Baber

(WRE #330)
TECHNICAL PUBLICATION 96-01

LITERATURE REVIEW ON THE EFFECTS OF GROUNDWATER DRAWDOWNS ON ISOLATED WETLANDS

by

Steve Mortellaro, Staff Environmental Scientist
Steve Krupa, Senior Hydrogeologist
Larry Fink, Supervising Professional
Criteria Assessment and Support Unit, Research Appraisal Division
Water Resources Evaluation Department
and
Joel VanArman, Supervising Professional, Planning Department

November 1995

South Florida Water Management District
West Palm Beach, Florida

LITERATURE REVIEW ON THE EFFECTS OF GROUNDWATER DRAWDOWNS ON ISOLATED WETLANDS

Table of Contents

Appendix -

List of Figures

List of Tables

ACKNOWLEDGEMENTS

This project was initiated by staff of the South Florida Water Management District Resource Assessment Division of the Water Resources Evaluation Department with support from staff of the Planning Department. The authors wish to acknowledge the other SFWMD staff who read this manuscript and provided many helpful and supportive comments:

Garth Redfield
Cecile Ross
Debbie Goss
Carl Havens
Dave Black
Doug Shaw

In addition, authors wish to express special appreciation to Chris Burns for preparation of the graphics and photographs and to Ted Rochow and Mike Hancock of the Southwest Florida Water Management District whose detailed review and comments greatly improved the quality of this report.

LITERATURE REVIEW ON THE EFFECTS OF GROUNDWATER DRAWDOWNS ON ISOLATED WETLANDS

1. INTRODUCTION

1.1 Need. Chapter 373 of Florida Statutes sets forth the public policy requiring the water management districts "[t]o preserve natural resources, fish and wildlife" through the implementation of consumptive use and surface water management permitting regulations. Several tools are provided in the statute which enable the water management districts to fulfill this responsibility through water use permitting. These tools include authority to adopt rules to maintain minimum flows and levels for the prevention of significant harm to water resources and ecology of an area, to reserve water for the protection of fish and wildlife, and to prohibit uses that are harmful to water resources.

Researchers at the SFWMD reviewed and analyzed information from the scientific literature to determine the effects of lowered groundwater levels on isolated wetlands. This report describes the results of the literature search, analysis of previous investigations, and discussion of how the results can be applied to support regulatory decisions in South Florida

Pursuant to Rule 40E-2.301(1)(c), F.A.C. water use permit applicants are required to provide reasonable assurances that a proposed use will not cause adverse environmental impacts. The need for scientifically-based groundwater drawdown criteria is underscored by the recent judgment against the St. Johns River Water Management District (SJRWMD). In the Final Order in the matter of Osceola County vs. SJRWMD (1991), an administrative hearing officer found that the applicant, South Brevard Water Authority, had failed to establish the severity of impacts and failed to meet its threshold burden of proof regarding the nature and extent of harm that could occur to wetlands due to a 0.34-foot modeled drawdown, particularly during dry periods. The hearing officer also determined that the required proof must be contained in the application for the permit. The proposed requirements for monitoring after the permit was issued was an insufficient means to protect the wetlands and did not adequately compensate for the failure to meet the burden of proof. The required reasonable assurances took into account the site specific characteristics of the potentially impacted wetland, including the soils, hydrology, flora and fauna of the area.

The statewide definition of a "wetland" (Chapter 373.019(17) F.S.) includes "those areas that are inundated or saturated by surface water or ground water at a frequency and a duration sufficient to support, and under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soils." This definition is applied in determining the extent of wetlands protected under the water use and surface water management programs.

Mathematical models have been developed by the District and others to simulate regional and local groundwater conditions and the effects of rainfall, recharge and groundwater withdrawals. Such models are commonly used by District staff, permit applicants and consultants as tools to evaluate effects of groundwater withdrawals, because models allow comparisons that involve a variety of alternative criteria and well configurations. Although ground water models have certain limitations and their results have a degree of uncertainty, most experts concur that they provide the

best available means to objectively estimate (predict) impacts of water withdrawals on ground water resources.

Hydrology is probably the single most important determinant for the establishment and maintenance of the specific types of wetlands and wetland processes (Mitsch & Gosselink 1986). Wetland hydrology is determined by the relationships between water entering and leaving a particular area. Although there are some questions as to what constitutes a "healthy" ecological system and how "harm" is defined (Karr et al. 1986; Lowe et al., 1994), the establishment of an ecologically defensible set of groundwater withdrawal criteria to protect isolated wetlands, such as marshes and cypress swamps, is one of the District's highest priorities, and requires a quantitative understanding of how changes in the timing, duration, frequency and magnitude (TDFM) of groundwater withdrawals affect these ecosystems. *Timing* is the season when the drawdown occurs (e.g. wet season, dry season, winter, spring, etc.); *duration* is the length of time that the drawdown persists; *frequency* is the incidence of reoccurrence of the drawdown; and *magnitude* is the change in depth of water from the natural level to an artificially maintained lower level. Such a quantitative understanding can only come from rigorous scientific research and long-term environmental monitoring.

