Community Relationships

### Peat Formation and Soil Loss in the Everglades

Peat is formed in the Everglades from remains of either slough vegetation (Loxahatchee peat), or sawgrass (Everglades peat) communities. Deep water (up to two

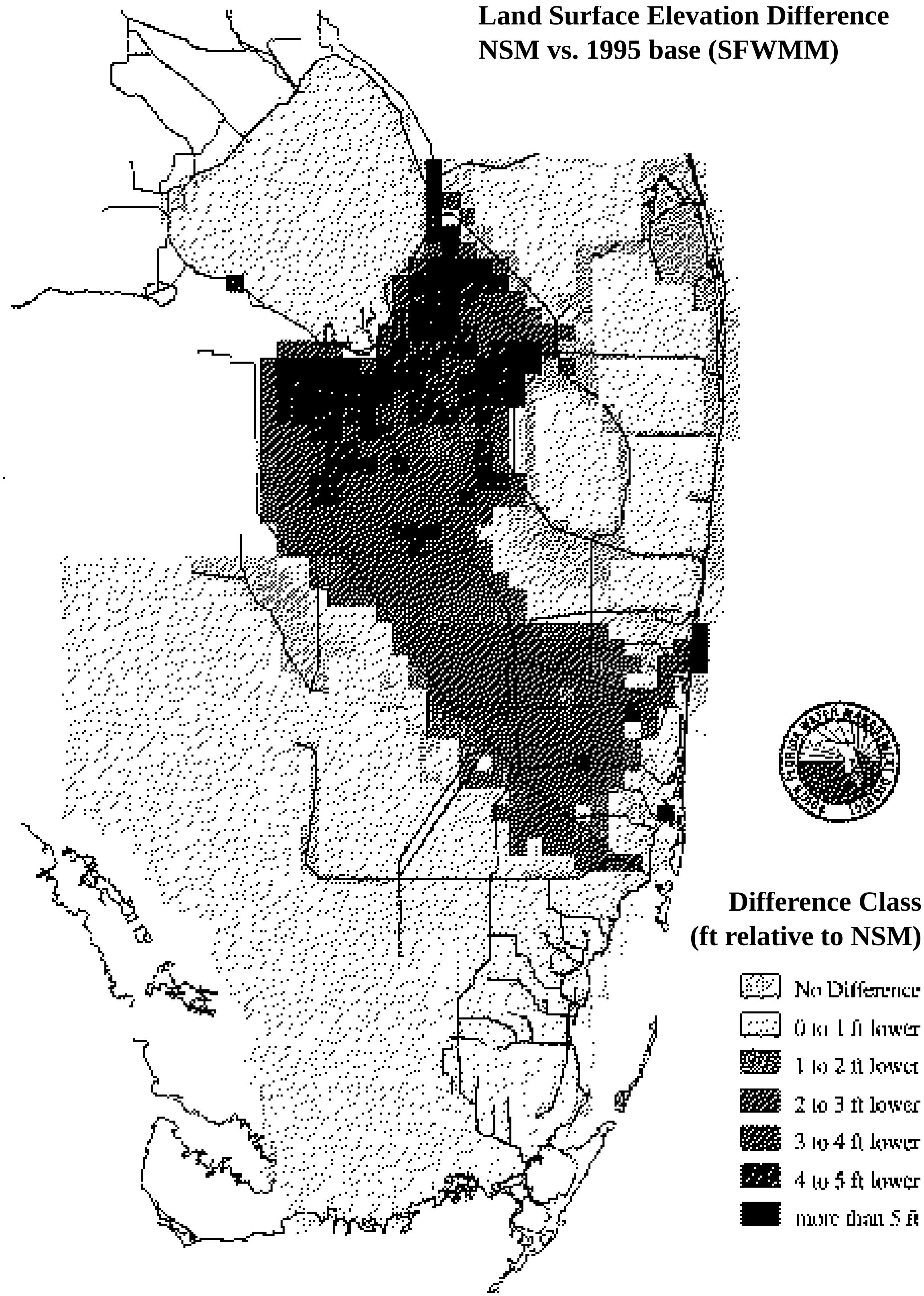


**Figure 17.** Soil Subsidence in the Everglades Region of South Florida.

feet deep) and long hydroperiod conditions tend to favor the formation of Loxahatchee peat, while shallower water depths and shorter hydroperiods favor the production of Everglades peat (Gleason and Stone, 1994; Tropical BioIndustries Inc., 1990). Based on soil surveys conducted by Jones (1948), Loxahatchee peat was found primarily in WCA-1, the northern portion of WCA-2A, western WCA-3A, WCA-3B, and the Shark River Slough region of Everglades National Park. Everglades peat was found primarily in southwestern WCA-2A, northeastern WCA-3A, northern WCA-3A and in the Holey Land and Rotenberger WMAs. **Figure 18** (adapted from Jones, 1948) shows the distribution of the major hydric soil types (Loxahatchee peat, Everglades peat, Perrine marl, Ochopee marl, and Rockland marl) found in the Everglades during the mid-1900s. The map of hydric peats is superimposed on a present day map of the hydrologic infrastructure, to show the relationship of the location of present day canals to associated water management gauges.

Formation of peat soils requires near permanently flooded or saturated soils with water depths averaging 1.5 to 2.0 feet deep and a hydroperiod of at least 9 to 10 months duration. Dry season water table recessions should not exceed more than one foot below ground for more than 30 days during a dry year. Under these conditions, surface peats remain saturated due to capillary action, pulling moisture from the underlying ground water table to provide aquatic plants and burrowing organisms with enough soil moisture to survive dry periods. Although water levels may occasionally drop more than one foot or more below ground during a major dry period, slough aquatic plants quickly recover from buried tubers, seeds, and other resting plant structures (Tropical BioIndustries Inc., 1990).

Peat accretion is a fundamental process that is needed to maintain a functioning wetland system. Average peat accretion rates in the Everglades range from 0.04 to 0.06 inches/year (Davis, 1946; McDowell et al., 1969) to 0.11 to 0.13 inches/year for WCA-3A and WCA-2A, respectively (Richardson and Craft, 1990). There is a large body of evidence indicating that construction and operation of the C&SF Project has altered the hydrologic regime of historic soil-plant communities. In many areas of the Everglades, reduced water levels and shortened hydroperiods have reversed the process of peat accretion, resulting in the oxidation of organic soils and lowering of ground level elevations. This process is called soil subsidence. Numerous studies have reported the results of extreme droughts within the Everglades system and their effects on organic soils, plant communities, and wildlife (Loveless, 1959; Craighead, 1971; Schortemeyer, 1980; Wade et al., 1980; Zaffke, 1983; Alexander and Crook, 1984; Hoffman et al., 1994; Gunderson and Snyder, 1994). For example, during the 1981 drought, water levels in northern WCA-3A receded 2-3 feet below ground for five months. During this and similar droughts, wildfires burned the roots out from under tree islands and exposed bedrock, resulting in peat losses of more than one foot over large areas of WCA-3A (Loveless, 1959; Schortemeyer, 1980; Zaffke, 1983).

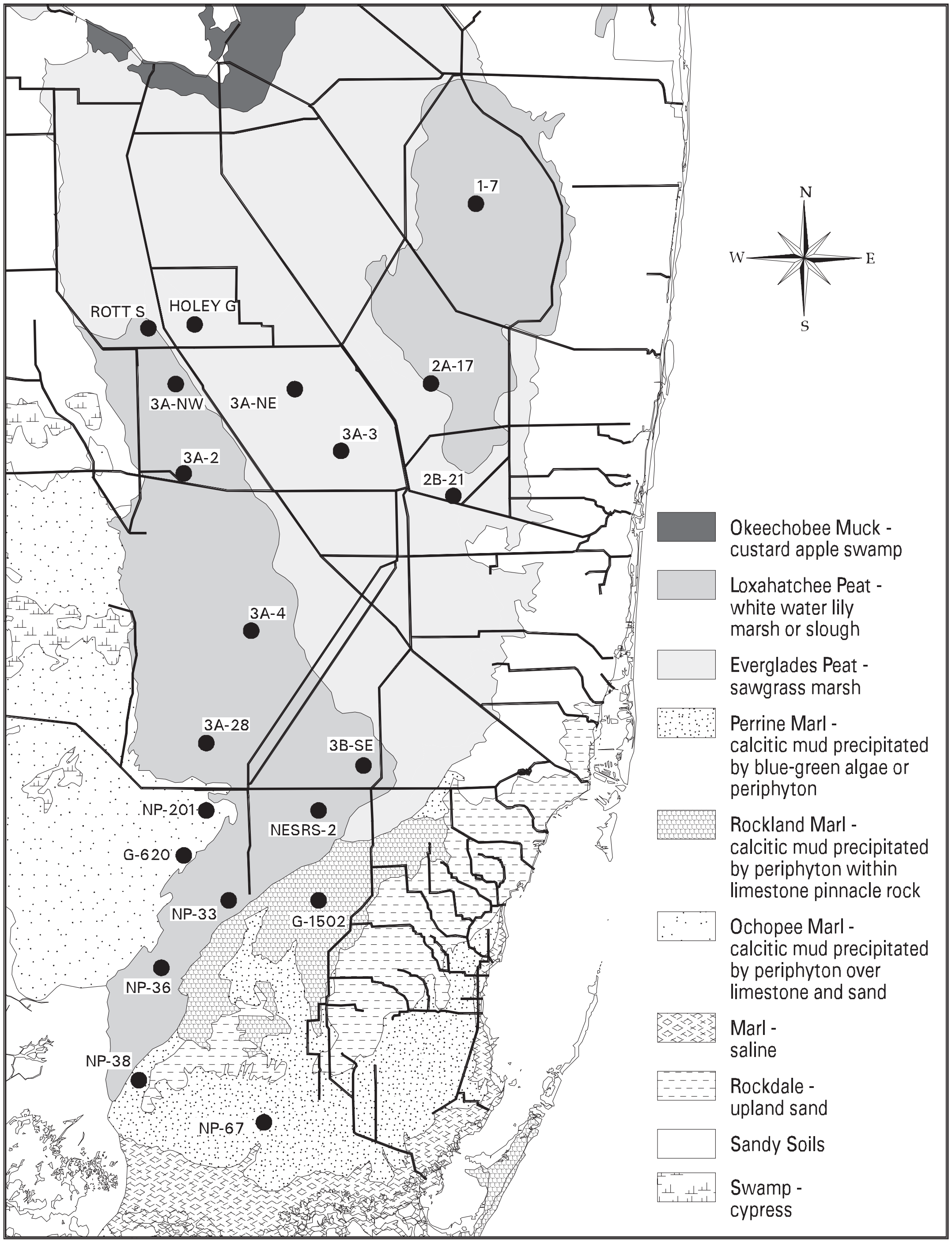


**Figure 18.** Spatial Distribution of the Major Hydric Soil Types within the Everglades in Relationship to the Key Water Management Gauges.

Results of a computer analysis are shown in **Figure 17**, indicating the differences in ground level elevations between predrainage conditions that were simulated by the Natural Systems Model (NSM), and present day conditions, as simulated by the South Florida Water Management Model (SFWMM). The greatest amount of soil subsidence, more than five feet in some areas, has occurred in the highly managed EAA, located south of Lake Okeechobee. Major losses within the WCAs occur primarily near the subsidence valleys that are located along major canals, the northern portion of WCA-3A, the southwest portion of WCA-2A, and northern WCA-3B (**Figure 17**). These data correlate well with recorded peat losses within the EAA (Stephens, 1984) and northern WCA-3A (Schortemeyer, 1980; Zaffke, 1983), where soil oxidation and muck fires have impacted wetland vegetation and wildlife communities. The largest peat losses occurred on tree islands, resulting in the permanent destruction of wildlife habitat. Hoffman et al. (1994) also reported the effect of fires and extensive peat losses in WCA-3A resulting from major drought events. Loss of these soils and their associated parent plant communities as a result of low water levels and reduced hydroperiods are a concern for several reasons:

- Under typical conditions, it takes from 200 to 300 years to produce one foot of peat soil. Best available data indicate that in many areas of the Everglades, peat soils are being lost from the system faster than they accumulate. The system is therefore not sustainable under the current hydrologic regime.
- Increased frequency of severe fires, which consume peat and damage Everglades plant communities and associated wildlife habitat, can result in ecological impacts that last from 3 to 10 decades (DeAngelis, 1994). These long-term changes represent significant harm to the Everglades ecosystem.
- Continued subsidence of organic soils and the associated loss of freshwater head will, over time, reduce the overall amount of water available in the regional system to protect coastal aquifer resources against saltwater intrusion, and maintain downstream estuarine communities within Florida Bay.

### Marl Deposition

Marl soils or calcitic muds are formed by the precipitation of calcite by blue-green algae in submerged algal mats (periphyton) under shallow water conditions. Marl soils form primarily in areas that receive runoff that contains high calcium carbonate concentrations derived from the weathering of underlying limestone formations. Marl formation in the Everglades requires water depths averaging approximately 8 to 9 inches and a hydroperiod lasting from 7 to 10 months (Tropical BioIndustries Inc., 1990). Dry season water table recessions should not fall more than 1.5 feet below ground during a dry year (T. Armentano, Everglades National Park, personal communication). These minimum values are derived from the fact that average soil depths within the Rocky Glades, northern Taylor Slough and several other marl forming regions of Everglades National Park range between 1.0 and 1.6 feet deep. Although marl has fine texture and is highly efficient in wicking ground water to the surface, this capillary action is lost once the water table recedes into the underlying limestone substrate. Under these conditions, marl soils quickly dry out and represent one of Florida's driest environments with a water content as low as three percent, well below the tolerances of most wetland plants (Davis, 1943b). Therefore, the minimum depth that water may recede during the dry season and still allow surface marl soils to maintain capillary connections to the underlying ground water table is approximately 1.5 feet below ground.

Another important feature of marl-forming wetlands in the Rocky Glades area of Everglades National Park is the presence of thousands of solution holes formed by erosion of the karst landscape. These shallow potholes serve as important dry-season aquatic refugia for crayfish, fishes, amphibians, reptiles, and aquatic invertebrates during drought periods (Loftus et al., 1992). The majority of these solution holes range between 0.5 and 1.5 feet in depth. Prior to drainage of the eastern portion of Everglades National Park by canals, these solution holes were filled with water and aquatic organisms at the onset of the dry season (October through November) and provided food for wading birds and other wetland predators (Loftus et al., 1992). Under current conditions, the majority of these solution holes no longer retain water during the dry season and dry out completely during droughts. When water depths recede 2.0 feet or more below ground, aquatic food, consisting of fishes, amphibians, and invertebrates, are no longer available to upper trophic level consumers. Lack of aquatic refugia also means that the wetlands take longer to recolonize when water levels are restored (Loftus et al., 1992). Loss of this early nesting season feeding habitat and the disruption of the timing of prey abundance within Everglades National Park has been strongly implicated in the decline of wading bird nesting success in the southern Everglades (Beard, 1938; Loftus et al., 1992). Loss of marl soil habitats to drainage and development along the eastern edge of Everglades National Park has reduced the areal extent and quality of these early nesting season feeding sites. For these reasons, a dry season recession of no more than 1.5 feet below ground, for no more than 90 days was selected as the minimum water depth and maximum allowable duration that would protect marl soils and their associated vegetation and aquatic fauna from adverse impacts due to drainage.

## Effects of Low Water Levels on Plant Communities and Wildlife Habitat

In addition to loss of peat soils, long-term reductions in water levels and shortened hydroperiods within the remaining Everglades have been found to reduce aquatic primary productivity, alter Everglades wildlife habitat by allowing terrestrial woody vegetation or introduced exotics to replace herbaceous wetland communities, and change the abundance and distribution of Everglades wildlife. In terms of areal extent, lowering of the water table and excessive drainage of the Everglades have probably impacted much larger areas of wetland habitat than the areas currently affected by nutrient enrichment.

### Reduction in Primary Productivity

When wetland hydroperiods are reduced, the species composition of a major component of the Everglades food web (periphyton algae) is changed and aquatic productivity per unit area is reduced (Browder, 1981). Shortened hydroperiods and reduced productivity decrease the ability of these wetlands to maintain adequate populations of forage fish and invertebrates that support higher trophic level organisms such as wading birds. Loss of suitable feeding habitat during low rainfall years, and the carry-over effect of increased drought frequency on the overall system, are considered to be major factors that have been responsible for the decline of Everglades wading bird populations (Robertson and Kushlan, 1984; Ogden et al., 1987).

#### Changes in Distribution and Abundance of Wetland Plant Communities

In addition to reduced productivity, over drained areas of the Everglades commonly experience shifts in plant composition as wet-adapted organisms are replaced by species that are more tolerant of drier conditions including introduced exotics (Gunderson and Loftus, 1993). Vegetation studies summarized by Davis et al. (1994) over the past 20 years have shown a 13 percent loss in the coverage of wet prairie/slough communities and a similar gain (11 percent) in sawgrass over the same time period. These changes appear to be closely linked to the effects of lowered water levels, altered hydroperiods, and interrupted flows caused by drainage activities associated with construction and operation of the C&SF Project (Davis et al., 1994).

#### Changes in Wildlife Abundance and Distribution

Loftus et al. (1992) provided evidence that lowering of ground water levels and repeated drying of the Rocky Glades east of Shark River Slough and Taylor Slough have reduced the ability of these wetlands to serve as dry season aquatic refugia for Everglades fish and alligators. Severe drying of the southern Everglades may have also reduced the biomass of Everglades forage fish per unit area as compared to the predrainage system (Loftus and Ekland, 1994).

### Fire

Fire is a natural force that has shaped the Everglades ecosystem. Periodic fires prevent the natural succession of fire adapted species such as sawgrass or maidencane to woody or brush vegetation. Communities maintained by fire are called fire subclimax communities. Conversely, severe fires that consume peat and damage wetland plant communities can result in ecological impacts that last from 3 to 10 decades (DeAngelis, 1994). Therefore, a potential increase in the frequency of severe fires within the Everglades relative to historic conditions is of concern.

Ecologists have examined the effects of extreme drought and fire on Everglades soils and the implications to vegetation and wildlife (Loveless, 1959; Craighead, 1971; Schortemeyer, 1980; Wade et al., 1980; Zaffke, 1983; Alexander and Crook, 1984; Gunderson and Snyder, 1994). Soil losses due to fire are relatively minor when water levels are above or near ground level. Cornwell and Hutchinson (1974) reported that Everglades fires which occur during normal hydroperiod cycles, when water levels do not recede below ground more than 4 to 5 inches, appear to have little effect on the dominant plant community. When water depths recede 1.5 to greater than 2.0 feet below ground, the peat becomes dry enough to burn (Stephens and Johnson, 1951). Under these conditions, peat fires consume the organic substrate as well as the roots of normally fire resistant plants resulting in a lowering of the soil surface and conversion to a different vegetation community, such as from aquatic slough to sawgrass (Alexander and Crook, 1973; Gunderson and Snyder, 1994). Vegetation and wildlife studies conducted in WCA-3A have shown peat fires to cause soil losses of up to one foot, with tree island communities burned down to bedrock, and subsequent loss of wildlife (Schortemeyer, 1980; Zaffke, 1983).

Incidence of severe fires in the Everglades in recent history has been qualitatively summarized and, where data were available, linked to drought periods (Robertson, 1953; Wade et al., 1980). Spatial and temporal fire patterns have been analyzed (Taylor, 1981) and ranked according to cycle dominance (Gunderson and Snyder, 1994); however, no study has been conducted to determine the effect of water management (artificially lowering water levels) on fire regimes (Wu et al., 1996).

**Figure 19** and **Table 5** provide a summary of the effects of several documented peat fires in the Everglades, as well as a summary of the hydrologic conditions preceding each fire (Gleason and Stone, 1974; Zaffke, 1983; FFWCC, unpublished data). Time series hydrologic data from gauges in WCA-3A were selected for their proximity to each fire. The best available stage data for the period from January 1973 to August 1990 were analyzed to determine the depth and duration that water levels declined below ground preceding each fire.

**Table 5.** Location, Extent, and Antecedent Water Conditions for Documented Historical Fires within WCA-3A.

| Nearest Gauge | Date of Fire | Observed Location (x's) | Observations | Max. Depth (ft) | Duration (days) |
|---|---|---|---|---|---|
| 3A-3 | March 1973 | East of Miami Canal, north of Alligator Alley | Large areas denuded of vegetation; bedrock visible, large tree islands destroyed (Gleason and Stone, 1974) | -0.5 | 50 |
| 3A-4 | June 1981 | South of Alligator Alley, east of the Miami Canal | Peat losses average 3.6 inches, Maximum soil loss up to 11 inches (Zaffke, 1983; FFWFC personal communication, 1993) | -0.9 | 30 |
| 3A-11 | March 1989 | NW corner of WCA-3A west of Miami Canal | (FFWCC personal communication, 1993) | -0.4 | 30 |
| 3A-3 | August 1990 | East of Miami Canal, north of Alligator Alley | Damage primarily to tree islands only (FFWCC personal communication, 1993) | -1.1 | Not determine d |
| 3A-11 | April 1999 | NW corner of WCA-3A, west of Miami Canal | Peat losses of 4 to 6 inches, max. soil loss up to 12 in., damage to willowheads and wildlife (SFWMD, 1999) | -1.8 | 33 |

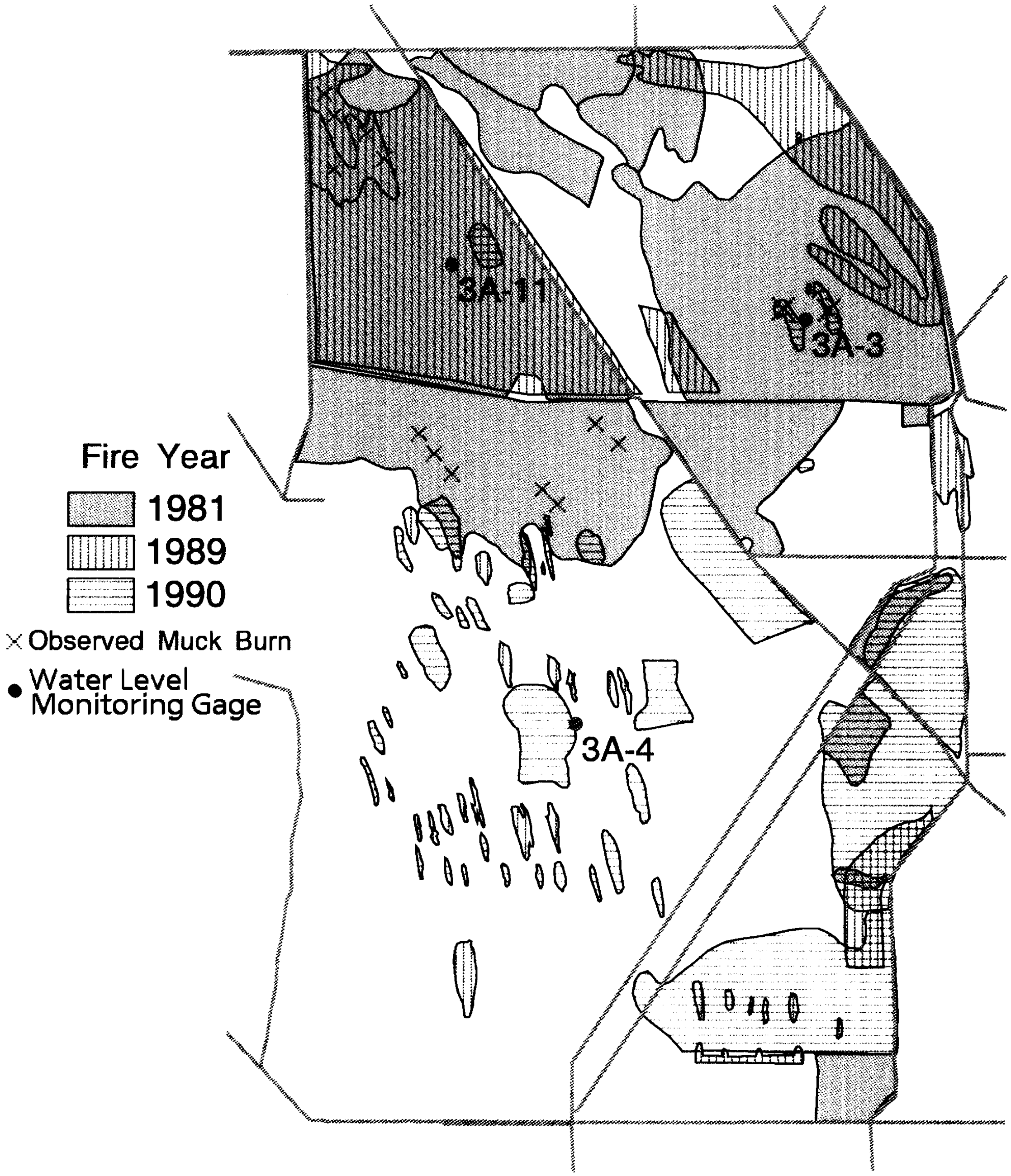


**Figure 19.** Location, Extent and Antecedent Water Conditions for Documented Historical Fires within WCA-3A.

Review of these data suggests that when water levels recede -0.4 to -1.8 feet below ground for a duration of 30 to 50 days, there is a significant risk that an intense fire may occur in the area, cause loss of peat soils, and impact tree islands and wetland plant communities. These results are within the range reported by Loveless (1959), who noted that “fires, which occur during normal hydroperiod cycles when water levels do not recede more than four or five inches below the surface of the ground, seemingly have little effect on dominant plant communities.” However, during extreme drought periods when water levels recede 3 to 4 feet below ground, fires not only consume the vegetation, but also destroy the upper, dry, compacted peat layers to a depth of 3 to 4 inches over large areas, and up to a foot or more in localized situations (Loveless, 1959). **Figure 19** also suggests that the amount of peat that can be consumed is related to water depth at the time of the fire. For example, during the June 1981 fire (Zaffke, 1983), the maximum amount of peat consumed was 11 inches which directly corresponds to the depth of the water table at the time of the fire (-0.9 feet or 11 inches below ground).

## Water Level Criteria for the Everglades

### Water Supplies for Sustaining the Everglades

The hydropattern and water quantity restoration goals for the Everglades will require a multifaceted approach, with the ultimate goal to create a sustainable ecosystem. Restoration and protection of the resource will be achieved by using the full range of options that are available to the agency, including design and construction of new facilities, water resource and water supply development projects, operation of new and existing facilities, and regulatory programs for water supplies during drought and non-drought conditions.

The resource protection framework for ensuring sufficient water supplies to sustain water resources, such as the Everglades, is depicted on **pages 7-9** of this document. This framework contemplates the use of water reservations to protect fish and wildlife; consumptive use permit criteria to protect water supplies from harm during non-drought conditions; and the use of minimum flows and levels and water shortage restrictions to manage water supplies during drought conditions by reducing the potential for significant harm and serious harm to the water resources. Each of these state water resource protection standards must be developed and implemented together to achieve the hydropattern restoration goals for the Everglades.

The Comprehensive Everglades Restoration Program (CERP) identifies projects and water supplies needed to achieve Everglades hydropattern restoration. In the CERP, the “restored” Everglades is primarily defined as the ecosystem that will exist when the completed CERP recommendations are in place in 2050, as described in Section 5.7 of the Final Integrated Feasibility Report (USACE 1999, p. 5-35). The specific hydropattern goals for the Everglades were identified as the hydrologic performance of the system in alternative “D13R” as modeled by the SFWMM (USACE 1999, Chapter 9). The D13R simulation defines Everglades water needs for the range of rainfall and drought conditions that occurred during the 31-year SFWMM calibration period.

## Water Supplies for Preventing Harm -- Everglades "No Harm" Standard

Minimum flows and levels are just one of the essential components of the resource protection framework being developed for the Everglades as part of LEC planning process. In order to assure ecosystem sustainability and achieve restoration, it is also essential to define the "no harm" conditions for the Everglades. Harm under the proposed resource protection framework is considered to be changes in the hydrology that cause short term (seasonal) adverse affects to water resource functions. Water resource functions to be protected from harm are based on the Everglades ecosystem restored under the CERP, as discussed previously in this document.

As shown in **Figure 1** in Chapter 1, "no harm" levels differ from the "significant harm" minimum levels. As a result, the "no harm" water demands, which account for a specific level of protection to sustain the restored system, are established under a separate legal directive. The protection standards associated with preventing harm are higher than those identified for significant harm, or MFLs, which should only occur during more extreme drought conditions. The Lower East Coast Regional Water Supply Plan (LECRWSP) recommendations will be implemented to achieve this level of protection. The no harm standard will be implemented using the full range of options that are available to the agency as stated above. In terms of allocating water, this standard helps to define water availability for use during normal to moderately dry conditions, including a 1-in-10 level of drought. Beyond the 1-in-10 year drought conditions, the Everglades MFL and associated water shortage restrictions will be used, in part, to prevent significant harm and serious harm to the Everglades resource functions.

For purposes of the LECRWSP, which has a 20 year planning horizon, specific Everglades "no harm" standards will be derived from SFWMM simulations for the year 2020 that include implementation of the CERP projects. It is anticipated that by 2020, most of these projects will be complete, except for 50% of the Lakebelt project features (without the completed Lakebelt project, MFLs cannot be fully met in Everglades National Park). A goal of the LECRWSP is to identify water supplies available under this model scenario and tools to provide and protect required water supplies, based on the resource protection framework discussed above.

### Everglades Significant Harm Standard

Most of the Everglades hydric soils lie directly above the Biscayne aquifer. Water levels observed in the Everglades (either above or below ground surface) can also be thought of as a surface expression of the Biscayne aquifer water table. Therefore, minimum water levels proposed for the Everglades are also minimum levels for the Biscayne aquifer where it underlies Everglades peat or marl soil west of the north/south perimeter levee.

Based on the information presented previously, minimum water level criteria were developed to protect Everglades soils, wetland vegetation, wildlife habitat, and regional ground water supplies by preventing the loss of hydric soils within the remaining Everglades system. Minimum criteria developed for the Everglades were designed to protect the above water resource functions by preventing the loss of hydric soils. Hydric soils (freshwater peat and marl) were selected for the following reasons:

- Peat and marl are the primary soils that characterize the Everglades. More than 90 percent of the remaining Everglades are comprised of these soils.
- Peat and marl soils sustain all of the major plant associations (sawgrass marshes, sloughs, wet prairies, and tree islands) and animal communities that characterize the Everglades.
- Review of the literature indicates that both of these soil types are reliable indicators of past hydrological/biological conditions within the Everglades.
- Sufficient data concerning historical and present day soil conditions exist that can be used as a reasonable basis for setting initial minimum water level criteria for the Everglades (Tropical BioIndustries Inc., 1990).

**Figure 18** shows the spatial distribution of the major hydric soil types within the historic Everglades in relation to key water management gauges. The proposed criteria are based on the rationale that ground water drawdowns and durations greater than those recommended will cause significant harm to hydric soils and their associated Everglades vegetation and wildlife communities. The numerical values for the proposed criteria were determined based on the following:

- A review of available literature that describes the hydrologic conditions necessary to sustain hydric soils and their parent wetland plant communities within the Everglades
- Comparison with historical water levels and fire records
- Comparison with simulated water levels derived from output of the NSM 4.5 during drought years.

## Definition of Terms

The proposed criteria consist of four components: a minimum water depth, duration of the event, frequency of occurrence, and potential for causing significant harm to the environment. These terms are defined below:

- <u>Minimum Water Depth</u> - The lowest water level which, if maintained for a specified period of time, is sufficient to protect Everglades water resources, soils, and plant and animal communities from significant harm during periods of deficient rainfall.
- <u>Duration</u> - The estimated period of time that water levels can remain below ground at the specified minimum water depth without causing significant harm to Everglades water resources, soils, and plant and animal communities.

- Frequency of Occurrence - The average periodicity that ground water levels recede to minimum levels over a prescribed period of time (e.g., once every five years). If minimum water level conditions recur more often than the stated criteria, the risk of significant harm to Everglades soils, vegetation, and wildlife predator/prey relationships are greatly increased.
- Significant Harm - Significant harm is defined as a loss of specific water resource functions that take multiple years to recover which result from a change in surface water or ground water hydrology. For the Everglades, adverse impacts include peat oxidation, increased frequency of severe fires, soil subsidence and loss of hydric soils; loss of dry season aquatic refugia; loss of tree island communities; long-term loss or change in wetland vegetation; and long-term loss or change in the distribution and abundance of wildlife communities. Once such changes have occurred, many years, decades or perhaps centuries may be required to restore these resources to their former condition.

## Criteria for Protection of Peat Soils and Associated Wetlands

To prevent significant harm to the water resources as indicated by loss of peat soils and associated wetland plant communities, the following minimum water level criteria are proposed for the peat-forming areas of the Everglades:

*Water levels within wetlands overlying organic peat soils within the WCAs, Rotenberger/Holey Land WMAs, and Shark River Slough (Everglades National Park) should not fall 1.0 feet or more below ground level for more than 30 days duration, at return frequencies not less than those shown in* ***Tables 6*** *and* ***7****.*

**Table 6.** Minimum Flows and Levels Criteria for Organic Peat and Marl-Forming Soils Located within the Remaining Everglades.

| Area | Soil Type | Depth below ground (ft.) | Duration below ground (days) | Allowable Return Frequency (years) |
|---|---|---|---|---|
| WCAs | Peat | 1.0 | 30 | 1-in-4 to 1-in-7[a] |
| Holey Land and Rotenberger WMAs | Peat | 1.0 | 30 | 1-in-2 to 1-in-3 |
| Shark River Slough (Everglades National Park) | Peat | 1.0 | 30 | 1-in-7 to 1-in-10 |
| Marl-forming wetlands located within Everglades National Park | Marl | 1.5 | 90 | 1-in-2 to 1-in-5 |

a. Return frequency depends on location relative to a specific water management gauge. See **Figure 18** and **Table 7**, for specific water management gauge locations and MFL criteria.

**Table 7.** Minimum Water Levels, Duration, and Return Frequencies for Key Water Management Gauges Located Within the Remaining Everglades.

| Area | Key Gauge | Indicator Region[a] | Soil Type | Minimum Depth (ft) and Duration (days) | Return Frequency (years)[b] |
|---|---|---|---|---|---|
| **Water Conservation Areas** | | | | | |
| WCA-1 | 1-7 | 27 | Peat | -1.0 ft >30 days | 1-in-4 |
| WCA-2A | 2A-17 | 24 | Peat | -1.0 ft >30 days | 1-in-4 |
| WCA-2B | 2B-21 | 23 | Peat | -1.0 ft >30 days | 1-in-3[c] |
| WCA-3A North | 3A-NE | 21 | Peat | -1.0 ft >30 days | 1-in-2 |
| WCA-3A North | 3A-NW | 22 | Peat | -1.0 ft >30 days | 1-in-4 |
| WCA-3A North | 3A-2 | 20 | Peat | -1.0 ft >30 days | 1-in-4 |
| WCA-3A North | 3A-3 | 68 | Peat | -1.0 ft >30 days | 1-in-3 |
| WCA-3A Central | 3A-4 | 17 | Peat | -1.0 ft >30 days | 1-in-4 |
| WCA-3A South | 3A-28 | 14 | Peat | -1.0 ft >30 days | 1-in-4 |
| WCA-3B | 3B-SE | 16 | Peat | -1.0 ft >30 days | 1-in-7 |
| **Everglades Agricultural Area** | | | | | |
| Rotenberger WMA | Rotts | 28 | Peat | -1.0 ft >30 days | 1-in-2 |
| Holey Land WMA | HoleyG | 29 | Peat | -1.0 ft >30 days | 1-in-3 |
| **Everglades National Park** | | | | | |
| NE Shark River Slough | NESRS-2 | 11 | Peat | -1.0 ft >30 days | 1-in-10 |
| Central Shark River Slough | NP-33 | 10 | Peat | -1.0 ft >30 days | 1-in-10 |
| Central Shark River Slough | NP 36 | 9 | Peat | -1.0 ft >30 days | 1-in-7 |
| Marl wetlands east of Shark River Slough | NP-38 | 70 | Marl | -1.5 ft >90 days | 1-in-3[d] |
| Marl wetlands west of Shark River Slough | NP-201<br>G-620 | 12 | Marl | -1.5 ft >90 days | 1-in-5 |
| Rockland marl marsh | G-1502 | 8 | Marl | -1.5 ft >90 days | 1-in-2[d] |
| Taylor Slough | NP-67 | 1 | Marl | -1.5 ft >90 days | 1-in-2[d] |

a. Indicator regions are groupings of model grid cells within the SFWMM consisting of similar vegetation cover and soil type. These larger grouping of cells were developed to reduce the uncertainty of evaluating results from a single 2 x 2 square mile grid cell that represents a single water management gauge. Figure F-2 in Appendix F provides the location of each indicator region.

b. Return frequencies for peat based wetlands located within the WCAs were based largely on output of the NSM 4.5. Return frequencies for marl wetlands located in Everglades National Park were based on model results, expert opinion and consideration of management targets developed for the Comprehensive Everglades Restoration Plan (CERP).

c. Expert opinion of District staff, and results from the NSM concur, that a 1-in-6 return frequency is needed to protect the peat soils of this region from significant harm. District staff recognizes that this value had to be modified to account for consideration of changes and structural alterations that have occurred to the hydrology of WCA-2B. Model results of the CERP and LEC water supply planning process suggest full restoration of WCA-2B may not be possible. A policy decision was made to present a MFL return frequency of 1-in-3 in this table to reflect conditions that can be practically achieved.

d. These return frequencies represent the expert opinion of District staff based on “agreed upon” management targets developed in the CERP and LEC planning processes, and output of the NSM. It is the expert opinion of ENP staff that NSM does not properly simulate hydrologic conditions within the Rockland marl marsh and Taylor Slough and the proposed return frequencies listed above may not necessarily protect these marl-forming wetlands from significant harm. They propose that a frequency of 1-in-5 is necessary to prevent significant harm from occurring to these unique areas of the National Park.