1.2 Purpose. The purpose of this report is to review and analyze information from the scientific literature on the effects of groundwater drawdowns on isolated wetlands. The literature search was conducted with the following specific questions in mind:

1. What are the effects of the four parameters -- timing, duration, frequency and magnitude (TDFM) of the groundwater drawdown -- on the ecology of wetlands?
2. What are the observed effects on wetlands, based on actual groundwater drawdowns versus effects predicted by simulation models?
3. What are appropriate regulatory criteria for TDFM of groundwater withdrawals, for different wetland types?
4. What types of additional information and data need to be obtained to provide better answers to these three questions?

1.3 Overview. Available information was compiled, from both the published scientific literature and the less-widely available reports of agencies and consultants, that addressed the cause and effect relationships between groundwater drawdowns and ecological impacts on isolated wetlands. Many of these studies indicate that groundwater hydrology of the shallow aquifer system is a major factor that influences the development and support of wetland plant communities. While most investigators determined that long-term lowering of surficial water levels impacts wetlands, very few studies provided quantitative relationships. Some data suggest that chronic reductions of water levels are associated with elimination or significant reduction in the hydroperiod (number of days per year that soils remain saturated or covered with water), and have significant effects on the plant community structure.

Some attempts have been made to apply mathematical models to predict effects of groundwater drawdowns on wetlands. A series of such studies conducted by the Southwest Florida Water Management District (SWFWMD) generally indicate that drawdowns of one foot or less, as predicted by a stress model, have been associated with observable shifts in plant communities from wetland species that tolerate long periods of soil saturation and standing water to wetland and upland plant species that prefer short hydroperiods. Future research needs to focus on development of

better methods for defining and measuring the response of wetland ecosystems to hydrologic stress.

1.4 Organization. This document is divided into 5 sections. Section 1 describes the study objectives and the questions that need to be addressed. Section 2 presents the methods used for analysis. Section 3 summarizes and discusses the information obtained from the literature search as it relates to effects of water level drawdowns on surface water, groundwater and wetlands and the need for additional research. Section 4 provides conclusions and recommendations relevant to the questions posed in Section 1. Literature citations are listed in Section 5.

2. METHODS

2.1. Approach and Scope. This report is a compilation of readily available information on the cause and effect relationship between TDFM of groundwater drawdowns and ecological impacts on isolated wetlands. This analysis is based on a review of scientific and regulatory agency literature and databases to locate relevant studies. An alternative approach is to initiate field studies and document examples of the ranges of natural and perturbed groundwater conditions that are associated with occurrence of various species of plants and animals. The latter approach is a longer-term effort, undertaken over the next several years, to support the District's regulatory process.

2.2. Literature Search. Scientific literature was obtained using online bibliographic search and manual location of hard copies. The computer search was conducted, using Dialog Information Service. The list of references obtained through this search was supplemented by additional listings obtained from the Literature Cited sections In the reports themselves. Previous literature summaries performed by the District or its contractors were also used, including *Hydroperiods and Water Level Depths of Freshwater Wetlands in South Florida* (Environmental Science & Engineering, Inc., 1991), *CREW Hydrologic and Hydraulic Study* (Gee & Jensen, 1991), and *Citrus/Wildlife Study* (Mazzotti et al., 1992). This combined initial list was then reduced to 88 articles or reports that appeared to document hydrologic and biotic impacts to isolated freshwater wetlands due to groundwater or surface water reduction. The abstract, summary, and/or conclusion sections of each article or report were examined for relevancy. An article was considered relevant if it contained information on isolated freshwater wetlands that were subjected to hydrologic alterations. Relevant articles and reports were then examined in more detail to select the 43 references that were cited in this document.

2.3. Contacts with Other Researchers. The South Florida Water Management District, Southwest Florida Water Management District, St. John's River Water Management District and the Suwannee River Water Management District librarians were contacted to obtain their published materials. Finally, a survey of professional researchers at the following agencies and institutions was conducted to obtain additional published and unpublished information: South Florida Water Management District, Southwest Florida Water Management District, St. John's River Water Management District, Suwannee River Water Management District, United States Army Corps of Engineers, Soil Conservation Service, United States Geological Survey, University of Rhode Island, North Carolina State University, the Nature Conservancy, United States Fish and Wildlife Service, A Natural Balance, Inc., Broward County Department of Natural Resource Protection, Dade County Department of Environmental Resource Management, Palm Beach County Department of Environmental Resource Management, the West Coast [Florida]

Regional Water Supply Authority, Azurea, Inc. and the United States Environmental Protection Agency.

3. RESULTS AND DISCUSSION

3.1. Literature Survey Results. There is apparently a limited amount of information in the scientific literature on the relationship between the timing, duration, frequency and magnitude (TDFM) of groundwater drawdowns and the nature and extent of impacts on isolated wetlands, especially studies conducted in South Florida. Approximately 24 articles and reports documented impacts to wetlands from human-induced lowering of groundwater levels, including 20 studies conducted in Florida, two in other parts of the United States, one in Denmark and one in Spain. Information from these articles, which were considered to be the most relevant to determining cause and effect relationships between hydrology and ecology for the types of wetland systems found in South Florida, is summarized in **Table 1.**

3.2. Importance of Hydrology. Appropriate combinations of hydrologic conditions, hydroperiod, soils, light, temperature, etc. are conducive to development of wetland plant communities. Hydroperiod of a wetland is one factor that determines the types of wetland plant and animal species present. Hydroperiod can also provide a basis to characterize wetlands, e.g., as permanently flooded, seasonally flooded, or intermittently flooded. Duever *et al.* (1986) suggest that hydroperiod is the dominant factor controlling wetland structure. In contrast, O'Brien and Motts (1980) consider that water level has a more significant effect on wetlands than does hydroperiod. Day et al. (1988) consider that frequency, duration, depth and timing of inundation are all critical factors in analyzing wetland function and structure. They suggest that hydrology is a major influence on wetland processes above and below the ground, and warn of "erroneous interpretation" that may arise by only observing surface water flooding.