### Criteria for Protection of Marl Soils and Associated Wetlands

Marl-forming wetlands occur primarily within Everglades National Park (**Figure 18**). The District will work with the National Park Service to define criteria that will protect specific areas and resources within Everglades National Park. Based on the examination of available data, the following criteria were developed to protect marl wetland communities within Everglades National Park:

*Water levels within marl-forming wetlands that are located east and west of Shark River Slough, the Rocky Glades, and Taylor Slough within Everglades National Park should not fall more than 1.5 feet below ground level for more than 90 days at return frequencies not less than those shown in **Tables 6** and **7**.*

### Impacts of Failure to Meet Proposed Criteria.

The following impacts can be expected to occur if the proposed criteria are exceeded:

- Reversal of the natural process of peat accretion and an increase in the rate of soil oxidation and soil subsidence (lowering of ground level elevations), which reduce the long-term sustainability of the Everglades ecosystem
- Reduced wetland aquatic productivity, disruption of food chains, loss of dry season aquatic refugia, shifts in wetland vegetation from wet-adapted species to those more tolerant of drier conditions, and invasion by exotic species such as melaleuca
- Increased frequency of severe fires that consume peat, damage tree islands, expose bedrock, lower ground level elevations, and destroy wildlife habitat that supports rare, threatened, or endangered species
- Continued loss of peat resources and associated freshwater head within the Everglades Protection Area, which has the potential to reduce the water storage capacity of the regional ecosystem and increase the threat of saltwater intrusion during droughts

### Considerations that may Affect Everglades Minimum Levels

In defining significant harm for an area, the Governing Board is required to consider changes and structural alterations to the hydrologic system as discussed in the section of this report entitled, *Identification of Baseline Conditions for Water Resource Functions* (**page 38**). The CERP recognized that in certain portions of the Everglades the hydrologic system cannot be fully restored due to changes and structural alterations that exist. The governing board in reviewing the proposed minimum levels for the Everglades may determine that for such areas, where full restoration may not be possible or desirable, the minimum level should be adjusted accordingly. District staff will be analyzing the performance of the CERP restoration alternative to determine locations in the Everglades hydrologic system where the proposed minimum levels are not met as a result of operational changes and structural alterations when all recommended components of the plan are in place. In such areas, the Governing Board may find it necessary to reassess the proposed minimum level to account for these shortfalls in the restored hydrologic system. This determination will be reflected in the final draft of this document.

# BISCAYNE AQUIFER

## Resource Functions

Water management criteria need to be established that will protect the water resource functions of the Biscayne aquifer. The following water resource functions were considered in the development of minimum water level criteria for the Biscayne aquifer:

- The Biscayne aquifer represents the primary source of water supply for urban and agricultural users within the LEC Planning Area.
- For this reason, ground water levels within the Biscayne aquifer should be maintained at sufficient levels to prevent saltwater intrusion. The highest risk for saltwater intrusion occurs during periods of seasonally high water demands and low rainfall.
- The Biscayne aquifer also provides base flow to important estuaries such as the Lake Worth Lagoon, Biscayne Bay, and Florida Bay during low rainfall years.

Under present operating conditions, cutbacks in water use by individual utilities in localized areas may be required during drought conditions. The District's goal through its planning, water resource development and water supply development efforts is to provide sufficient water so that significant cutbacks occur no more often than once every 10 years (i.e. a 1-in-10 year level of certainty). Decisions to restrict water use for individual utilities were historically based on chloride concentrations in monitoring and production wells.

Minimum operational water levels for the coastal canals are proposed in this report, recognizing that water levels in the canals are directly related to water levels in the aquifer system adjacent to these canals, but only indirectly related to chloride levels in saltwater intrusion monitoring wells. The proposed minimum operational canal levels will be used by the District, other agencies and local interests as regional indicators that saltwater intrusion may become a problem if water levels remain below these levels for more than 180 days duration. In such cases, a regional response would occur, such as providing additional releases to coastal canals from the regional system. Development of minimum water level criteria for the canals as a means to protect the aquifer from significant harm should not change the application of existing drought management methods and criteria that affect operation of individual wellfields.

# Technical Relationships Considered in Defining Significant Harm

Saltwater intrusion poses a continuing threat to the Biscayne aquifer. In order to restrict the inland migration of the saline interface, a sufficient freshwater head must be consistently maintained within the aquifer. Inadequate water levels occurred in 1939, when more than 10,000 water supply wells in South Florida were affected by high chloride concentrations, including the partial loss of five major wellfields (Parker et al., 1955). Since that time, a number of different actions have been taken to protect public and private wellfields from the threat of saltwater intrusion. Coastal water control structures were completed in the 1950's, monitoring efforts have significantly improved and the SFWMD Consumptive Use Permitting program has been established.

## Definitions of Harm and Significant Harm

The water resource protection framework to sustain the Biscayne aquifer is based on the conceptual model shown in **Figure 1** in Chapter 1 of this document. As discussed herein, protection of the Biscayne aquifer is based on the aquifer's function as a water supply source. As a result, the definitions of harm and significant harm to this function are based on the extent of movement of the saltwater interface into the vicinity of, and eventually into existing and future water supplies.

### Biscayne Aquifer -- No Harm Standard

Harm to the Biscayne Aquifer in terms of saltwater intrusion is considered to be movement of the saltwater interface to a greater distance inland than has occurred historically as a consequence of seasonal water level fluctuations up to and including a 1-in-10 year drought event.

In order to prevent harmful movement of the saltwater interface in the Biscayne aquifer, the District manages coastal ground water levels by operating the primary canal network, regulating surface water control elevations for developments (through surface water management permitting) and by limiting coastal consumptive use withdrawals. Operational criteria for the coastal canals that are maintained by the District to prevent harm are shown as the "Control Levels" on **Table 8**. These management levels vary seasonally as the District works to balance the goals of flood protection (wet season control level) and water supply (drought management control level). The drought management control levels represent target management elevations during the dry season. Water supply releases are made from regional storage sources (WCAs, Lake Okeechobee) to achieve these targets whenever possible. These canal levels in turn influence the adjacent dry season ground water elevations within the Biscayne Aquifer.

The consumptive use permit conditions for the protection of coastal fresh ground water dovetail with these canal operational levels by requiring coastal users to maintain a groundwater divide between the withdrawal point and the source of saline water. This is described as follows in the SFWMD Basis of Review document, Volume III, p A-37 (SFWMD, 1994b):

**Table 8.** Recommended Minimum Canal Operational Levels for the Biscayne Aquifer.

| Canal/Structure | Wet Season Control Level (ft NGVD) | Average Canal Level (ft NGVD) | Drought Management Control Level (ft NGVD) | Proposed Minimum Canal Operational Levels Needed to Protect Against MFL[a] Violations During Drought Conditions (ft NGVD) |
|---|---|---|---|---|
| C-51/S-155 | 8.50 | 8.12 | 7.80 | 7.80 |
| C-16/S-41 | 8.20 | 8.23 | 7.80 | 7.80 |
| C-15/S-40 | 8.20 | 8.39 | 7.80 | 7.80 |
| Hillsboro/G-56 | 7.70 | 7.43 | 6.75 | 6.75 |
| C-14/S-37B | 7.20 | 6.82 | 6.50 | 6.50 |
| C-13/S-36 | 5.60 | 4.43 | 4.00[b] | 3.80 |
| North New River/ G-54 | 4.00 | 3.68 | 3.50 | 3.50 |
| C-9/S-29 | 3.00 | 2.16 | 1.80 | 2.00 |
| C-6/S-26 | 4.40 | 2.55 | 2.50[b] | 2.00 |
| C-4/S-25B | 4.40 | 2.55 | 2.50[b] | 2.20 |
| C-2/S-22 | 3.50 | 2.86 | 2.50[b] | 2.20 |

a. Duration Criterion - water levels within the above canals may fall below the proposed minimum canal level for a period of no more than 180 days per year.

b. These levels will be maintained if sufficient water is available

*"Cumulative withdrawals from a fresh water aquifer may only occur in such manner that a hydraulic barrier between the withdrawal facility or facilities and the source of saline water is maintained. This is accomplished through the maintenance of a fresh water mound or ground water divide in the aquifer located between the source of saline water and the point of withdrawal at all times of the year. Staff will not recommend a newly proposed use for approval or an increase in allocation for an existing use under the following circumstances:*

*A. The hydraulic gradient between the wellfield and saline water is such that a hydraulic gradient (mound of fresh water) less than one foot National Geodetic Vertical Datum (NGVD) exists between the wellfield and saline water source during the months of November through April*

*B. Monitoring wells within 800 feet of a production well reflect chloride concentration increases at the base of the aquifer, indicating long term advancement of the saline front toward the wellfield or within the fresh water portions of the aquifer*

*C. Other evidence shows saline water intrusion will be a serious threat to the wellfield and natural resource if pumpage is allowed or increased*

*Withdrawals of fresh water must not result in significant upconing of saline water. Significant movement is defined as a movement of one-third of the original distance separating the bottom of the screened or open interval of a production well from the boundary of saline water below it."*

These two programs (canal operations and consumptive use permitting), implemented as described above, have been successful in preventing harmful movement of saltwater within the Biscayne aquifer, except for some very localized events in areas where the saltwater interface has not been stable. Studies show that movements of saltwater in these areas were most likely the result of drainage associated with land development activities and surface water management systems (Merritt, 1996).

### Biscayne Aquifer Significant Harm Standard

Significant harm occurs to the Biscayne aquifer when coastal saline groundwater moves inland to an extent that it actively limits the ability of consumptive users to develop fresh groundwater in the amounts specified in existing and future consumptive use permits and will require several years for the freshwater source to recover for use.

These extreme conditions would be determined on a localized scale, based on measured water quality and water level data which document the actual extent and movement of saltwater. These conditions are projected to occur, pursuant to the resource protection framework shown in **Figure 1** in Chapter 1, under drought conditions that exceed the 1-in-10 year level of certainty associated with the consumptive use permit program. In cases where the potential for significant harm exists, permitted allocations may be restricted under a District water shortage order to prevent further inland movement of saltwater that could cause serious harm to the water resource. These restrictions are imposed in phases (**Figure 1** in Chapter 1), which require more severe withdrawal cutbacks with increasing potential for harm, or inland movement of the saltwater front.

Once the determination has been made that the saltwater front has moved inland and potentially may limit existing and future withdrawals (i.e. cause significant harm), phase three water shortages would be imposed on consumptive users. Under these conditions, it has been the policy of the District to require a level of withdrawal cutbacks that could potentially cause economic losses to consumptive users.

## Relationship Between Canal and Ground Water Levels and Saltwater Intrusion.

The District tried several approaches to determine if a relationship exists between groundwater fluctuations and saltwater movement. The following is a discussion of that evaluation.

### Review of Previous Studies

Loss of the freshwater mound that previously existed behind the coastal ridge system is generally regarded as one of the major causes of saltwater intrusion within South

Florida (Parker et al., 1955; Fish and Stewart, 1991). Prior to the development and drainage of South Florida, a large freshwater mound formed behind the Atlantic Coastal ridge during the rainy season. Ground water flows seaward were so large that boils or freshwater springs occurred off the coast and were used by early mariners to replenish their ship's stores with fresh water.

The ground water hydrology of the LEC Planning Area has been permanently altered by urban and agricultural development and construction of the C&SF Project. Construction of a series of canals has drained both the upper portion of the Biscayne aquifer and the freshwater mound behind the coastal ridge. This has resulted in a significant decline in ground water flow towards the ocean and, consequently, has allowed the inland migration of the saline interface during dry periods. Large coastal wellfields have also been responsible for localized saltwater intrusion problems. Construction of coastal canal water control structures, beginning in the 1940s, has helped to stabilize or slow the advance of the saline interface, although isolated areas still show evidence of continued inland migration of salt water.

An example of the effect of saltwater intrusion over time is shown in the 1904 map of Miami-Dade County (**Figure 20**), which indicates the condition of the area prior to the construction of major drainage projects. As drainage systems were built, ground water elevations were reduced and seawater moved landward principally along the major canals systems. By 1953, several saltwater control structures had been built in order to control the inland extension of seawater. By 1962, the system had stabilized with significant rollback of the freshwater-saltwater interface along the Little River and Biscayne canals. Significant regional droughts occurred in 1971, 1981, 1985, and 1990. The effects of recovery are shown in the more recent 1984 and 1995 maps (**Figure 20**). Comparison of the 1984 map with recent data from 1995 indicates that conditions remain relatively stable and in some areas the line has moved further seaward (Fernald and Purdum, 1998).

Saltwater intrusion of the Biscayne aquifer continues to be a threat today. Severe droughts, such as in 1981, resulted in widespread inland movement of the saline interface. In 1987, the city of Hallandale permanently reduced total pumpage by 50 percent and shut down their primary wellfield (SFWMD, 1993b). Koszalka (1995) reports that the saline interface moved inland in Broward County between 1980 and 1990 due to the lowering of regional ground water levels and increased pumpage. Sonenshein and Koszalka (1995) report similar situations in central and southern Miami-Dade County. Recent monitoring data from Coral Gables, Hallandale, Pompano Beach, southern Martin County, and Boca Raton show that the saltwater front continues to advance inland (Lietz et al., 1995).

Work conducted at Cutler Ridge in South Miami-Dade County indicates that the saltwater front is dynamic and not static as originally assumed (Kohout, 1960). In addition, the observed actual position of the saline interface is several miles seaward of the position calculated using the Ghyben-Herzberg relationship (GHR) (see GHR discussions in Chapter 3 and below). Kohout (1960) observed that as salt water moved inland, a significant portion of the diluted sea water was circulated back toward the sea along the zone of diffusion. It is estimated that up to 20 percent of the salt water that intrudes the aquifer is returned to seawater, with the remaining 80 percent being retained in the aquifer

**Figure 20.** Historical Extent of Saltwater Intrusion at the Base of the Biscayne Aquifer in the Greater Miami Area (from: Fernald and Purdum, 1998).

(Kohout, 1960). This cyclic flow acts, in part, as a deterrent to further saltwater intrusion since a percentage of the salt water is returned to the sea.

The city of Hallandale, in southeastern Broward County, is an area that continues to be susceptible to saltwater intrusion. A series of monitoring wells located perpendicular to the coast have recorded the inland migration of the saline interface for more than 25 years. Evaluation of the data suggests that the saltwater front has consistently migrated inland at a rate of approximately 80 feet per year. Andersen et al. (1988) conducted a detailed evaluation of the saltwater interface in the vicinity of Hallandale using a coupled, flow/solute transport, three-dimensional finite element model. They evaluated several potential causes for continued saltwater intrusion, including wellfield pumpage, rainfall deficiencies, and lowering of inland canal stages due to urbanization. Although their model could not localize the cause of saltwater intrusion, their results demonstrated the sensitivity of ground water stages for maintaining the saline interface. These modeling studies also indicated that lowering inland canal stages by only several tenths of a foot could result in widespread movement of the saline interface. In addition, a significant lag time exists between the lowering of the hydraulic head and the subsequent movement of the saline interface (Andersen et al., 1988).

Merritt (1996) also conducted a detailed assessment of saltwater intrusion in southern Broward County. Analysis of monitoring well data from the period from 1945 to 1993 indicated that the front had migrated inland up to one half mile in some areas. Merritt (1996) then developed a cross-sectional model of southeastern Broward County to simulate movement of the saltwater interface, using both a sharp interface and diffusion model code. An important result from his work is that the position of the saline interface may vary seasonally but its long-term position is governed by average annual or long-term ground water levels rather than by seasonal fluctuations.

### Review of Water Level and Monitoring Data

Regional water level monitor data show a close relationship between the water level stages maintained in the District's primary canals and groundwater elevations within the Biscayne aquifer. This is particularly true in south Broward and Miami-Dade counties where permeability of the Biscayne aquifer is very high. However, the relationship between surface water level fluctuations and the movement of the salt water interface is poorly understood for the Biscayne aquifer at this time. As a result, it is difficult to conclusively determine what canal stages would result in significantly harmful movement of salt water along the coastal margin of the Biscayne aquifer.

### Ghyben-Herzberg Relationship

On a conceptual level, one of the first approaches District staff used to estimate a minimum level that would prevent saltwater intrusion of the aquifer was the Ghyben-Herzberg relationship (The GHR). This well-established principle examines the density differences between fresh water and salt water at equilibrium. For each 40 feet of aquifer thickness, a freshwater head of one foot is required to maintain or stabilize the saltwater front under static conditions. The equation derived to explain this relationship is known as the GHR named in honor of the two scientists who independently discovered this principle in the late 1800s-early 1900s. Application of the GHR provides a conservative estimate of the location of the saltwater interface, assuming hydrostatic conditions in a homogenous, unconfined coastal aquifer.

The aquifer system along Florida’s southeast coast ranges in thickness from approximately 100 to 300 feet. Therefore, to ensure that saltwater intrusion does not occur within these aquifer systems, a freshwater head of between 2.5 and 7.5 ft NGVD would theoretically be needed to maintain or stabilize the saltwater front based on the GHR.

Although the GHR can provide an initial estimate of the minimum level needed to prevent saltwater intrusion under static conditions, actual field observations indicate that the equation may over estimate the required freshwater head in systems showing fluid flow (Freeze and Cherry, 1979). This over estimation may be due in part, to the heterogeneous aquifer characteristics associated with the surficial aquifer system, horizontal and vertical flow components, and the transient nature of the saltwater interface. District staff utilized this conservative approach to determine the theoretical position of the saline interface within the Biscayne aquifer as compared to its actual position (**Figure 21**) and to provide a means of comparison to other statistical approaches developed by District staff to determine minimum freshwater heads that should be maintained to protect the aquifer.

For comparison purposes, the GHR was analyzed to determine its ability to stabilize the saltwater interface. The relationship considers water levels, density differences of salt water and fresh water, and thickness of the aquifer to determine the distance to the saltwater interface. The depth to the base of the Biscayne aquifer in Miami-Dade, Broward and Palm Beach counties was determined from existing hydrogeologic work conducted by Fish (1988), Fish and Stewart (1991), and Shine et al. (1989). Results of these analyses indicate that the actual position of the saline interface is seaward of the theoretically calculated location. This relationship is shown in **Figure 21**. These data suggest that the GHR provides a relatively conservative estimate of the required freshwater head necessary to stabilize the saltwater interface and supports Kohout's (1960) work, which reported that up to 20 percent of saline water that intrudes the Biscayne aquifer is returned to sea along the seepage face. Details of these analyses may be found in **Appendix A** of this report.