Figure 1 shows hydrologic conditions associated with a "natural" wetland and how these conditions are affected by human activities such as groundwater withdrawals and construction of surface water drainage systems. Natural wetlands (**Figure 1a**) experience a range of water levels throughout the year, resulting in a gradient of habitats from adjacent uplands that remain dry most of the year through areas that are exposed to increasing depth and duration of standing water. Water levels fluctuate cyclically to provide seasonal and temporary flooding, resulting in zonation of plant and animal communities in adjacent areas. The topography, geology, hydrology and rainfall patterns are the dominant factors that determine the type of wetlands that may be found in a particular location. The hydroperiod and water levels of a particular wetland may result in its characteristic zonation of plant and animal communities. In south Florida the wetlands tend to be depressional such as cypress swamps and pickerelweed marshes or flat (low relief) such as the wet flatwoods, prairies and the Everglades.

Native plants and animals have adapted to the range of hydrologic conditions that occur in natural wetlands. Both groundwater withdrawals (**Figure 1b**) and surface water management systems (**Figure 1c**) can reduce water levels and alter hydroperiods, resulting in adverse impacts to such wetlands. One of the most obvious impacts is the reduction in wetland size. Topography determines how much area will be affected by a given drawdown. Drawdowns of equal magnitude may

Table 1. Results of literature review to determine impacts of groundwater withdrawals on wetlands.

Citations	Year	Wetland Type	Number of Wetlands Monitored	Number of Wetlands Affected	Magnitude of Drawdown (ft)	Duration Of Study (Years)	Type of Impact	Effect Of Impact	Location
Bernaldez et al.	1993	Forest Shrub Herbaceous	60mi x 37.3mi	5classes	3.0-4.0[a]	19	Wellfield	39% to 83% area loss shift to drier species	Spain
Biological Research Associates	1992a	River-1 Lake-2 Cypress-9 Marsh-8	20	12	1.0[b]	14	Cross Bar Wellfield	Reduced water levels and hydroperiods: wetland plants to more terrestrial; one site noted 400 dead turtles.	Florida
Biological Research Associates (cited in Rochow 1994)	1992b	N/G	15		1.0[b]	10	Morris Bridge Wellfield	Monitoring began 7 years after pumping began; increase of plant species that tolerate dry conditions.	Florida
Biological Research Associates	1993	River-1 Lake-2 Cypress-9 Marsh-9	21	16	1.0[b]	15	Cross Bar Wellfield	Reduced hydroperiods/water levels; invasion of plant species that tolerate dry and disturbed conditions; surface water present only in augmented sites within the 1-foot modeled contour.	Florida
Burns	1984	Cypress	2	1	1.0[a]	16	Wellfield	Reduction in biomass and net productivity	Florida
Carter et al.	1973	Cypress	2	1	1.0[a]		Ditch	40% reduction in cypress productivity	Florida
CH_2M Hill	1988	Herbaceous	26	5	1.0 to 2.0[a]	1.5	Ditch	Reduced water levels and hydroperiods; shifts in vegetation zone I from wetter to drier species.	Florida
CH_2M Hill	1991	Cypress Marsh	58	N/G	1.0[b] or greater	N/G	J.B. Starkey Wellfield	Flowering plants showed reduced reproduction and growth; reduced hydroperiods and water levels; increased fire damage.	Florida
Dooris et al.	1990	Cypress Marsh lake	65	N/G	1.0[b] or greater	19	Wellfield	Reduced hydroperiods/water levels to complete dry out; invasion of woody species such as sand pine (*Pinus clausa*).	Florida
Environmental Science and Engineering	1993	Cypress Marshes	161	N/G	1[b] or greater	N/G	Cypress Creek Wellfield	Replacement of wetland plants with upland plants; reduced hydroperiods and water levels; soil subsidence; reduced tree growth (popash) and increased tree mortality.	Florida
Hald & Petersen	1992	Danish Fen	2	2	N/G	6	Drainage Tubes	Shift in wetlands species to more terrestrially adapted species.	Denmark
Harris & Vickers	1984	Cypress	6	3	N/G	0.58	Ditches	Shift in frequency of herpetofauna from aquatic to terrestrial species	Florida
Henigar and Ray (cited in Rochow 1994)	1992	Cypress Marsh	48	16	1.0 to 2.2[b]	N/G	J.B. Starkey Wellfield	Reduced hydroperiod and water levels; invasion of upland species; buildup of understory vegetation may cause destructive fire damage in the future.	Florida
Hofstetter & Sonenshein	1990	Herbaceous	1	1	<7.0[a]	6.0	Wellfield	Reduced water levels and hydroperiods, dried out wetlands.	Florida

N/G = data not provided in the report;
[a]=field measured groundwater drawdown;
[b]=modeled groundwater drawdown;

Table 1. Results of literature review (Continued)

Citations	Year	Wetland Type	Number of Wetlands Monitored	Number of Wetlands Affected	Magnitude of Drawdown (ft)	Duration Of Study (Years)	Type of Impact	Effect Of Impact	Location
Kirschner, et. al.	1988	Red Maple	2	1	N/G	0.5	Ditch	Dried out wetland; no vegetative data; Reduced wildlife usage.	Maryland
Rochow, et al.	1979	Riverine-4 Lake-1 Cypress-7 Marshes-3	12	7	N/G	4	J.B. Starkey Wellfield	Reduced hydroperiod and water levels; invasion of upland species to become s grass prairie, cypress pond and mud lake dried up completely or nearly so for a year or more; reduced uses of the area by aquatic and semiaquatic birds (herons, coots and ducks) and increased use by non-aquatic birds (ground doves, quail and meadowlarks).	Florida
Rochow	1982	Cypress-8 Marshes-3	11	6	1[b] to 2[b]	7	J.B. Starkey Wellfield	Reduced hydroperiod and water levels; invasion of upland species; buildup of understory vegetation may cause destructive fire damage in the future.	Florida
Rochow	1985a,c	Cypress-5 Marshes-4	9	8*	N/G	10	Cypress Creek Wellfield	Reduced water levels and hydroperiods to total dewatering of the wetland; decrease in aquatic plants and increase of upland plants; sinkholes.	Florida
Rochow	1985b	Cypress-12 Marshes-3	15	7	N/G	10	J.B. Starkey Wellfield	Reduced hydroperiod and water levels; invasion of upland species; buildup of understory vegetation may cause destructive fire damage in the future.	Florida
Rochow and Rhinesmith	1991	Cypress	5	2	0-7[a]	2-3	Wellfield	Reduced water levels/hydroperiods; soil subsidence; vegetation shifts; fish were extirpated from three sites; amphibian use was low to absent at 2 sites; decrease in wetland use by birds.	Florida
Rochow	1994	Cypress Marsh	N/G	N/G	1.0[b] to 0.05[b]	18	Morris Bridge Wellfield	Reduced hydroperiod and water levels; invasion of upland plants; loss of canopy cover;increased cypress mortality.	Florida
Water and Air Research	1992	Cypress-18 Lake/Pond-1 Riparian-3	22	(none affected)	N/G	N/G	NW Regional Wellfield	Plant communities appeared to be healthy.	Florida
West Coast Regional Water Supply Authority	1989	Cypress-18 Lake/Pond-1 Riparian-3	22	(none affected)	-6.75 to 2.25	N/G	NW Regional Wellfield	Plant communities appeared to be healthy.	Florida
Wilkie & Larson	1980	Forest Shrub Herbaceous	16 sites covering an area with 1/2 mile radius	varied from 4% to 1005	N/G	20	Wellfield	Reduced water regimes: shift in wetland plants and upland plants.	MA

N/G = data not provided in the report;
[a] = field measured groundwater drawdown;
[b] = modeled groundwater drawdown;
*3 of these wetlands were impacted by well production, however, augmentation has maintained the wetland but changed its character

Figure 1a. Hydrologic Conditions in a Natural Wetland.