It should be emphasized that District staff did not use the GHR to develop any minimum level recommended in this report. Its use in this report is for comparison purposes only.

### Aquifer Water Level/Water Quality Relationships

In addition to the Ghyben-Herzberg analysis, staff conducted a review and analysis of water level and water quality data from more than 500 wells located within the LEC Planning Area. Water level and water quality data collected from these wells were analyzed to determine if a statistical relationship exists between water levels, duration of low water level events and subsequent movement of the saltwater interface in response to low water events. Water level data from each well was evaluated to determine average dry season and wet season levels as well as long-term trends. Chloride concentrations were also examined to determine whether or not the saltwater front had reached a particular well, appeared to be stable, and/or appeared to be either moving inland or retreating seaward. In addition, stage duration curves were developed for each coastal water control structure to determine mean (50th percentile) and standard deviation (84th percentile) water levels at each salinity control structure. These data are presented in detail in **Appendix A**.

In addition to the above effort, detailed statistical analyses were performed on 49 monitoring wells in Broward County to investigate the correlation between observed chloride concentration and water table elevation. Each monitoring well was classified based upon its distance to the coast and its geographical location. Water levels were converted to equivalent freshwater heads to account for the denser salt water contained in some wells. These data are provided in **Table A-1** of this report. Results of these analyses

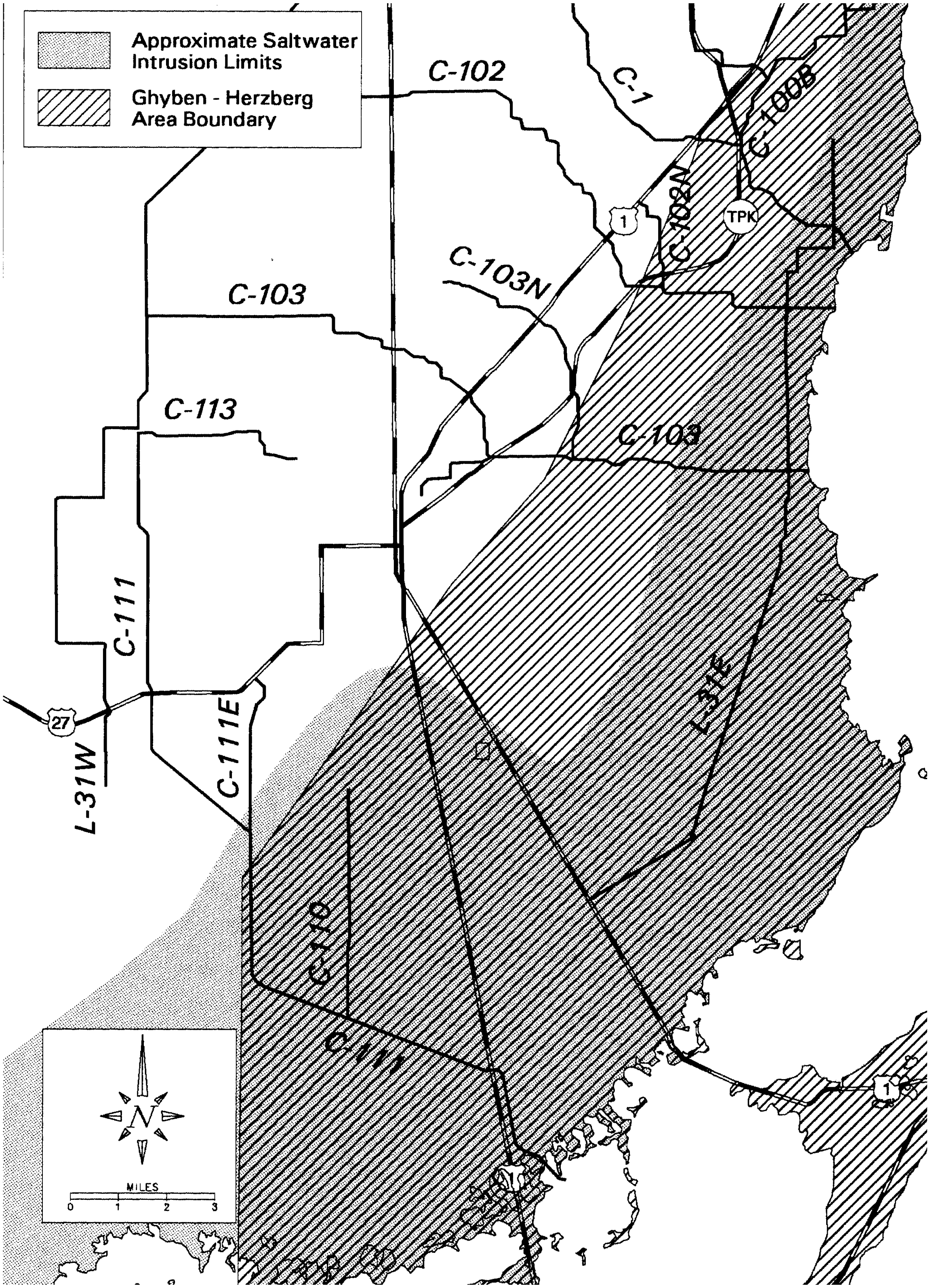


**Figure 21.** Theoretical and Actual Position of the Saline Interface Based on the Ghyben-Herzberg Relationship in the Biscayne Aquifer Located in Miami-Dade, Broward, and Palm Beach Counties.

indicate that no significant correlation of chloride concentration to freshwater head was observed for the Broward County wells.

In contrast, there does appear to be some correlation between the duration of low water periods and seasonal versus permanent movement of the saltwater interface. For example, at monitoring well G-1179, average annual water levels in 1985 were depressed for a period of four months resulting in a noticeable movement of the saline interface. The saltwater front retreated back to its former position after water levels had recovered during the following year. However, in 1989-1990, when average annual water levels were depressed for an extended period of time, the saltwater front moved inland and did not return to its previous position. These observations support the numerical simulations conducted by Merritt (1996), which show that short-term water level fluctuations do not result in long-term movement of the saltwater interface. However, preliminary interpretation of best available data suggests that movement of the interface, which occurs when water levels are depressed for more than six months, may take more than five years to recover, if recovery occurs at all, thus affecting the average chloride concentration at that location.

As discussed above and in Chapter 3, based on analysis of 500 monitoring wells, little or no saltwater intrusion occurred in areas where canal stages were maintained within one standard deviation of the mean. While the relationship between canal water levels and significant saltwater intrusion is not known, establishing a no movement/no harm criterion as an operational standard for the Biscayne aquifer appears prudent. This criterion may be revisited after further research is conducted to better define the relationship between canal stage and the movement of saltwater in the aquifer.

Review of historical water level and water quality information collected from over 500 wells located within the LEC Planning Area showed that the relationship between chloride concentrations and water levels were not as strongly correlated as might have been expected. In general, the higher the water level, the less likely that salt water was present in the well. However, even when freshwater levels were in excess of five ft NGVD, six percent of the observations showed chloride concentrations in excess of 1,000 parts per million. In addition, when water levels were below sea level, only 41 percent of the readings had chloride concentrations in excess of 1,000 ppm. Results of these analyses are presented in **Table A-2**.

Another method used to establish the freshwater-saltwater interface was the review and analysis of chloride and water level data from approximately 200 long-term monitoring wells located within the LEC Planning Area. Average dry and wet season water levels and average chloride concentrations were calculated for each well over time and well depths were recorded. Individual data from each monitoring well are presented in **Appendix A**. Analyses of these data indicate that when water levels were maintained at, or above, the level calculated by the GHR, approximately 95 percent of the wells showed no significant saltwater intrusion. However, more than 40 percent of the wells that had water levels below those specified by the GHR indicated some form of saltwater intrusion.

### Temporal Relationship between Ground Water Levels and Saltwater Movement

Best available information indicates that the position of the saline interface is dependent upon average annual ground water levels. This hypothesis is supported by the modeling work of Andersen et al. (1986, 1988) and Merritt (1996) as well as the results of this study. These studies indicate that short-term variations in ground water levels may result in temporary movement of the saline interface, but the interface retreats to its former position once ground water levels return to their normal range. Furthermore, prolonged, depressed ground water levels may result in significant and permanent movement of the interface even after these water levels have returned to normal or above normal conditions. To illustrate this point, **Figure 22** provides a schematic diagram that shows the movement and retreat of the saline interface under various low water conditions.

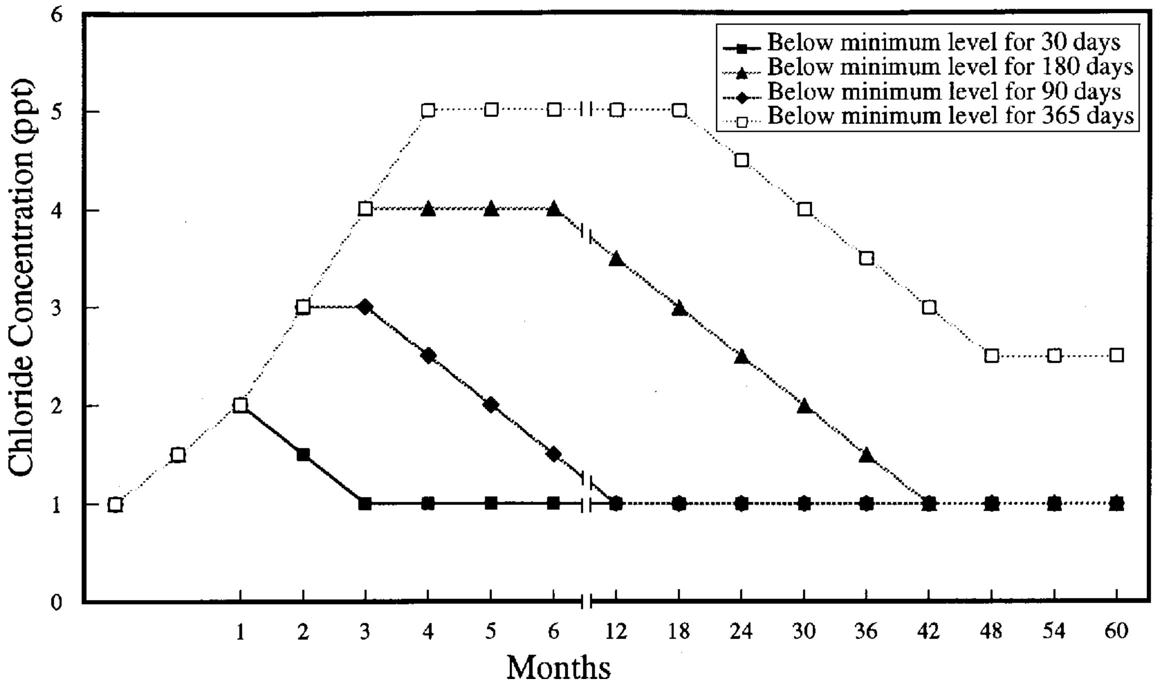


**Figure 22.** Schematic Illustration of the Potential Effects of the Duration of Below Minimum Water Levels and the Time Required for Chloride Concentrations to Recover in the Biscayne Aquifer. (This illustration was estimated from a review of historical data.)

As shown in **Figure 22**, it is anticipated that ground water levels can be depressed for periods of up to 180 days per year and the saline interface will retreat to its previous position, although it may take from several months to several years of average rainfall conditions for this recovery to occur. When ground water levels are depressed for periods in excess of six months duration, movement of the saline interface could take multiple (more than five) years to retreat, as shown in **Figure 22**. It is proposed that this relationship should be used as the basis to establish a minimum canal operation level and duration component for protection of the Biscayne aquifer until such time that better information becomes available. Such new information might apply detailed transient solute transport modeling and site specific ground water monitoring of the Biscayne aquifer to refine the proposed minimum ground water duration component.

Support for the six month duration component comes from several other sources. During the 1989-1990 drought, canal stages fell below the recommended minimum level for more than six consecutive months at several coastal structures. Of particular interest was central Miami-Dade County, where water levels in the C-2 and C-4 canals were allowed to fall below 2.5 ft NGVD for a period of seven months. Within approximately one year of this event, two monitor wells in the vicinity of the C-2 canal recorded significant movement of the saline interface (wells G-901 and G-432) and these wells have not yet recovered after seven years. A similar situation may have also occurred in south Palm Beach County, where depressed water levels were noted at the S-40 Structure and the adjacent E-4 Canal during 1989-1990. Noticeable movement of the interface was observed within several years of this event at two monitor wells in reasonably close proximity to the structure. Those observations suggest a relationship between the movement of the saline interface and canal stages, and also imply a duration component that is consistent with the six-month period proposed above.

### Relationship between Coastal Canal Stages and Saltwater Intrusion

**Regional Modeling.** The SFWMD maintains the coastal canal network to provide drainage for agricultural and urbanized areas during rainfall events and recharge local ground water resources during periods of drought. In setting a minimum canal operational level to prevent saltwater intrusion of the Biscayne aquifer, it was necessary to evaluate the effect of the primary canal network on water levels within the Biscayne aquifer. To increase our understanding of this relationship, two separate model simulations were executed using the South Florida Water Management Model (SFWMM):

1. In the first simulation, the system was operated under present conditions. Coastal canals were maintained by the regional system during drought periods, and continued to receive water from the WCA system and Lake Okeechobee during low rainfall years.
2. In the second simulation, coastal canals were not maintained for water supply purposes during drought years. District operations incorporated into the model run did not attempt to maintain dry season water levels in the coastal canals.

Results of the two simulations described above were compared at 20 key monitoring locations. **Table A-3** provides a summary of these results. When the coastal canals were not maintained during dry periods, there was an increase in the number of days that coastal ground water levels fell below 1 ft NGVD. The threat of saltwater intrusion significantly increased. When coastal water levels were below 1 ft NGVD for longer periods of time, a reverse gradient developed as coastal aquifer water levels fell near or below sea level. Denser salt water from the ocean could then move inland into the freshwater portions of the aquifer. Results of these simulations indicate, that for most areas, coastal water levels appear to be highly influenced by water levels in the regional canal network. Water levels in the coastal canals largely govern the expected inland extent of the saline interface. Managing coastal canals at appropriate water levels during drought periods provides a means to stabilize the saltwater interface and restrict inland migration of the saltwater front. **Appendix A** provides a detailed summary of results of these simulations for north, central, and south Palm Beach County, Broward County, and Miami-Dade County.

**Evaluation of Coastal Canal Stages.** Since coastal canals are used to help control aquifer levels along the lower east coast of Florida, an evaluation of canal stage levels was necessary. Upstream canal water levels from eleven primary canals were obtained from historical records. Daily stages, where available, were obtained from each structure for the period from 1980 to the present. Structures in south Miami-Dade County were not included in this evaluation due to the uncertainty associated with developing minimum flows for Biscayne Bay and Florida Bay. Hydrographs and stage duration plots for each structure were developed for the same time frame and are provided in **Appendix B.** The mean stage (50th percentile) and the 84th percentile stage for each primary canal and water management structure are presented in **Table 8**. The 84th percentile statistically represents one standard deviation from the mean. Also included in **Table 9** are the canal maintenance levels used by the District, as simulated in the SFWMM.

**Table 9.** Stages at Key Water Management Structures within the LEC Planning Areas (Stages are in ft NGVD).

| Canal/Water Management Structure | Mean or 50th percentile Stage (ft NGVD) | 84th Percentile[a] (ft NGVD) | Canal Stages Maintained by SFWMD[b] (ft NGVD) |
|---|---|---|---|
| C-51/S-155 | 8.12 | 7.74 | 7.80 |
| C-16/S-41 | 8.23 | 7.72 | 7.80 |
| C-15/S-40 | 8.39 | 7.59 | 7.80 |
| Hillsboro Canal/G-56 | 7.43 | 6.75 | 6.75 |
| C-14/S-37B | 6.82 | 6.60 | 6.50 |
| C-13/S-36 | 4.43 | 4.15 | 3.80 |
| North New River/G-54 | 3.68 | 3.28 | 3.50 |
| C-9/S-29 | 2.16 | 1.90 | 1.80 |
| C-6/S-26 | 2.55 | 2.07 | 2.00 |
| C-4/S-25B | 2.55 | 1.95 | 2.20 |
| C-2/S-22 | 2.86 | 2.04 | 2.20 |

a. 84th percentile represents one standard deviation from the mean.

b. Canal stages maintained by the District at specific canals as simulated by the SFWMM.

The levels used in the SFWMM represent the average water level at each structure, during times when water supply deliveries were made, as determined from an evaluation of historical canal stages. When simulated canal stages fall below this level, the SFWMM imports water into the canal from the WCAs or Lake Okeechobee.

The model simulations results show a general decline in coastal canal levels maintained by the District from north to south, due primarily differences in the topography between these two areas. With the exception of the Coastal Ridge, ground elevations decrease from 15-20 ft NGVD in Palm Beach County, to less than 5 ft NGVD in parts of southwest Broward County and Miami-Dade County. Local canal levels must be maintained below adjacent ground elevations to prevent urban and agricultural flooding.

**Localized Saltwater Intrusion Modeling.** The final approach used to investigate the relationship between canal water levels and movement of the saline interface was the application of an existing saltwater intrusion model to study three simulated conditions. The model code utilized was the SWICHA model, a finite element solute transport/flow model developed by Andersen et al. (1986). This two-dimensional cross-sectional model was slightly modified to allow various simulations at five idealized transects located along the southeast coast of Florida. These models simulate steady-state conditions and therefore do not address temporal variations in water levels that may occur seasonally, monthly or daily within the system. The five transects (or slices) through the aquifer included south-central Palm Beach County, northeastern Broward County, central Broward County, southeastern Broward County, and north-central Miami-Dade County. The model was run using the following three scenarios at each transect to simulate various canal maintenance operations:

- Setting the minimum canal level based on the mean stage or 50th percentile level, based on historical data.
- Setting the minimum canal level based on the 84th percentile (one standard deviation from the mean) level, based on historical data.
- For comparison purposes, setting the minimum canal stage based on the theoretical GHR.

The models were used to evaluate the position of the salt water interface for various canal levels. The models simulate a transect or slice through the aquifer. The eastern edge of the model simulation is the Atlantic Ocean and the western edge is the District’s primary canal. Three separate runs were made to evaluate the predicted position of the salt water interface for each of the canal levels (mean, dry season, and GHR). The models were run under dry season steady state conditions. The position of the interface predicted for each of the model runs was then compared to the actual present day position of the interface. The scenario that closely matched the present day position of the interface was then used to derive the proposed minimum operational canal level.