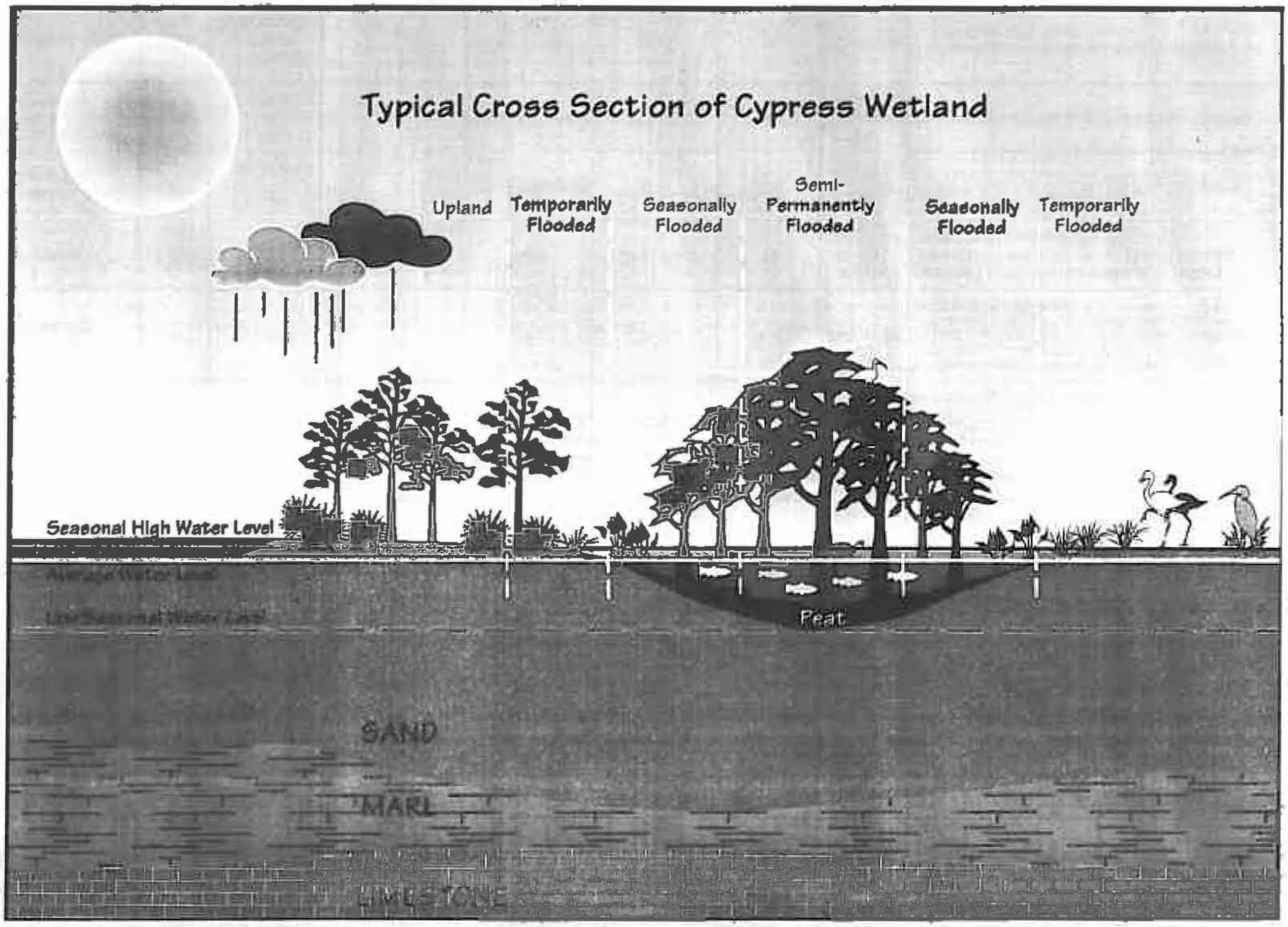


Figure 1b. Effects of Groundwater Withdrawals (Wells) on a Wetland.