The basis for this approach is that selection of a canal level that moved the interface seaward would represent a recovery situation. Likewise, choosing a canal level that allowed additional landward movement of the interface could potentially result in long term movement of the interface (significant harm). If movement continued unabated, it could eventually cause a permanent shift in the interface (serious harm). It should be noted that this approach assumes that the harm and significant harm standards are nearly identical in terms of maintaining canal levels, but differ in the time period (duration) that the minimum canal operational level is exceeded.

Results of the three SWICHA model simulations and accompanying stage duration curves are presented in detail in **Appendix A**. Model results showed historical water levels that ranged between the mean (50th percentile) and one standard deviation from the mean (84th percentile) for each of the five transects modeled represented the most appropriate levels that would restrict movement of the saline interface without adversely affecting flood control. These data represented the closest fit to establish canal operational levels that prevent further inland saltwater movement, for each of the five tranects modeled.

The canal water levels that are equivalent to the 84th percentile (**Table 8**) correlate well with the drought management control levels maintained by the District (**Table 9**). These drought management control elevation targets for the coastal structures have been in place for decades. Review of historic saltwater intrusion and canal stage records show two noteworthy conclusions:

- The saltwater interface appears to have been generally stable in the groundwater aquifer adjacent to these structures (a possible exception occurs in well G-432, located in the C-4 canal basin Miami/Dade County, where chloride levels increased in 1989-90 and remained elevated); and
- During the dry season, there are a number of days when the canal stages drop below the target management levels without measurable saltwater movement.

In summary, the model simulations showed no apparent correlation between canal water levels and movement of the saltwater interface. In addition, several other important factors were observed:

- Water levels along coastal Miami-Dade, Broward, and Palm Beach counties are largely controlled by the District's primary canal system. Regionally, these canal systems control the position of the saltwater interface.
- Results of these simulations indicate that on a regional scale, the position of the saltwater interface can be regulated by management of water levels in the District's canal system. Localized saltwater intrusion problems still need to be addressed through detailed investigations and permitting.
- The ability to manipulate canal water levels as a means to control saltwater intrusion is greatly reduced in areas of Miami-Dade and Broward counties that have low ground level elevations.

- The use of historic drought management control elevations for the selected coastal canals appears appropriate to restrict movement of the saltwater interface within the Biscayne aquifer. While this “no movement” standard may be more restrictive than the significant harm standard called for under the MFL legislation, it may be prudent to establish this as the standard until a better relationship between movement of saltwater and the lowering of canal stages or some better measurement is defined.

Based on a review of these modeling results and a review of aquifer level and water quality relationships, minimum canal operating levels are proposed for each of the District’s eleven primary water management structures (**Table 8**) to prevent saltwater intrusion.

## Water Level Criteria for the Biscayne Aquifer

### Selection of Minimum Canal Operational Levels to Protect the Biscayne Aquifer

Ground water levels within the Biscayne aquifer are controlled by local rainfall and by canals and structures that are regionally operated by the SFWMD. The aquifer system becomes more rainfall driven and less canal dependent as the distance from the canals increases. However from the data presented in this report, it appears that canal water levels play a major role in determining the elevation of freshwater levels in the Biscayne aquifer throughout most of South Florida. Because of this relationship, initial minimum operational levels are proposed for eleven of the District's primary coastal canals as a means to protect a major portion of the Biscayne aquifer against further saltwater intrusion. The proposed criteria consist of a minimum canal operational level and duration of the event:

- Minimum Canal Operational Level - The minimum water level in a canal, which, if managed for a specific period of time, is sufficient to restrict saltwater intrusion within the coastal aquifer and prevent significant harm from occurring during a period of deficient rainfall.
- Duration - The estimated period of time that canal water levels may remain below the minimum level without causing significant harm to coastal ground water resources.

Minimum canal operational levels are proposed for eleven primary control structures located within the LEC Planning Area. Key requirements for selecting these structures were that they must be connected to the regional system and have a sufficient canal conveyance capacity to receive water from outside of their drainage basins. The values proposed in **Table 8** represent canal operational levels necessary to protect the Biscayne aquifer and stabilize the saline interface. **Table 9** also shows water levels that are presently maintained by the District in 11 primary canals during wet, dry and average rainfall conditions.

In general, these minimum canal operational levels were derived from a review of historical stage duration curves, using values that ranged between the mean (50th percentile) and the 84th percentile (one standard deviation from the mean) for each canal, based on best professional judgement. Details of these analyses are presented in **Appendix A**.

On a regional scale, the SFWMD will manage canal levels at or above the proposed minimum operational levels specified in **Table 8** for each of the 11 principal water control structures located along the southeast coast. Water levels are managed at these levels by delivering water from the regional system. Water levels may be allowed to go below the specified level during times when water is not available to maintain the canal system or when significant rainfall has occurred that requires opening of the control structures to prevent upstream flooding. Water levels within the canals can fall below the proposed minimum operational level for a period of no more than 180 days per year. These canal levels, however, need to recover sufficiently after a drought or discharge event so that, on average, water levels will be managed at or above the specified average canal levels shown in **Table 8** on an annual basis. Actual operation of the C&SF Project canal system will be addressed in detail in the MFLs recovery and prevention section of the LEC Regional Water Supply Plan.

**Table 8** also shows that operationally levels proposed for certain canals located within Broward County (C-13 and C-9) and Miami-Dade County (C-2, C-4 and C-6) will be managed at slightly higher levels during dry periods, as compared to currently proposed minimum operational levels, if sufficient water is available. The purpose of increasing these water levels is to restrict further saltwater intrusion from occurring.

## Proposed Canal Operational Levels

### Biscayne Aquifer Minimum Level

*Water levels in the Biscayne aquifer associated with movement of the saltwater interface landward to the extent that ground water quality at the withdrawal point is insufficient to serve as a water supply source for a period of several years before recovering.*

### Actions Needed to Protect the Aquifer

To manage the resource to minimize the risk of the MFL being violated, the District will do the following:

1. Maintain coastal canal stages at the minimum operation levels shown in **Table 8**
2. Issue Consumptive Use Permits, consistent with the "no harm" standard.
3. Monitor Biscayne aquifer ground water levels and water quality on a regional and localized basis

4. Implement the District's water shortage program pursuant to District Rule 40E-21 F.A.C. whenever the resource is threatened or impacted by saltwater

5. Conduct further research to refine the relationships among saltwater migration, water levels in the Biscayne aquifer, and water levels in coastal canals

### Implementation

The goal of the proposed canal operational levels recommended in this report is to minimize the threat of long-term movement of the saline interface in the aquifer without adversely affecting flood control. It is proposed that this be accomplished from a regional perspective by maintaining coastal canal levels during drought events at the levels specified in **Table 8.** Canal levels are seen as a surrogate measurement to indicate periods when local conditions may be favorable for saltwater intrusion. Maintenance of these levels should help prevent significant harm from occurring within the aquifer.

However, actual monitoring and implementation of water use restrictions for the LEC Planning Area will continue to be managed using the established system of ground water monitoring wells and water restriction declaration criteria. The existing network directly monitors the position of the saltwater interface within the Biscayne aquifer. Water use restriction phases are imposed when ground water levels fall near or below sea level, or when water quality tests at monitoring wells indicate that saltwater intrusion is occurring. Because this approach represents a direct measurement of the position of the saltwater interface, it is proposed these criteria continue to be used to establish water shortage restrictions for the LEC Planning Area. Additional data are needed to define the relationship between duration and frequency of low water levels in the coastal canals, the magnitude of conductivity change in the aquifer and the ability of the aquifer to recover. Strategies and methods for importing water from the regional system to maintain the canal system at the levels specified in **Table 8** will be developed as part of the Minimum Flows and Levels Recovery and Prevention Plan in the LEC Water Supply Planning process.

## Surface and Ground Water Flows in South Miami-Dade County, Florida

The hydrology in south Miami-Dade County is highly complex. Historically, ground water flowed eastward and discharged into Biscayne Bay, while surface waters generally flowed southward towards the eastern Everglades, eventually reaching Florida Bay, Barnes Sound, and Card Sound. With subsequent draining of south Miami-Dade County, both surface and ground water flows to Biscayne Bay were significantly altered (Buchanan and Klein, 1976). Ground water and surface water flows toward northeastern Florida Bay also appear to have been altered, although additional work is needed to determine the extent. In addition to drainage, salinity regimes and circulation patterns in Florida Bay and Barnes Sound appear to have been modified by the construction of Flagler's Florida Keys Railroad (McIvor et al., 1994).

A secondary problem in southern Miami-Dade County is the relatively thin soil. Due to these shallow soils, canals are cut into the oolitic and bryozoan facies of the Miami Limestone and have penetrated into the Fort Thompson Formation in some areas. As a result, these canals are directly connected to some of the most permeable sections of the Biscayne aquifer. It is therefore difficult to maintain canal stages for extended periods of time without using a significant volume of water from regional storage.

For the reasons discussed above, this report will not establish MFLs for Florida Bay, Biscayne Bay, Card Sound, and Barnes Sound, located in southern Miami-Dade County. Results of this study and others show that a strong relationship exists between the position of the saltwater interface and the volume of ground water that flows into these important estuaries. However, District staff is concerned that setting a minimum level for the Biscayne aquifer in south Miami-Dade County, based solely on maintaining the existing position of the saline interface has the potential to restrict critical ground water and surface flows that move east towards Biscayne Bay and south towards Florida Bay. Setting a MFL for southern Miami-Dade County based solely on this information could result in unsatisfactory ground water and surface water flows to these estuaries. Therefore, it is recommended that the MFL for the Biscayne aquifer in southern Miami-Dade County be developed concurrently with the development of MFLs for Biscayne Bay, Florida Bay, Card Sound, and Barnes Sound.

# Chapter 5
# CONCLUSIONS AND RECOMMENDATIONS

This report recommends Minimum Flows and Levels (MFLs) for Lake Okeechobee, the Everglades, and Biscayne aquifer. Structural changes or alterations that have occurred within South Florida, the effects these changes have had, and the constraints they impose on the water resources were considered as part of the process for developing MFL criteria. When establishing a minimum flow or level, the District shall consider the effect such constraints or alterations have had on the hydrology of the area. Such considerations shall not allow significant harm caused by withdrawals. For the purpose of this study, significant harm is defined as loss of specific water resource functions that take multiple years to recover, which result from a change in surface or ground water hydrology.

## LAKE OKEECHOBEE

### Structural Changes and Alterations to Lake Okeechobee

Construction and operation of the C&SF Project has reduced historical lake levels to prevent hurricane flooding of lakeside communities and provide water supply to downstream agricultural and urban interests. Construction of levees around the perimeter of the lake has dramatically reduced the size of the lake's littoral zone and moved littoral zone habitats to new locations.

### Water Resource Functions of Lake Okeechobee

The development of a minimum level and definition of significant harm for Lake Okeechobee focus on protecting the following water resource functions: water supply and storage, protection of the Biscayne aquifer against saltwater intrusion, fish and wildlife habitat, and navigation and recreational use. Enough water must be maintained within the lake to make deliveries to the LEC Planning Area during drought periods to maintain a freshwater head in coastal canals that will prevent significant harm due to saltwater intrusion of the coastal aquifer. The lake must also provide water for Everglades National Park and, during low rainfall periods, provide supplemental water supplies for the EAA, the Caloosahatchee and St. Lucie basins, and Seminole tribal water entitlements. Also, enough water must be maintained to protect fish and wildlife habitat, including the lake's littoral zone, sport and commercial fisheries, and resident threatened and endangered species populations. Finally, the occurrence of low water stages that restrict navigation and recreational use of the lake by the public must be minimized.

## Lake Stage and Supply-Side Management

To protect the water resource functions of the lake, an adequate lake stage must be maintained. Historical records show that when lake levels fall below 11 ft NGVD, severe water shortage restrictions have been imposed within the LEC Planning Area. Best available information indicates that frequent or prolonged drawdowns of Lake Okeechobee below an elevation of 11 ft NGVD will cause significant harm by reducing the District's ability to store enough water within the lake to maintain coastal canal levels and prevent saltwater intrusion during dry periods. Once water levels fall below 10.5 ft NGVD, the physical limitations of the lake's primary outlet structures make it increasingly difficult to convey water from the lake to coastal canals.

The District has developed a *Supply-Side Management Plan* (Hall, 1991) that includes phased water shortage restrictions to keep water levels in Lake Okeechobee from dropping below 11 ft NGVD by the end of the dry season. The top of Supply-Side Management Zone C, from April 15 through July 15, represents the significant harm limit for protecting Lake Okeechobee's water supply (**Figure 15** in Chapter 4). When water levels fall below the top of Zone C within this time period, there is a significant risk that not enough water is stored in the lake to maintain a freshwater head in LEC Planning Area canals to protect the Biscayne aquifer from the threat of saltwater intrusion. Water deliveries to the EAA, the Seminole Indian Tribe, the Caloosahatchee and St. Lucie basins during severe regional droughts are determined based on the District's *Supply-Side Management Plan*.

Water needs of Everglades National Park are met by applying a water delivery model called the Rainfall Plan, that provides a more natural timing of water deliveries. Water deliveries from Lake Okeechobee to the Everglades are also made pursuant to the District's Best Management Practices (BMPs) Make-Up Water Rule, which replaces water lost due to implementation of BMPs within the EAA.

Best available scientific information indicates that significant harm occurs within the littoral zone community and its associated fish and wildlife habitat when lake levels recede below 11 ft NGVD. When lake levels drop to 11 ft NGVD, Geographic Information System models indicate that 94 percent of the littoral marsh is dry and no longer functions as habitat for fish and other aquatic-dependent wildlife. Large areas of the marsh become vulnerable for further expansion by melaleuca, and spike rush habitat within the western littoral zone (Moonshine Bay) are exposed and become susceptible to invasion by torpedo grass. Lake Okeechobee, the Water Conservation Areas (WCAs), and Everglades National Park represent important habitat for the federally-designated endangered snail kite. Lake Okeechobee may function as a habitat of last resort for this endangered species during a major drought when the WCAs and Everglades National Park are dry.

When lake levels fall below 12.56 ft NGVD, navigation of the Okeechobee Waterway becomes impaired. Best available data indicate that once water levels drop near 10 ft NGVD, recreational access to the lake becomes significantly restricted.

Existing scientific information is not currently sufficient to establish a minimum duration or return frequency for the proposed 11 ft NGVD minimum level. For this reason, District staff used the lake's historic period of record (1952-1996) to provide an initial estimated of minimum duration and return frequency that lake levels could be allowed to recede below 11 ft NGVD (**Figure 16**). Research over the next several years will better define ecologically-based duration and return frequency criteria.

## Minimum Level Criteria for Lake Okeechobee

Based on the above conclusions, both operational and water supply planning MFL criteria have been developed. Operational criteria identifies when the MFL has been exceeded on a day-to-day basis. The water supply planning criteria provides information as to how often, and for what duration, the MFL can be exceeded based on the expected frequency of natural drought events.

**Operational MFL Criteria:** *Water levels in Lake Okeechobee should not fall below 11 ft NGVD. From April 15 to July 15 water levels may occasionally fall below 11 ft NGVD as long as they do not drop below the top of Supply-Side Management Zone C, as shown in **Figures 12** and **15**.*

**Water Supply Planning MFL Criteria:** *For water supply planning purposes, water levels in the lake should not fall below 11 ft NGVD for more than 80 days duration, more often than once every six years on average.*

## Proposed Research for Lake Okeechobee

Proposed research programs for Lake Okeechobee include development of an updated littoral zone vegetation map that will be correlated with recent variations in lake water levels to provide a more precise relationship between hydroperiod and littoral zone plant community response. These data will be used to establish ecologically-based MFL duration criteria for the lake. In addition, field monitoring and a series of controlled experiments will be conducted to determine the primary factors that are responsible for the expansion of torpedo grasses within the lake's littoral zone.

# THE EVERGLADES

Minimum water level limits need to be established within the remaining Everglades to prevent the occurrence of long-term, low water levels that impact the sustainability of the Everglades system. The remaining Everglades consists of the WCAs, the Holey Land and Rotenberger Water Management Areas (WMAs), and the freshwater region of Everglades National Park, excluding Florida Bay. Development of the proposed MFL criteria were based on an extensive review of the literature, comparison of the proposed criteria to historical water levels and fire histories within the Everglades, and comparison to the Natural System Model, version 4.5 (NSM 4.5) as an estimate of minimum predrainage water levels.

## Everglades Water Resource Functions

The following water resource functions were considered in the development of minimum water level criteria for the Everglades. The Everglades provide the following:

- Recharge and prevention of saltwater intrusion to the Biscayne aquifer
- Surface and ground water flow to the south to maintain aquatic resources in Everglades National Park and the salinity balance of coastal estuaries
- Hydrologic conditions that promote the production of organic detritus and promote accretion of peat and marl soils. Organic detritus is the basis of the Everglades food chain. Peat and marl soils are the primary substrates that support the Everglades ecosystem.
- Hydrologic conditions that reduce the rate of soil oxidation, loss of organic soils, soil subsidence, and the risk of severe muck fires
- Hydrologic conditions needed to sustain habitat for Everglades wildlife, including threatened and endangered species
- Hydrologic conditions that provide dry season aquatic refugia for Everglades fish, amphibians, aquatic invertebrates, and other wildlife during droughts
- Hydrologic conditions to ensure survival of plant and animal communities in coastal estuaries
- Reduction in the susceptibility of the marsh to invasion by terrestrial woody vegetation and introduced exotics such as melaleuca
- Natural biologic filtering to improve water quality by removing nutrients, suspended soils, and metals

## Minimum Level Criteria for the Everglades

Minimum criteria developed for the Everglades were designed to protect the above water resource functions by preventing the loss of hydric soils. Proposed MFL criteria are based on the rationale that ground water drawdowns and durations greater than those recommended have the potential to cause harm to hydric soils and associated wetland vegetation and wildlife.