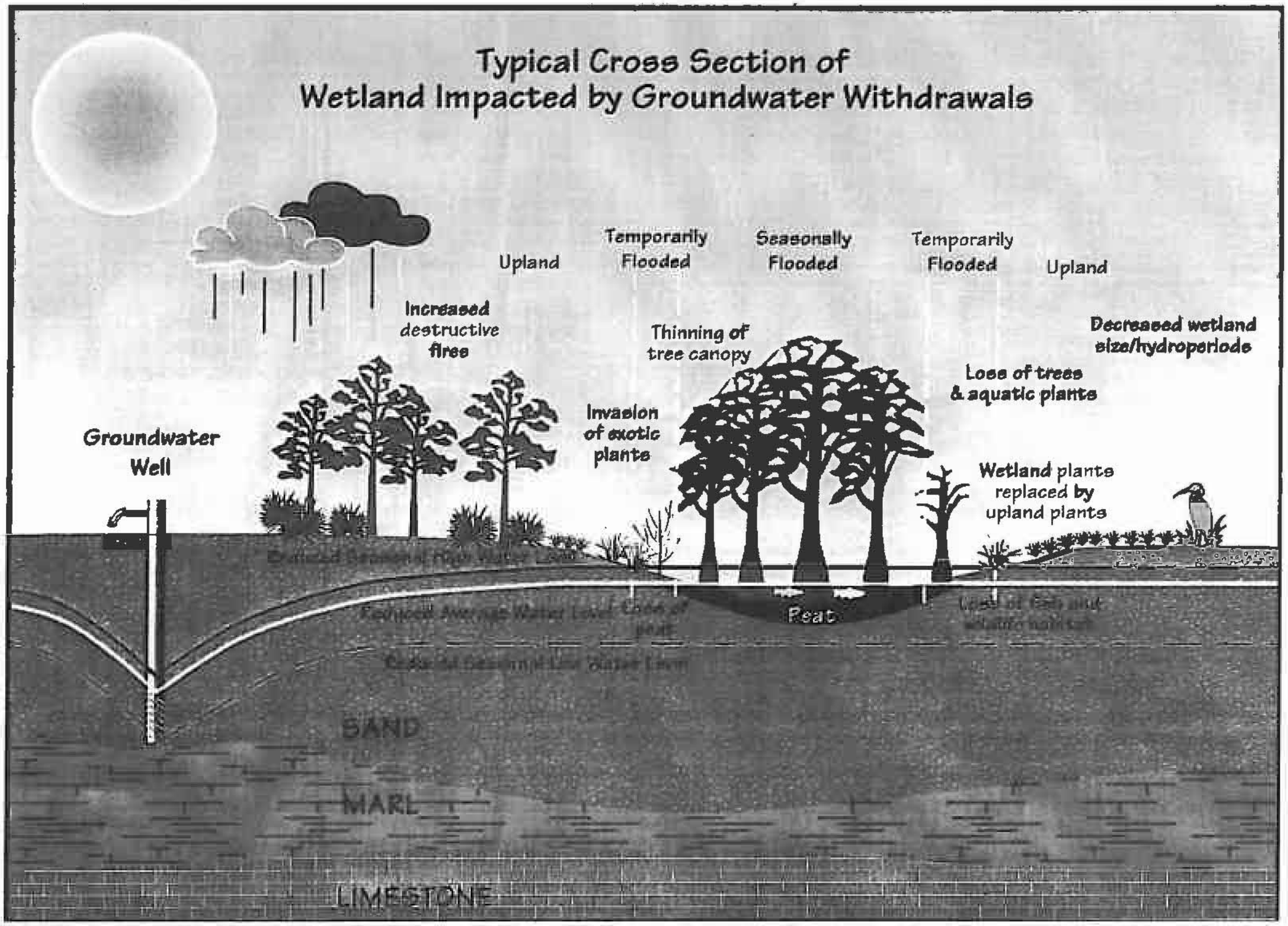
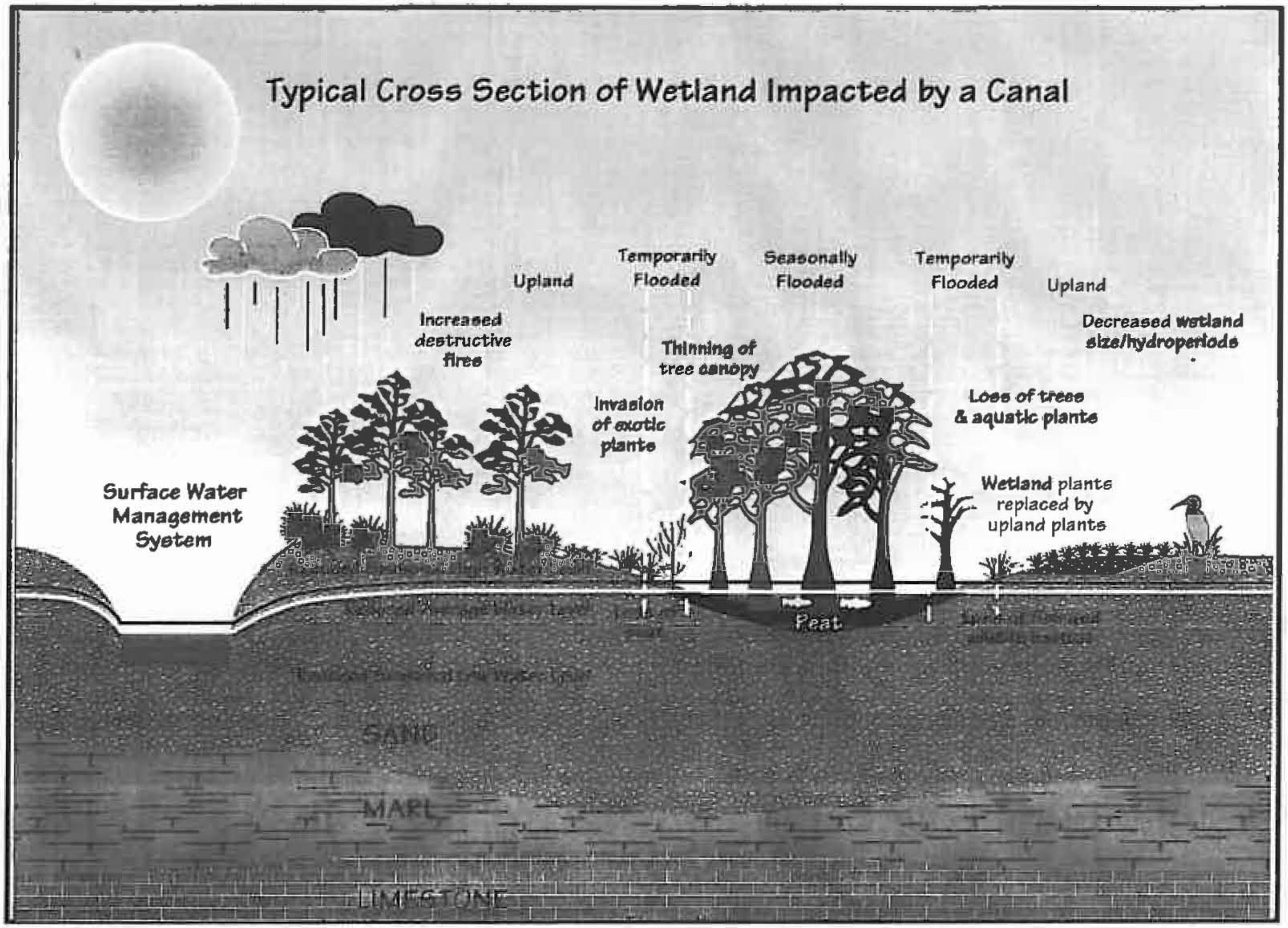


Figure 1c. Effects of Surface Water Management Systems (Ditches and Canals) on a Wetland.



therefore have dramatically different effects, depending on the size and configuration of the wetland. Flat, shallow wetlands may have a large amount of wetland surface exposed, whereas deep depressional wetlands may have very little additional exposed surface. Many of the isolated wetland systems in southwest Florida are characterized by low relief, short hydroperiods and shallow water depths and are very sensitive to hydrologic changes. Even slight alterations of the hydrology may eliminate large areas of native wetland habitat. Other impacts include increased fire, replacement of wetland fauna and flora by upland species, invasion of exotic plants, loss of tree cover, thinning of tree canopy, loss of organic soils and reduced wetland habitat and wildlife values.

3.3. Assessing Impacts. Determination that harm or damage has occurred to an ecosystem is a critical consideration in the development of criteria for regulatory application. Any unnatural reduction in the surface area or depth of an isolated wetland will adversely affect plant and animal use of the habitat for reproduction, foraging, or predation avoidance. Although there has been an attempt to define harm to an ecosystem on a statewide level, an acceptable definition has not been derived (Lowe et al. 1994). According to Karr et al. (1986), an ecosystem exhibits biological integrity or "health . . . when its inherent potential is realized, its condition is stable, its capacity for self-repair when perturbed is preserved, and minimal external support for maintenance is needed." Conversely, an ecosystem is unhealthy when it is underproductive, oscillating, or unable to restore itself to its original structure, function and productivity following a strong perturbation, and requires constant and significant management for propagation. Without a State-adopted definition of harm, the above concepts can only serve as general guidelines for protecting wetlands.

There is as yet no accepted scientific determination of the point at which the effect of an environmental stress factor crosses the line from (1) unobservable to observable; (2) ecologically insignificant to ecologically significant; and (3) acceptable to unacceptable impairment or harm. More research is needed to document the relationships between groundwater drawdowns and wetland system response and define what is meant by the term "harm" as it applies to wetland ecosystems. Statistically significant results from well-designed controlled field studies and improved monitoring will help to develop a defensible hydrologic criterion that can protect isolated wetlands from unacceptable impacts.

The scope of investigation is also important. Reports on the effects of hydrologic perturbations on isolated wetlands generally have focused mainly on the flora, with only limited attention given to the fauna. Impacts may have occurred during a study period but were unrecognized because monitoring focused on an organism that was insensitive to, or tolerant of, reduced water levels and shortened hydroperiods. Comprehensive studies need to be conducted in the future that examine all the major components (plant, animal, microbial) of Florida wetland ecosystems.

3.4. Florida Examples. Both surface water drainage systems and groundwater withdrawals affect wetlands hydrology throughout Florida. Surface water drainage systems (Wang & Overman 1981) and wellfield withdrawals (Sonenshein and Hofstetter 1990) can lower the regional and local water tables. The primary focus of our literature review was on groundwater relationships. Some rather detailed studies (Hofstetter and Sonenshein 1990; Rochow 1994) have addressed the impacts of groundwater withdrawals for public water supply on wetlands.

3.5. Ground Water. The literature contains more than a dozen cases that document regional or local effects of groundwater withdrawals on wetlands. Groundwater fluctuations can occur naturally, on a seasonal basis, or be induced by man, due to well pumpage or excavations such as ditches. Pumping of water from groundwater wells creates a cone of withdrawal centered about each well. Depth and steepness of the cones are determined by aquifer characteristics and pumping rate. Wellfield drawdowns can be relatively constant over time or change with seasonal demand. When local and regional water tables are lowered, soils dry out more often and hydroperiods change. Although few studies have attempted to rigorously quantify the relationship between actual water levels below ground and wetland structure, available data suggest that long-term modeled water level reductions on the order of one foot or less have significant effects on wetland structure and function.

Tampa Bay Region. Regional studies to monitor groundwater conditions in the North Tampa Bay (Tampa, Florida) area, conducted by the SWFWMD, indicate that water levels have declined up to 20 feet in the Floridan Aquifer System. These declines were attributed to cumulative pumpage from various wellfields. The cones of influence of these wellfields overlap and have affected water levels within an estimated area of 800 to 1,000 square miles (Mike Hancock, SWFWMD, Personal Communication 1994). The Floridan Aquifer System in this region behaves as both an unconfined and a confined aquifer system. Drawdowns from the Floridan aquifer propagate to the surficial aquifer system to impact wetlands. Rochow (1994) summarized his and other monitoring efforts (Biological Research Associates 1992a,b; Dooris *et al.* 1990; Environmental Sciences and Engineering 1991; Rochow 1982, 1985b, 1989; Rochow and Rhinesmith 1991; SWFWMD 1979; Water and Air Research 1992; Watson *et al.* 1990) on the effects of drawdowns at the Cypress Creek, Starkey, Eldridge-Wilde, Cross Bar, Morris Bridge, Northwest Hillsborough Regional and Section 21 wellfields. These researchers generally agreed that the following impacts were observed on cypress and marsh wetlands: extensive invasion of weedy upland plant species; increase in destructive fires; abnormally high treefall; excessive soil subsidence/fissuring; and disappearance of wetland wildlife.

Cypress Creek Wellfield Studies. The effects of drawdowns on isolated wetlands due to long-term pumping has been documented at the Cypress Creek wellfield (Rochow 1985b; Rochow 1994). SWFWMD has monitored the hydrology and biology of wetlands within and around this wellfield since the mid 1970's, based on quantitative sampling at seven sites, qualitative sampling at 40 sites and observations at ten staff gauges. These studies indicated that pumpages from water wells can completely eliminate the surface water from wetlands and change wetland vegetation structure, but still maintain a community dominated by "indicator" wetland plant species . The hydrograph in **Figure 2** (SWFWMD draft, 1994) shows the relationship between water levels in wetland "D" and groundwater pumpage at Cypress Creek Wellfield. **Figures 3-6** represent a photographic sequence, from 1975 to 1991, of the effects of pumpage on a wetland "D" (Rochow, personal communication; 1994b). Before pumping began, water levels fluctuated seasonally between 67 and 69 ft NGVD (0.5 to 3 ft above ground surface elevation of 66.5 ft). After pumping began during 1976, water elevations dropped below ground level (66.5 feet NGVD) and have not come above ground level since that time. In 1975, before pumpage commenced (Figure 3), the wetland was dominated by pickerelweed (*Pontederia cordata*) and maidencane (*Panicum hemitomon*). Both species are classified as obligate wetland plants (Reed 1988). **Figures 4-6**, taken after pumpage began in 1976, show drying of the wetland and changing of the dominant species from pickerelweed to maidencane. Although under natural conditions both of these species can exist in deep water/long hydroperiod systems, maidencane can