### Proposed Minimum Criteria for Peat-Forming Areas of the Everglades

*Water levels within wetlands overlying organic peat soils within the WCAs, the Rotenberger and Holey Land WMAs, and Shark River Slough (within Everglades National Park) should not fall 1.0 foot or more below ground level for more than 30 days duration, at return frequencies that are not less than those shown in* ***Tables 6 and 7*** *of this report.*

### Proposed Minimum Water Levels for Marl-Forming Wetlands Located within Everglades National Park

*Water levels within marl-forming wetlands that are located east and west of Shark River Slough, the Rocky Glades, Taylor Slough, and the C-111 Basin within Everglades National Park should not fall below 1.5 feet below ground level for more than 90 days, at a return frequency ranging from 1-in-2 to 1-in-5 years as shown in* ***Tables 6 and 7****.*

The following impacts can be expected to occur if the proposed criteria are exceeded:

- Reversal of the natural process of peat and marl accretion and an increase in the rate of peat oxidation and soil subsidence (lowering of ground level elevations), which reduce the long-term sustainability of the Everglades ecosystem
- Reduced wetland aquatic productivity, disruption of food chains, loss of dry season aquatic refugia, shifts in wetland vegetation from wet-adapted species to those more tolerant of drier conditions, and invasion by exotic species such as melaleuca
- Increased frequency of severe fires that consume peat, damage tree islands, expose bedrock, lower ground level elevations and destroy wildlife habitat that supports rare, threatened, or endangered species
- Continued loss of peat resources and associated freshwater head within the Everglades, which has the potential to reduce the water storage capacity of the regional ecosystem and increase the threat of saltwater intrusion during droughts

## Proposed Research for the Everglades

A number of research activities are under way or have been proposed to validate and/or refine the proposed MFL criteria for the Everglades:

- Peat accretion studies within WCA-2A and Everglades National Park
- A five-year study of tree islands in WCA-3A and WCA-3B
- Ongoing nutrient threshold studies
- Everglades vegetation mapping correlated with hydrological information
- Studies of plant and animal communities in short hydroperiod marl wetlands
- Identification of the spatial distribution of Everglades soils including their physio-chemical properties as they relate to flooding and drying
- Wading bird nesting and foraging studies as they relate to flooding and drying

- Studies of the distribution and abundance of apple snails as they relate to Everglades hydrology
- Systematic reconnaissance flights to document the effects of regional water levels on the movement and abundance of Everglades wading bird populations

# COASTAL BISCAYNE AQUIFER

Minimum water level limits need to be established for the Biscayne aquifer to protect its water resource functions. Development of the proposed MFL criteria were based on evaluation of existing literature; water quality, water level, and canal stage data; comparison to the Ghyben-Herzberg relationship; model results of the influence of canal levels on coastal aquifer water levels; and model results to determine the influence of various canal stages on the position of the saline interface.

## Biscayne Aquifer Water Resource Functions

The Biscayne aquifer provides the primary source of water supply for urban and agricultural users within the LEC Planning Area. Therefore, ground water levels within the aquifer must be maintained at sufficient levels to prevent saltwater intrusion. The highest risk for saltwater intrusion occurs during periods of seasonally high water demands and low rainfall. During low rainfall years, the Biscayne aquifer also provides base flow to important estuaries such as Lake Worth Lagoon, Biscayne Bay, and Florida Bay. These water resource functions were considered in the development of minimum water level criteria for the Biscayne aquifer.

## Structural Changes and Alterations to the Biscayne Aquifer

Development of minimum levels also considered the modifications that have occurred to the Biscayne aquifer. The ground water hydrology of South Florida has been permanently altered by urban and agricultural development and construction of the C&SF Project. Canal construction has drained the Biscayne aquifer, resulting in inland migration of the saline interface. Construction of the coastal canal structures has helped to stabilize the saline interface, although some areas still show evidence of continued saltwater intrusion.

## Minimum Canal Operational Levels to Protect the Biscayne Aquifer

Model simulations and statistical review of historical water levels within wells and the regional canal system show that ground water levels within the Biscayne aquifer are largely controlled by local rainfall and the operation of District water management structures along major canals. Because of this relationship, minimum operational water levels are proposed for coastal canals to protect the Biscayne aquifer on a regional scale.

Modeling results show that short-term variations in ground water levels may result in temporary movement of the saline interface, but the interface retreats to its former position once ground water levels return to their normal range. In contrast, prolonged, depressed ground water levels may result in permanent movement of the interface even after these water levels have returned to normal or above normal conditions. Best available data suggest that permanent movement of the interface occurs when water levels are depressed for more than six months, thus affecting the average annual water level at that location. This relationship was used to establish the minimum ground water level duration component for protection of the Biscayne aquifer until better information becomes available.

Results of this study indicate that managing coastal canals at appropriate water levels during dry periods is a practical means for stabilizing the saltwater interface and preventing further inland migration of the saltwater front. Based on these results, minimum canal operational levels for each of the District's eleven primary water management structures are proposed in **Table 8**. The proposed canal operational levels were selected based on minimizing the threat of saltwater intrusion without adversely affecting flood control.

Based on best available information, District staff recommends the following approach for protection of the Biscayne aquifer against significant harm:

- Manage freshwater elevations within the Biscayne aquifer in a manner that will protect the existing orientation of the freshwater/saltwater interface on a regional and local scale.
- Maintain coastal canal stages at the minimum operation levels shown in **Table 8** of this report for each of the existing 11 primary salinity control structures located within the LEC Planning Area.
- Issue Consumptive Use Permits, consistent with the "no harm" standard.
- Monitor Biscayne groundwater levels and water quality on a regional and localized basis.
- Implement the District's water shortage program pursuant to District Rule 40E-21 F.A.C. whenever the resource is threatened or impacted by saltwater intrusion.
- Conduct further research to refine the relationship between saltwater migration and stage elevations in the Biscayne aquifer.
- Develop a detailed ground water model that can adequately simulate movement of the saline interface under transient conditions and use this model to refine the minimum canal operation levels and duration component proposed in **Table 8**, which are intended to protect the aquifer against saltwater intrusion.
- Improve the existing Biscayne aquifer monitoring program to integrate the chloride monitoring network and the canal stage network. If water

levels in the regional canal network remain below the minimum level specified in **Table 8** for extended periods of time, an investigation will need to be undertaken to determine the cause of the depressed canal levels and associated remedies.

- The *LEC Regional Water Supply Plan* will investigate the need to maintain water levels in additional canals, or modify the stages recommended in **Table 8**, as a result of proposed changes in the Central and Southern Florida Project Comprehensive Review Study (Restudy)/ Comprehensive Everglades Restoration Plan (CERP).

### Minimum Water Levels for the Biscayne Aquifer

*Water levels in the Biscayne aquifer associated with movement of the saltwater interface landward to the extent that ground water quality at the withdrawal point is insufficient to serve as a water supply source for a period of several years before recovering.*

### Minimum Canal Operational Levels

*The minimum water level in a canal, which, if managed for a specific period of time, is sufficient to restrict saltwater intrusion within the coastal aquifer and prevent significant harm from occurring during a period of deficient rainfall. These operational levels are defined in **Table 8**.*

Minimum levels for the Biscayne aquifer in southeastern Dade County are not recommended at this time. The methodology used in this report assumes a goal of stabilizing the saline interface and does not account for freshwater flows that are moving towards coastal water bodies. The District is presently undertaking several studies to assess the ground water flow needs of both the Biscayne and Florida bays. It is recommended that minimum flows for the Biscayne aquifer in southeastern Dade County be developed when minimum flows are developed for the Biscayne and Florida bays to ensure protection of these two coastal water bodies.

## GENERAL RECOMMENDATIONS

The criteria developed in this document should be used as the basis for District rule development, and to incorporate monitoring of the MFL criteria as a factor to be considered in the issuance of Consumptive Use Permits, both individually and cumulatively, within the LEC Planning Area.

These criteria may need to be reviewed, and perhaps revised, as additional data becomes available through MFL research and monitoring projects, or as environmental conditions may change over time (e.g., due to sea level rise or climate change), or as additional experience is gained through the Consumptive Use Permitting process.

# PROPOSED RESEARCH PROGRAMS

A number of research efforts are currently under way, or proposed, over the next several years, to validate and/or refine initial estimates of MFLs for Lake Okeechobee, the Everglades, and the Biscayne aquifer. Below is a brief description of each of these programs.

## Lake Okeechobee Research and Monitoring Programs

Given the uncertainty regarding the length of time water levels may recede below 11 ft NGVD before significant harm occurs, the following research projects are proposed for FY 1999-2001. These include both District projects and collaborative efforts designed to validate the proposed 11 ft NGVD depth criterion and obtain information needed to establish an ecologically-based MFL duration criterion:

### Geographic Information System Studies

District staff have recently updated a Geographic Information System (GIS) map of littoral zone vegetation. These data will be integrated with existing ground level information and lake level variations over the past several years to provide a more precise relationship between hydroperiod and littoral zone plant community structure response.

### Torpedograss Research

The following studies have been proposed to provide additional information regarding the effects of lake level variation and the expansion of torpedo grass within the littoral zone:

- A second year of controlled experiments will be conducted by the wetland ecology group at the USACE-WES, in order to investigate how water depth affects the ability of torpedograss to expand laterally into established stands of native plants.
- District staff continue to monitor the expansion of torpedograss at various scales of resolution. This includes yearly comparison of GIS maps of fixed 1 $km^2$ reference plots, and semi-yearly comparison of torpedograss expansion along a number of distinct fronts. Numerous small plots (1 $m^2$) are being evaluated on the ground at quarterly intervals, to quantify changes in the relative density of torpedograss versus native plant stems. All of these studies are being done across a range of hydroperiods, so that the results can be combined with the information from experimental studies to better define the effects of water level on the community.

### Submerged Plant Research

- In the spring of 1999 District staff began a quarterly program to quantify the biomass and species composition of submerged plants at 45 sites along the north, west, and south lake shore. Information from this study, along with results from controlled experiments planned for 2000-2001, will be used to define an optimal "window" of lake stages for the submerged plant community. That information also can support an ecological basis for the MFL.

## Everglades Research and Modeling

A number of research and modeling efforts are under way to provide additional information that can be used to refine initial estimates of MFLs for the Everglades and Florida Bay. Concurrent with these efforts are investigations of interactions between hydrology, nutrient inputs, and other forces that affect ecosystem structure and function. Research projects include hypothesis-driven field, mesocosm, and greenhouse research. Key indicators of hydrologic conditions are being monitored. These indicators include peat accumulation/subsidence, vegetation change, tree growth, and nutrient fate and transport. Hydropattern models are also being developed to predict ecological responses to planned or proposed management actions. All research projects have been peer reviewed.

### Field Research

#### Peat Accretion Studies

Along nutrient gradients in WCA-2A and hydrologic gradients in Taylor Slough in Everglades National Park, there are a total of 20 sites where Sediment Erosion Tables and feldspar marker horizons have been installed. The Sediment Erosion Tables measure long-term wetland elevation change. Feldspar marker horizons measure local deposition/ sedimentation patterns. Together they are used to evaluate if organic deposition and peat formation is in equilibrium with peat soil oxidation and decomposition. It is possible that if water levels are low for long periods of time, then oxidation may exceed deposition and critical habitats such as sawgrass ridges and tree islands may lose elevation and subside below some healthy threshold. Sediment Erosion Tables and feldspar, measured annually, enable researchers to determine whether implemented hydropatterns are successful in retarding peat oxidation.

#### Tree Island Studies

Flood control and water management have altered predrainage hydropatterns within the WCAs and Everglades National Park causing significant impacts to tree island communities. Prolonged low water levels in northern WCA-3A have resulted in increased frequency of muck fires and destruction of tree island communities. In contrast, prolonged high water levels have severely impacted tree island communities in WCA-2A and southern WCA-3A. A five-year study has been proposed to collect data on tree island development, persistence, and restoration from nine tree island reference sites located in

WCA-3A and WCA-3B. Tasks include collection of tree island topography and peat depths, determination of peat accumulation rates, delineation of tree island boundaries, seed bank composition, tree growth studies, soil and plant nutrient content, and effects of deer grazing and plant recruitment. These data will provide the necessary information needed to develop MFLs and water management plans that will preserve remaining tree islands and provide a basis for restoring tree island habitat in areas where it has been lost to high water levels or overdrainage.

### Short Hydroperiod, Marl-Forming Wetlands Research

Most of the plant and animal communities that exist in the remaining marl-forming wetlands within, and adjacent to, Everglades National Park have been severely impacted by development and overdrainage. Studies of remaining communities have provided some limited information concerning the appropriate depths and durations of water levels needed to sustain their characteristic vegetation and wildlife communities. Additional information, however is required to determine an appropriate return frequency for drought conditions that can be tolerated by both plant and animal populations without causing significant harm to their structure and function. Research on short hydroperiod, marl-forming wetland plant and animal communities is needed to determine a) the distribution, extent, and structure of these communities in the historic Everglades and their potential distribution in the restored system; b) their historic and potential future role and significance as sources of food for wading birds and other vertebrates; and c) the seasonal dynamics of fish and macroinvertebrate populations, especially the amount of time that sustained high water levels are required to maintain aquatic productivity.

### Nutrient Threshold Studies

The Everglades Forever Act requires that the SFWMD conduct research and monitoring to define nutrient levels that will cause no imbalance in flora or fauna. Large field-scale mesocosms (five-feet diameter chambers) have been set up in WCA-2A and WCA-1, to which phosphorus is dosed and ecological responses are observed. As part of this program, hydrologic experiments have been added to evaluate nutrient and hydropattern interactions. For example, seed germination rates and seedling growth can be evaluated in these mesocosms by placing incubation trays at different depths. These mesocosm experiments on hydrology and phosphorus interactions are being supplemented by very controlled, flow tank experiments in the Everglades Botanical Research Complex (EBRC) at Florida Atlantic University (FAU). These experiments include hydrologic evaluations of seed germination rates, plant-soil interactions, root development, oxygen transport, and plant recovery after fire.

### Everglades Vegetation Mapping

Long-term changes in vegetation (both native and nuisance species) are captured using aerial photography, satellite imagery, and ground truthing to provide a database for determining the influence of natural and societal influences. Average water level depths, duration and return frequency data can be correlated with existing vegetation associations.

### Everglades Soil Nutrient Research

The Everglades have evolved as a nutrient-poor ecosystem with the majority of phosphorus inflows derived from direct rainfall. However, over the past 30 years, the Everglades have received increased phosphorus loading from adjacent agricultural and urban lands. Current research is designed to identify the spatial distribution of these soil nutrients as a means of assessing the impact of nutrients on the ecosystem. The SFWMD has collected over 400 soil cores throughout the WCAs and the Holey Land and Rotenberger WMAs to define their distribution and long-term nutrient accumulation rates, as well as the effects of flooding and drying of these soils on their physiochemical properties and phosphorus retention characteristics.

### Wading Bird Nesting Success

Wading bird nesting success in response to changes in hydrologic conditions and food availability within the WCAs is quantified in this study. This study provides information that is essential to assess the impacts of water management practices on wildlife as they relate to Everglades hydrology.

### Wading Bird Foraging Experiments

The wading bird foraging experiments quantify wading bird foraging as a function of water depth and prey density. While anecdotal information exists, this study is the first attempt to quantify this relationship statistically. The study is conducted in 15 impoundments that can be hydrologically manipulated and stocked with various levels of fish prey. This study, in combination with several others, will lead to a clearer understanding of how water levels should be varied over time and space to maximize wading bird abundance and survival.

### Snail Kite Food Web Study

The relationship between snail kites *(Rostrhamus sociabilis)* their major prey item, apple snails *(Pomacea paludosa)* and hydrology was studied in this project. The study investigated the distribution and abundance of apple snails in the WCAs relative to vegetation type, water depth, and water quality. In addition, snail kite feeding and nesting is being monitored, since changes in their population status usually corresponds to changes in hydrology, localized food depletion, and/or changes in water quality. These studies on apple snails and snail kites can be used to assess the ecological impacts of water management alternatives and thresholds associated with MFLs.

### Systematic Reconnaissance Flights

Several agencies have funded long-term studies of bird populations and their movement in South Florida. Although bird surveys may not provide direct information for establishing MFLs, knowing their numbers and relationship to Everglades water levels will be useful information. The District is currently funding studies to analyze these data.

## Model Development

### Everglades Landscape Model (ELM)

The Everglades Landscape Model (ELM) is a regional-scale ecological model that simulates Everglades hydropatterns, nutrient fate and transport, and landscape vegetation changes as a function of human-influenced and natural factors, including water management. The ELM can simulate how vegetation patterns change and how peat accretes or subsides under different water management scenarios, thereby yielding information on the long-term effects of water management decisions, as well as the potential effects of implementing proposed MFL criteria. The ELM uses empirically-based soil total phosphorus algorithms, but incorporates the mechanisms of macrophyte growth and succession in response to changes in hydrology, nutrients, and disturbance. It is important to emphasize those MFLs identified by the ELM may not equate with hydropatterns and nutrient conditions that will restore the Everglades.

### SAWCAT (Sawgrass-Cattail Transition) Model

SAWCAT is a transition probability model developed by Wu (1997) to understand the impact of soil phosphorus concentrations, hydrology, and nearest neighbor interactions on cattail invasion in WCA-2A. The model examines satellite maps of cattail expansion to calculate the likelihood of sawgrass change for each 400-square mile grid cell, This change was dependent, in the model, upon the cell’s hydrology, proximity to cattails, and nutrient inputs. The model estimated a 50 percent increase in cattails in WCA-2A by 2020 if hydroperiods are not restored to historic patterns (as predicted by NSM) and water quality inputs do not improve from those typically measured during the 1970s. SAWCAT can be used to examine the relative differences of MFLs in WCA-2A.

### Everglades Landscape Vegetation Model (ELVM)

The Everglades Landscape Vegetation Model (ELVM) is a dynamic spatial simulation model, similar to ELM, but without the simulated nutrient and hydrologic dynamics. The ELVM is a high-resolution grid (30 meter x 30 meter) plant growth model where the plants respond to hydropattern, water quality, and competitive interactions between vegetation species. For any given water quality regime, this model predicts tree island demise, recovery, and sustainability in WCA-2A. Using the SFWMM as hydrologic input, the ELVM will be able to compare the relative differences of MFLs and water management alternatives on the vegetation communities in the WCAs.

## Florida Bay Research

### Florida Bay Paleoecology and Sediment Cores

The purpose of the Florida Bay paleoecology and sediment cores study is to describe the historical characteristics of Florida Bay. Sediment cores have been collected to determine historical salinity and biological conditions during the past two hundred years within the Bay. This information is essential for identifying Florida Bay restoration goals, to successfully meet the intent of Section 373.4593 of the Everglades Forever Act, and to help develop MFL criteria. Knowing past salinity records will aid in estimating freshwater inputs required to sustain appropriate salinity concentrations and prevent significant harm to the biological resources of the bay. Cores have also been taken in the mangrove coastal zone to determine long-term historical (1000s of years) hydropatterns through correlation with past floral and faunal records. These cores may be able to establish vertical patterns of soil nutrients, peat accumulation rates, and vegetation succession patterns using pollen. Cores will be obtained and dated using radiotracer methods. Among other things, the data collected in this research will be used to relate long-term vegetation associations as a means to estimate historical predrainage hydropatterns.

Paleoecological profiles are also being developed from coral cores. The objective of this contract is to gain a retrospective knowledge of salinity conditions of Florida Bay during the past 100 years. By dating bands within coral cores and measuring isotopic variability, past salinity variations of Florida Bay can be estimated, perhaps on a time scale of weeks or months. Information on how much salinity has historically varied within the bay in relationship to upstream freshwater inputs is essential to guide restoration efforts and the development of MFL criteria.

### Florida Bay Seagrass Studies

The Florida Bay seagrass studies will quantify spatial and temporal patterns of seagrass growth and mortality in northern Florida Bay and will elucidate the relationship of these patterns to freshwater inflow. Seagrass beds are the habitat of important fauna, such as fish and shrimp. Therefore, understanding their response to fresh water is important for the fisheries resource.

### Florida Bay Salinity Transition Zone

The Florida Bay salinity transition zone study will determine the extent to which current changes in Florida Bay are dependent upon ecological functions in the salinity transition zone (mainly mangrove areas). The salinity transition zone is affected by changing hydrology in South Florida and rising sea level. Rates of peat accretion, sedimentation, primary production, decomposition, and nutrient influx and efflux are being measured at the transition zone. In order to understand the cause of sustained algal blooms and possible effects on seagrass beds in Florida Bay, we need to know the extent to which there is a net transport of nutrients between the bay and the transition zone, and how this transport is affected by water management practices. An additional reason for understanding salinity transition zone dynamics, in relation to freshwater inflows and MFLs, is that it is a nursery for fish and shrimp, and habitat for wading birds such as the roseate spoonbill.

### Florida Bay Seagrass and Plankton Model (FBSPM)

The Florida Bay Seagrass and Plankton Model (FBSPM) is a spatially average dynamic simulation model that will capture the interactions between light, nutrients, phytoplankton, and salinity on the growth and reproduction of seagrass within a unit area of bay bottom. Work on this model is expected to begin in 2000 with funding from the National Park Service. The FBSPM will evaluate the ecological significance of salinity patterns (ranges and variability) which, in turn, will be related to water management, operational schedules, restoration goals, and the establishment of MFLs.

### Mangrove Fish Study

This research has quantified the spatial and temporal dynamics of fish populations within the marshes of the salinity transition zone. These mangrove marshes are vital foraging grounds for populations of wading birds, including the threatened roseate spoonbill. Linkages between upstream hydrology and the abundance of fish communities are critical to our understanding of the spoonbill and the Florida Bay ecosystem. This study can be used to help set criteria for MFLs and understand the effects of water management. The demographic results of this study needs to be analyzed within the context of establishing MFLs for the coastal mangrove and lagoon system in Florida Bay. The USGS modeling program for the Everglades (ATLSS) has initiated a mangrove fish model which should help this analysis.

## Biscayne Aquifer Research and Monitoring Programs

The criteria proposed in **Table 9** of this report are intended to provide interim minimum levels for the Biscayne aquifer until better criteria can be established. It is hoped that the research and monitoring efforts described below can be completed within the next few years so that these results can be incorporated into the next update of the *LEC Water Supply Plan*.

### Development of a Solute Transport Ground Water Model

In the late 1980s, the District developed a site specific transport model to evaluate saltwater intrusion problems in southern Broward County (city of Hallandale area). Since that time, significant advancements have been made in the development of ground water models that can simulate movement of the saltwater interface under transient conditions. Future efforts should be undertaken to develop a solute transport model that simulates larger areas of the LEC Planning Area, especially for those areas where saltwater intrusion is suspected to impact the aquifer. This model should be developed over the next five years by District staff, or through contractual or cooperative agreements with other agencies and consultants, so that the results can be incorporated into the *LEC Water Supply Plan Update*. Key information to be derived from development of the solute transport ground water model include the following:

- More precise location of the saline interface as well as seasonal and long-term movement patterns
- A better understanding of the relationship between canal water levels maintained at the 11 key water management structures and potential movement of the saltwater interface

- A better scientific estimate of the length of time water levels may fall below the recommended minimum canal operational levels (**Table 9**) before significant harm occurs (movement of the saltwater interface).

### Saltwater Intrusion Monitoring

The *Interim Plan for the LEC Regional Water Supply Plan* (SFWMD, 1997) recommended that the existing saltwater intrusion monitoring program should be evaluated to determine it's reliability to detect the movement of the saline interface and expanded to identify the interface throughout the entire LEC Planning Area.

Various activities are presently under way between the District and other agencies to expand and improve the existing network of monitoring wells. The District has mapped the location of the saline interface and identified areas where additional wells are needed. Additional transects are presently being established across the saline interface and some additional wells have been constructed to understand how the interface moves and is influenced by seasonal and long-term changes in water levels. Additional funding will be required to construct the remaining wells. Once data from these additional wells become available and are analyzed, the improved solute transport model can also be used to develop a better understanding of the location and movement of the saltwater interface over time.

### Relationship Between Canal Stages and Saltwater Intrusion

The District is also working cooperatively with other agencies to develop a comprehensive monitoring program to integrate the chloride monitoring network and the canal stage network for the LEC Planning Area. Collection and analysis of these data, in conjunction with improved modeling techniques, will also help refine the proposed Biscayne aquifer MFL criteria by providing and improved understanding of relationships between canal water levels and movement of the saline interface.

### Minimum Canal Level Duration

The improved ground water model and additional data collected from the expanded monitoring network will also be applied to validate and/or refine the minimum canal level and duration components proposed in **Table 9** of this report

### Other Investigations

The effectiveness of the proposed MFL Recovery and Prevention Plan evaluation process will be tested using the SFWMM initially. If water levels in the aquifer or regional canals remain below the minimum level specified in **Table 9** for extended periods of time, with the proposed water storage and water distribution projects in place, further investigations will be undertaken to determine causes of the depressed canal and aquifer levels and potential remedies.

# REFERENCES

Alexander, T.R. and A.G. Crook. 1973. Recent and long term vegetation changes and patterns in South Florida, Part I, Appendix G, *Preliminary Report of the South Florida Ecological Study*. University of Miami, Coral Gables, FL.

Alexander, T.R. and A.G. Crook. 1984. Recent vegetation changes in South Florida. In: Gleason (ed.) *Environments of South Florida: Past and Present.* Miami Geological Society, Miami, FL.

Andersen, P.F., H.O. White, J.W. Mercer, and P.S. Huyakorn. 1986. *Numerical Modeling of Groundwater Flow and Saltwater Transport in the Vicinity of Hallandale*. Florida. Geotrans, Herdon, VA.

Andersen, P.F., J.W. Mercer, and J.W. White. 1988. Numerical modeling of salt-water intrusion at Hallandale, Florida. *Groundwater.* 26 (5): 619-630.

Aumen, N.G. 1995. History of human-related impacts to Lake Okeechobee, Florida (U.S.A.), related research, and lake management issues. *Archiv fur Hydrobiologie*, Advances in Limnology. 45:1-30.

Aumen, N.G. and S. Gray. 1995. Research synthesis and management recommendations from a five-year, ecosystem-level study of Lake Okeechobee, Florida (USA). *Archiv fur Hydrobiologie*, Advances in Limnology. 45:343-356.

Aumen, N.G. and R.G. Wetzel. 1995. Ecological studies on the littoral and pelagic systems of Lake Okeechobee, Florida (USA). *Archiv fur Hydrobiologie*, Advances in Limnology. Vol. 45.

Bancroft, G.T. 1993. Florida Bay-An endangered North American jewel. *The Florida Naturalist*. Spring 1993.

Bancroft, G.T., A.M. Strong, R.J. Sawicki, W. Hoffman, and S.D. Jewell. 1994. Relationships among wading bird foraging patterns, colony locations, and hydrology in the Everglades. In: *Everglades: The Ecosystem and Its Restoration*, ed. S.M. Davis and J.C. Ogden. St. Lucie Press, Delray Beach, FL.

Bear, J. 1972. *Dynamics of Fluids in Porous Media*. American Elsevier, New York, NY.

Bear, J. and D.K. Todd. 1960. *The Transition Zone Between Fresh and Salt Waters in Coastal Aquifers*. Water Resources Center Contribution No. 29, Hydraulic Laboratory, University of California, Berkeley, CA.

Beard, D. B 1938. *Wildlife Reconnaissance, Everglades National Park Project*. Report of the U.S. Dept. of the Interior, National Park Service, Washington, D.C.

Bell, F.W. 1987. *The Economic Impact and Valuation of the Recreational and Commercial Fishing Industries of Lake Okeechobee, Florida*. Technical Report, Florida Game and Fresh Water Fish Commission, Tallahassee, FL.

Bennetts, R.E., and W.E. Kitchens. 1997. *The Demography and Movements of Snail Kites in Florida.* Technical Report No. 56, Biological Resources Division.

Bennetts, R.E., M.W. Collopy, and J.A. Rodgers, Jr. 1994. The snail kite in the Florida Everglades: A food specialist in a changing environment. In: *Everglades: The Ecosystem and Its Restoration* ed. Davis, S.M. and J.C. Ogden (Eds) 1994. St. Lucie press, Delray Beach, FL.

Bodle, M. J., A.P. Ferriter and D.D. Thayer, 1994. The biology, distribution and ecological consequences of *Melaleuca quinquenervia* in the Everglades. In: Davis, S.M. and J.C. Ogden (Eds). Everglades: *The Ecosystem and Its Restoration*. St. Lucie Press, Delray Beach, FL.

Boesch, D.F., N.E. Armstrong, C.F. D'Elia, N.G. Maynard, H.W. Paerl, and S.L. Williams. 1993. *Deterioration of the Florida Bay Ecosystem: an Evaluation of the Scientific Evidence*. Report to the Interagency Working Group on Florida Bay, Nat. Fish and Wildlife Foundation, Nat. Park Service, So. Fla. Water Management District, Sept. 15, 1993. 27 pp.

Brooks, H.D., 1974. Lake Okeechobee. In: Gleason (ed.) *Environments of South Florida: Past and Present, Memoir 2,* Miami Geological Society, Miami FL. pp. 256-286.

Browder, J.A. 1981. *Perspective on the Ecological Causes and Effects of the Variable Algal Component of Southern Everglades Periphyton*. South Florida Research Center Report T-643, National Park Service, Everglades National Park, Homestead, FL.

Buchanan, T.J. and H. Klein, 1976. Effects of Water Management on Fresh Water Discharge to Biscayne Bay. In: Biscayne Bay, Past/Present/Future. Proc. Biscayne Bay Symposium I, April 2-3, 1976. University of Miami (Florida), Sea Grant Special Report No. 5. pp 271-277.

Cornwell,G. and E.C. Hutchinson 1974. *An Ecological Analysis of an Everglades Township in Southwest Palm Beach County, Florida*. Ecoimpact Inc., Gainesville, Fl.

Chamberlain, R.H., D.E. Haunert, P.H. Doering, K. Haunert, and J. Otero. 1995. *Preliminary Estimate of Optimum Freshwater Inflow to the Caloosahatchee Estuary, Florida*. South Florida Water Mangement District, West Palm Beach, Fl.

Cohen, A.D. and W. Spackman, 1977. Phytogenic organic sediments and sedimentary environments in the Everglades-mangrove complex. Part II. The origin, description and classification of the peats of southern Florida. Palaeontographica, 162 (Abt.B):71-114.

Costanza, 1975. *The Spatial Distribution of Land Use Systems, Incoming Energy and Energy Use in South Florida from 1900 to 1973*. Masters Research Project, Department of Architecture, University of Florida, Gainesville, FL 254 pp.

Craighead, F.C. Sr. 1969. Vegetation and recent sedimentation in EvergladesNational Park. *Fla. Nat.* 42:157-166.

Craighead, F.C. Sr. 1971. *The Trees of South Florida*, Vol I: *The Natural Environments And Their Succession*, Uni. of Miami Press, Coral Gables, FL.

Dachnowski-Stokes, A.P. 1930. Peat profiles of the Everglades of Florida: The stratigraphic features of the "upper" Everglades and correlation with environmental changes. *J. Wash. Acad. Sci.* 20:89-107.

Davis, J.H. 1943a. *The Natural Features of Southern Florida, Especially the Vegetation of the Everglades*. Bulletin No. 25, Florida Geological Survey, Tallahassee FL.

Davis, J.H., Jr. 1943b. Vegetation of the Everglades and conservation from the point of view of the plant ecologist. *Proceedings of the Soil Science Society of Florida*, 5-A:105-113.

Davis, J.H. 1946. The Peat deposits of Florida - Their Occurrence, Development, and Uses. Bulletin No. 30:1-247, Florida Geological Survey, Tallahassee FL.

Davis, S.M., L.H. Gunderson, W.A. Park, J.F. Richardson, and J.E. Mattson. 1994. Landscape dimension, composition, and function in a changing Everglades ecosystem. In: Davis, S.M. and J.C. Ogden (Eds) 1994. *Everglades: The Ecosystem and Its Restoration*. St. Lucie press, Delray Beach, FL.

Davis, S.M. and J.C. Ogden (Eds) 1994. Everglades: *The Ecosystem and Its Restoration*. St. Lucie press, Delray Beach, FL. 826 pp.

DeAngelis, D.L. 1994. Synthesis: Spatial and temporal characteristics of the environment. In: Davis, S.M. and J.C. Ogden (Eds) 1994. *Everglades: The Ecosystem and Its Restoration*. St. Lucie press, Delray Beach, FL. pp. 307-322

Dineen, J.W. 1972. Life in the tenacious Everglades. *In Depth Report* 1(5):1-10. Central and Southern Flood Control District, West Palm Beach, FL.

Domenico, P.A. and Schwartz, F.W., 1990. *Physical and Chemical Hydrogeology.* John Wiley and Sons, New York, NY, 824 p.

Egler, F.E. 1952. Southeast saline Everglades; vegetation of Florida and its management. *Vegetation*, 3:213-265.

EFA. Everglades Forever Act, Florida Statutes 373.4592

Fenemma, R.A., C.J. Neidrauer, R.A. Johnson, T.K. MacVicar, and W.A. Perkins, 1994. A computer model to simulate natural Everglades hydrology. In: Davis, S.M. and J.C. Ogden (Eds) 1994. *Everglades: The Ecosystem and Its Restoration*. St. Lucie press, Delray Beach, FL. pgs. 249-290.

Fish, J.E., 1988. *Hydrogeology, Aquifer Characteristics, and Ground-water Flow of the Surficial Aquifer System, Broward County, Florida*. U.S. Geological Survey Water-Resources Investigations Report 87-4034, Tallahassee, FL, 92 p.

Fish, J.E., and Stewart, M., 1991. *Hydrogeology of the Surficial Aquifer System, Dade County, Florida*. U.S. Geological Survey Water-Resources Investigations Report 90-4108, Tallahassee, FL, 50 p.

Fernald and Purdum. 1998. *Water Resource Atlas of Florida*. Institute of Science and Public Affairs, Florida State University, Tallahassee, FL, 312 p.

FGFWFC. unpublished data (Fire history maps provided by Steve Coughlin, Florida Game and Freshwater Fish Commission, West Palm Beach, FL.

Florida Electric Power Coordinating Group, Inc., et al, Petitioners, Florida Engineering Society Inc., Intervenors vs. Suwanee River Water Management District, et al.

Respondents, 17 FALR 3242 (DOAH Final Order July 24, 1995) (Aff'd 672 So. 2d 141 (Fla 4th DCA 1996).

FDEP. 1997. *Water Management District's Minimum Flows and Levels Combined 1997 Priority Lists*. February 16, 1998. 1p. Florida Department of Environmental Protection, Tallahassee Florida.

Florida Game and Freshwater Fish Commission, Personal Communication. Letter dated May 10 1993, from Stephen Coughlin to David Swift, concerning Everglades properties managed by the FGFWFC. 7pp.

Fox, D.D., S. Gornak, T.D. McCall, D.W. Brown and C.J. Morris. 1995. *Lake Okeechobee Fisheries Investigations. State of Florida, Florida Game and Freshwater Fish Commission, Lake Okeechobee-Kisssimmee River Project*. Completion Report (Fiscal years 1992-1993 and 1994-1195). Florida Game and Fresh Water Fish Commission, Tallahassee, Fl., 177 pgs.

Furse, J.B. and D.D. Fox 1994. Economic fishery valuation of five vegetation communities in Lake Okeechobee, Florida. *Proceeedings of Annual Conference Southeast Association of Fish and Wildlife Agencies*. 48, pp. 575-591.

Freeze, R.A. and Cherry, J.A., 1979. *Groundwater.* Prentice Hall, Inc., Englewood Cliffs, NJ, 604 p.

Gleason, P. J. 1972. *The Origin, Sedimentation, and Stratigraphy of a Calcite Mud Located in Southern Freshwater Everglades*. Ph.D Dissertation, Pennsylvania State University, University Park PA.

Gleason, P.J. and W. Spackman. 1974. Calcareous periphyton and water chemistry in the Everglades. In: *Environments of South Florida: Present and Past*, P.J. Gleason (Ed.), Memoir No. 2, Miami Geological Society, Miami, FL, pp. 146-181.

Gleason, P.Jand P. Stone. 1974. *Special Report on the Effects of Recent Burning of Conservation Area 3 North of Alligator Alley.* South Florida Water Management District Report.

Gleason, P.J. and P.A. Stone. 1994. Age, origin, and landscape evolution of the Everglades peatland. In: *Everglades: The Ecosystem and Its Restoration.* S.M. Davis and J.C. Ogden (Eds.), St. Lucie Press, Delray Beach, FL., chap. 7.

Gunderson, L.H. and W. F. Loftus. 1993. *Competing Land Uses Imperil the Biotic Communities of a Vast Wetland*. South Florida Research Center, Everglades National Park, Homestead, FL.

Gunderson, L.H. and J.R. Snyder. 1994. Fire patterns in the southern Everglades. In: Davis, S.M. and J.C. Ogden (eds). *Everglades: The Ecosystem and Its Restoration*. St. Lucie Press, Delray Beach, FL. pgs. 291-306.

Hall, C.A. 1991. Lake Okeechobee Supply-Side Management Plan. Operations and Maintenance Dept., South Florida Water Management District, West Palm Beach, Fl.

Harper, R.M. 1927. Natural Resources of South Florida. 18th annu. Rep. Florida Geological Survey, Tallahassee, FL.

Haunert, D.E. 1988. Sedimentation characteristics and toxic substances in the St. Lucie Estuary, Florida. Technical Publication 88-10. South Florida Water Management District, West Palm Beach, FL. 40 pp.

Havens, K.E., L.A. Bull, G.A. Warren, T.L. Crisman, E.J. Phlips & J.P. Smith. 1996. Food web structure in a subtropical lake ecosystem. *Oikos*, in press.

Havens, K.E., N.G. Aumen, R.T. James and V.H. Smith 1996. Rapid ecological changes in a large subtropical lake undergoing cultural eutrophication. *Ambio* 25, pp.150-155

Havens, K.E. and B.R. Rosen 1997. Lake Okeechobee conceptual model. Techncial report. South Florida Water Management District, West Palm Beach, Fl.

Havens, K.E., L. Manners, and R. Pace. 1998. Priority hydrologic performance measures for Lake Okeechobee. Techncial document developed in support of the C&SF ProRestudy Project, Alternative Evaluation Team report.

Hoffman, W., G.T. Bancroft, R.J. Sawicki. 1994. Foraging habits of wading birds in the Water Conservation Areas of the Everglades. In: Davis, S.M. and J.C. Ogden (eds) 1994. Everglades: *The Ecosystem and Its Restoration*. St. Lucie press, Delray Beach, FL

Hoffmeister, J.E., 1974. *Land from the Sea*, Miami, FL, 143 p.

Hutchinson, G.E. 1957. A treatise on limnology, Volume.1, Geography, physics, and chemistry. John Wiley and Sons, New York, N.Y., 1015 pp.

Huyakorn, P.S., Mercer, J.W., and Andersen, P.F., 1986. SWICHA: A Three-Dimensional Finite Element Code for Analyzing Seawater Intrusion in Coastal Aquifers. Geotrans, Herndon, VA, 167 p.

J.M. Montogemery, Inc. 1986. The study of water supply and the selection of future wellfield sites in Broward County, Florida

Jensen, J., K. Rutchey and, M. Koch and S. Narumalani 1995. Inland wetland change detection in Everglades Water Conservation Area 2A using a time series of normalized remotely sensed data. *Journal of Photogrammetric Engineering and Remote Sensing*, 61 (2):199-209.

Jones, L.A. 1948. Soils, geology and water control in the Everglades region. Bull. Vol. 442, University of Florida Agricultural Experiment Station. Prepared in cooperation with the USDA Soil Conservation Service. Gainesville, FL, 168 pp.

Klein, H., J.T. Armbruster, B.F. McPherson and H.J. Freiberger. 1975. Water and the South Florida environment. Water Resources Investigation 24-75. U.S. Geological Survey, Tallahassee, FL, 165 pp.

Klein, H. and J.E. Hull 1978. Biscayne aquifer, Southeast Florida. U.S. Geological Survey Water-Resources Investigations 78-107.

Kohout, F.A. 1960. Cyclic flow of salt water in the Biscayne aquifer of southeastern Florida. Journal of Geophysical Research, V 65 (7), pp 2133-2141.

Koszalka, E.J. 1995. Delineation of saltwater intrusion in the Biscayne aquifer, eastern Broward County, Florida, 1990. U.S. Geological Survey Water-Resources Investigations Report 93-4164.

Light, S.S. and J.W. Dineen 1994. Water control in the Everglades: A historical perspective. In: *Everglades: The Ecosystem and Its Restoration.* S.M. Davis and J.C. Ogden (Eds.), St. Lucie Press, Delray Beach, FL, pp. 461-484.

LOLZTG. 1988. Assessment of Emergency Conditions in Lake Okeechobee littoral Zone: Recommendations for interim management. Preliminary report by the Lake Okeechobee Littoral Zone Technical Group (LOLZTG) to John R. Wodraska, Executive Director, South Florida Water Management District, West Palm Beach, FL.

Lietz, C., T. Richards, and R. Krulikas 1995. Water resources data, Florida, 1994, Volume 2B, South Florida Ground Water. U.S. Geological Survey Water-Data Report FL-94-2B. Miami, FL, 780 pp.

Lockhart, C.S. 1995. The effect of water level variation on the growth of melaleuca seedings from the Lake Okeechobee littoral zone. MS thesis, Florida Atlantic University, Boca raton, FL.

Loftus, W.F., R.A. Johnson, and G. Anderson. 1992. Ecological impacts of the reduction of groundwater levels in the rocklands. In: *Proc.. 1st Int. Conf. of Ground water Ecology,* J.A. Stafford and J.J. Simon (Eds.) American Water Resources Association, Bethesda, Md. pp.198-208.

Loftus, W.F. and Anne-Marie Ekland. 1994. Long-term dynamics of an Everglades small-fish assemblage. In: *Everglades: The Ecosystem and Its Restoration.* S.M. Davis and J.C. Ogden (Eds.), St. Lucie Press, Delray Beach, FL, pp. 461-484.

Loveless, C.M.1959. A study of the vegetation of the Florida Everglades. Ecology, 40(1):1-9.

MacVicar, T.K. 1985. A wet season field test of experimental water deliveries to northeast Shark River Slough. Technical Publication 85-3, South Florida Water Management District, West Palm Beach, FL.

McCormick, P.V., R.B.E. Shuford, J.G. Backus, and W.C. Kennedy. 1997. Spatial and seasonal patterns of periphyton biomass and productivity in the northern Everglades. *Hydrobiologia,* in press.

McDowell, L.L., J.C. Stephens, and E.H. Stewart. 1969. Radiocarbon chronology of the Florida Everglades peat. *Soil Sci. Soc. Am. Proc.* 33:743-745.

McIvor, C.C., J.A. Ley and R.D. Bjork. 1994. Changes in freshwater inflow from the Everglades to Florida Bay including effects on biota and biotic processes: A Review. In: Davis, S.M. and J.C. Ogden (Eds) 1994. Everglades: *The Ecosystem and Its Restoration*. St. Lucie press, Delray Beach, FL.

Merritt, M. L. 1996. Assessment of saltwater intrusion in southern coastal Broward County, Florida. U.S. Geological Survey, Water Resources Investigations Report. 96-4221, Tallahassee, Fl. 133 p.

Milleson, J.F. 1987. Vegetation changes in the Lake Okeechobee littoral zone, 1972-1982. Technical Publication 87-3. South Florida Water Management District, West Palm Beach, Fl. 157 pp.

Neidrauer, C.J. and R.M. Cooper. 1989. A two-year field test of the rainfall plan: A management plan for water deliveries to Everglades National Park, July 1985-1987. Technical Publication 89-3. South Florida Water Management District. West Palm Beach, FL, 98 pp.

Neidrauer, C. J., Trimble, P.J., and E.R. Santee. 1997. Simulation of alternative operational schedules for Lake Okeechobee. Hydrologic Systems Modeling Division, Planning Department, South Florida Water Management District, West Palm Beach, FL. 22 pp.

NPS-SFRC 1989. Technical and Management Report. U.S. Department of the Interioir, National Park Service, South Florida Research Center, Everglades National Park, Homestead, FL.

Ogden, J.C., W. F. Loftus and W. B. Robertson, Jr. 1987. Woodstorks, wading birds and freshwater fishes. Statement Paper. U.S. Army Corps of Engineers, General design memorandum on modified deliveries to Everglades National Park, South Florida Research Center, Homestead, FL.

Olmstead, I.C. and L.L. Loope. 1984. Plant communities of Everglades National Park. In: *Environments of South Florida: Present and Past*, P.J. Gleason (Ed.), Memoir No. 2, Miami Geological Society, Miami, FL., pp. 167-184.

Olmsted, I. C., L.L. Loope and R.E. Rintz. 1980. A survey and baseline analysis of aspects of the vegetation of Taylor Slough, Everglades National Park. South Florida Research Center Technical Report T-586. Everglades National Park, Homestead, FL.

Parker, G.G., G.E. Ferguson, and S.K. Love. 1955. *Water Resources of Southeastern Florida with Special Reference to the Geology and Groundwater of the Miami Area*. Water Supply Paper 1255, U.S. Geological Survey, U.S. Government Printing Office, Washington, D.C., 965 pp.

Perkins, W.A. and T.K. MacVicar. 1991. A computer model to simulate natural south Florida hydrology, Draft report, South Florida Water Management District, West Palm Beach, FL.

Pesnell, G.L. and R.T. Brown, III. 1973. The vegetation of the Lake Okeechobee, Florida (map). Central & Southern Florida Flood Control District. West Palm Beach, FL.

Puri, H.S. and R.O. Vernon. 1964. Summary of the geology of Florida and guidebook to the classic exposures. *Fla. Geol. Surv. Spec. Publ.*, No. 5, 312 pp.

Restrepo, J., Bevier, C. and Butler, D. 1992. A three dimensional finite difference ground water flow model of the Surficial Aquifer System, Broward County, Florida. Tech. Pub. 92-05, South Florida Water Management District, West Palm Beach, FL.

Richardson, C.J. and C.B. Craft. 1990. Phase One: A preliminary assessment of nitrogen and phosphorus accumulation and surface water quality in Water Conservation Areas 2A and 3A of South Florida. Publication 90-01. School of Forestry and Environmental Studies,Duke Wetland Center, Duke University, Durham, NC.

Richardson, J.R., T.T. Harris. 1995. Vegetation mapping and change detection in the Lake Okeechobee marsh ecosystem. *Archiv. fur Hydrobiologie, Advances in Limnology,* Vol. 45, pp.17-39.

Richardson, J.R., T.T. Harris, and K.A. Williges. 1995. Vegetation correlations with various environmental parameters in the Lake Okeechobee littoral marsh ecosystem. *Archiv. fur Hydrobiologie, Advances in Limnology,* vol. 45, pp.41-61.

Robertson, W.B. Jr. 1953. A survey of the effects of fire in Everglades National Park. Everglades National Park, National Park Service, United States Department of the Interior, Homestead, FL.

Robertson, W. B. and J.A. Kushlan. 1984. The southeastern Florida avifauna. In: Gleason (ed.) *Environments of South Florida: Past and Present*. Miami Geological Society, Miami Fl.

Rutchey, K. and L. Vilchek 1994. Development of an Evergaldes vegetation map using SPOT Image and the Global Positioning System. *Journal of Photogrammetric Engineering and Remote Sensing,* 60 (6):7767775.

Schomer, N.S. and R.D. Drew. 1982. An ecological characterization of the lower Everglades, Florida Bay, and the Florida Keys. FWS/OBS-82/58.1. U.S. Fish and Wildlife Service, Office of Biological Services, Washington, D.C., 246 pp.

Schortemeyer, J. L. 1980. An evaluation of water management practices for optimum wildlife benefits in Conservation Area 3A. Florida Game and Freshwater Fish Commission, Ft. Lauderdale, FL.

Science Subgroup, 1994. South Florida ecosystem restoration: scientific information needs. Draft Sept. 27, 1994. Management and Coordination Working Group, Interagency Task Force on the South Florida Ecosystem.

Scientific Working Group. 1995. Record of the proceedings of the Scientific WorkingGroup meetings of August 29-31, 1994 conducted at the Palm Beach Hilton Hotel, West Palm Beach, Florida in support of the Lower East Coast Regional Water Supply Plan, South Florida Water Management District, West Palm Beach, FL.

SFWMD, 1998. Interim Plan for Plan for Lower East Coast Regional Water Supply, Planning Dept., South Florida Water Management District, West Palm Beach, Fl., March, 1998.

Sheng, Y.P. and H.K. Lee. 1991. Computation of phosphorus flux between the vegetation area and the open water in Lake Okeechobee. Final Report, Contract Investigation. Prepared for South Florida Water Management District, West Palm Beach, FL.

Shih, G. 1983. Data analysis to detect rainfall changes in south Florida. Technical Memorandum. South Florida Water Management District, West Palm Beach, FL.

Shine, M., D. Padgett, and W.M. Barfknect. 1989. Ground water resource assessment of eastern Palm Beach County, Florida. Technical Publication #89-4, South Florida Water Management District, West Palm Beach, FL.

Smith, J.P., J.R. Richardson & M.W. Callopy. 1995. Foraging habitat selection among wading birds (Ciconiiformes) at Lake Okeechobee, Florida, in relation to hydrology and vegetative cover. *Archiv fur Hydrobiologie*, Advances in Limnology, 45: 247-285.

SFWMD. 1987. Staff Manual for the Management of Water Shortages. Operations and Maintenance Dept., South Florida Water Management District. West Palm Beach, FL.

SFWMD. 1989. Interim Surface Water Improvement and Management (SWIM) Plan for Lake Okeechobee. South Florida Water Management District. West Palm Beach, FL.

SFWMD. 1992. Draft Surface Water Improvement and Management Plan for the Everglades. Planning Department, South Florida Water Management District. WPB, FL.

SFWMD 1993a. Surface Water Improvement and Management (SWIM) Plan. Update for Lake Okeechobee, Volume 1, Planning Document. South Florida Water Management District, West Palm Beach FL. January, 1993

SFWMD. 1993b. Public Water Supply Permit Renew, City of Hallandale. South Florida Water Management District. WPB, FL.

SFWMD, 1994a. Lower West Coast Water Supply Plan. Planning Department, South Florida Water Management District. West Palm Beach, FL. February 1994.

SFWMD, 1994b. Part A: Basis of Review for Water Use. *Management of Water Use Permitting Information Manual Volume III for the South Florida Water Management District*. SFWMD, West Palm Beach, FL.

SFWMD. 1995a. An update of the Surface Water Improvement and Management Plan for Biscayne Bay. Planning Dept. South Florida Water Management District. WPB, FL.

SFWMD. 1995b. District Water Management Plan, Volume 1, Planning Dept. South Florida Water Management District. West Palm Beach, FL, April 1995.

SFWMD, 1997a. Surface Water Improvement and Management (SWIM) Plan- Update for Lake Okeechobeee, Vol. 1, Planning Document..Planning Department, South Florida Water Management District. West Palm Beach, FL.

SFWMD, 1997b. Draft Lower East Coast Interim Plan, .Planning Department, South Florida Water Management District. West Palm Beach, FL.

Sonenshein, R.S., 1994. A hydrogeologic approach to identify land uses that overlie ground-water flow path, Broward County, Florida. U.S. Geological Survey Water-Resources Investigations Report 94-4167.

Sonenshein, R.S., and Koszalka, E.J. 1995. Trends in water-table altitude (1984-1993) and saltwater intrusion (1974 -1993) in the Biscayne aquifer, Dade County, Florida. U.S. Geological Survey Open-File Report 95-705.

Spackman, W., C.P. Dolson, and W. Riegel. 1966. Phytogenic organic sediments and sedimentary environments in the Everglades-Mangrove complex, Part 1: Evidence of a transgression sea and its effects on environments of the Shark River area of southwestern Florida. *Palaeontographica*. 117(8):135-152.

Steinman, A.D., R.H. Meeker, A.J. Rodusky, W.P. Davis, and C.D. McIntire. 1997. Spatial and temporal distribution of algal biomass in a large subtropical lake. *Archiv fur Hydrobiologie*, 139: 29-50.

Stephens, J.C. and L. Johnson. 1951. Subsidence of organic soils in the upper Everglades region of Florida. Soil Science Society of Florida proceedings, Vol. XI, pp. 191-237.

Stephens, J.C. 1984. Subsidence of Organic soils in the Florida Everglades - a review and update. In: Gleason (ed.) *Environments of South Florida: Past and Present.* Miami Geological Society, Miami FL.

Stone, P.A. 1978. Floating Islands--Biogeomorphic Features of Hillsboro Marsh, Northeastern Everglades, Florida, M.A. thesis, Florida Atlantic University, Boca Raton, FL.

Stone, P.A. and P.J. Gleason. 1983. Environmental and paleoenvironmental significance of organic sediments (peats) in southeastern United States. In: *Variation in Sea Level on the South Carolina Coastal Plain*, D.J. Colquhoun (Ed.) Department of Geology, University of South Carolina, Columbia, pp. 121-141.

Swift, D. R., C. Anclade, I.H. Kantrowitz. 1987. Algal blooms in Lake Okeechobee, Florida and management strategies to mitigate eutrophication. *National Water Summary 1987- Hydrological Events and Water Supply and Use.* U.S. Geological Survey Water Supply Paper 2350.

Swift, D.R. and R.B. Nicholas. 1987. Periphyton and water quality relationships in the Everglades Water Conservation Areas. Technical Publication 87-2. South Florida Water Management District, West Palm Beach, FL.

Tarver, D.P., J.A. Rodgers, M.J. Mahler and R.L. Lazor. 1986. Aquatic and Wetland Plants of Florida. Bureau of Aquatic Plant Research and Control, Florida Department of Natural Resources, Tallahassee, FL.

Taylor, D.L. 1981. Fire history and fire records for Everglades National Park 1948-1979. South Florida Research Center Report T-619, U.S. Department of Interior, National Park Service, (April), 121 pp.

Thayer, P.L. and W.T. Haller. 1990. Fungal pathogens, *Phoma* and *Fusarium*, associated with declining populations of torpedo grass growing under high water stress. Proceddingins of the European Water Resource Society 8th Symposium on Aquatic Weeds, pp. 209-214.

Todd, D.K. 1980. Groundwater Hydrology. John Wiley & Sons, NY, 535 pp.

Trimble, P. and G. Marban. 1988. Preliminary evaluation of the Lake Okeechobee Regulation Schedule. Technical Publication 88-5. South Florida Water Management District, West Palm Beach, FL. 73 pp.

Tropical BioIndustries, Inc. 1990. Hydroperiod conditions of key environmental indicators of Everglades National Park and adjacent East Everglades area as guide to the selection of an optimum water plan for Everglades National Park. Tropical BioIndustries, Inc., Miami, FL.

USACE. 1991. Central and Southern Florida Project, Water control plan for Lake Okeechobee and Everglades Agricultural Area, Jacksonville District,, Jacksonville, FL., March 1991.

USACE. 1992. Water control plan for Water Conservation Areas-Everglades National Park, and ENP-South Dade Conveyance System, Central and Southern Florida Project for Flood Control and other Purposes, Jacksonville District,, Jacksonville, FL., October 1992.

USACE. 1994. Central and Southern Florida Project. Final Integrated General Reevaluation Report and Environmental Impact Statement. Canal 111 (C-111), South Dade County, Florida., Jacksonville District,, Jacksonville, FL., May 1994.

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 District, Jacksonville, Fl. and the South Florida Water Management District, West Palm Beach, Fl. (April 1999).

Wade, D.D., J.J. Ewel, and R. Hofstetter. 1980. Fire in south Florida ecosystems. General Tech. Report SE-17. U.S. Dept. of Agriculture Forest service Asheville, N.C.

Werner, H.W. 1976. Distribution, habitat, and origin of the Cape Sable seaside sparrow. Masters thesis. University of South Florida, Tampa, FL.

White, W.A. 1970. The geomorphology of the Florida peninsula. *Florida Bureau of* Geology Bulletin Number 51.

Willis, R. and B.A. Finney 1988. Planing model for optimal controls of salt-water intrusion. Journal of Water Resources Planning and Management, Vol. 114, pp 163-178.

Wirojanagud, P. and R.J. Charbeneau. 1985. Saltwater upconing in unconfined aquifers. Journal of Hydraulic Engineering, V111, March 1985, pp 417-434.

Worth, D. F. 1988. Environmental responses of Water Conservation Area 2A to reduction in regulation schedule and marsh drawdown. Technical Publication 88-2. South Florida Water Management District, West Palm Beach, FL.

Wu, Yegang, F. Sklar, K. Gopu, K. Rutchey. 1996. Fire simulations in the Everglades landscape using parallel programing. In: Ecological Modeling (in press).

Wu Y. (1997) Analysis and simulation of fragmentation patterns in the Everglades. Ecological Applications, Vol. 7, No. 1 pages 268-276.

Zaffke, M. 1983. Plant communities of Water Conservation Area 3A: Baseline documentation prior to the operation of S-339 and S-340. Tech. Memo. South Florida Water Management District, West Palm Beach, FL.