Figure 2. Relationship between water levels in wetlands and groundwater pumpage at the Cypress Creek Wellfield (SWFWMD 1994b)

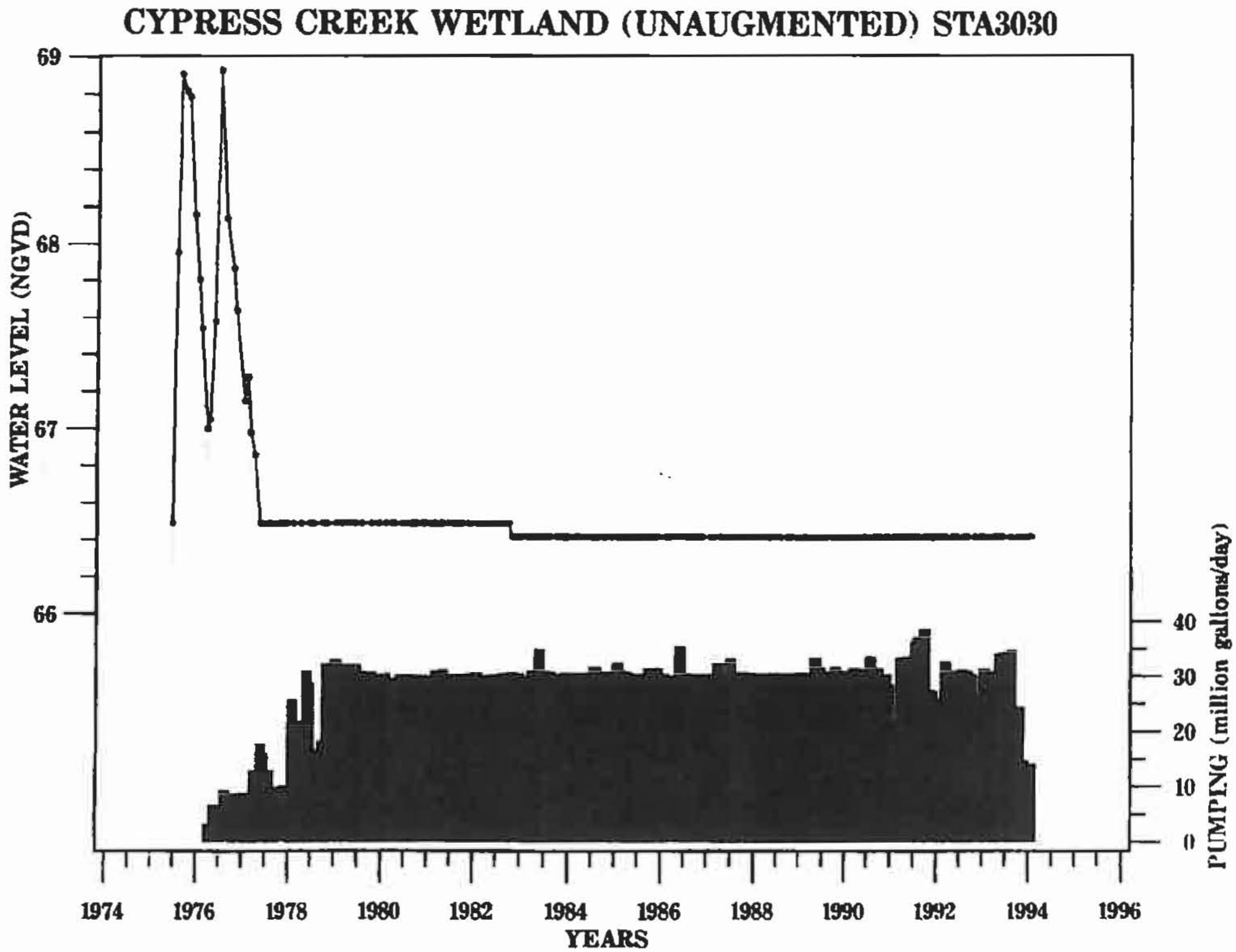


Figure 3. Wetland "D" in Cypress Creek wellfield on 8/12/75, before pumpage commenced. Wet season photo showing dominance and even distribution of pickerelweed (broad leaved plants in foreground) and less abundance of maidencane (narrow leaved plants). Standing water is present throughout the area. Dense vegetation obscures monitoring plots.

Figure 4. Wetland "D" in Cypress Creek wellfield on 5/20/80, after pumpage commenced. Dry season photo showing reduction of pickerelweed (dark clumps and bands) and increase in maidencane (light stubble). No standing water occurs in the area. Seasonal dieback of vegetation makes the monitoring plots visible.

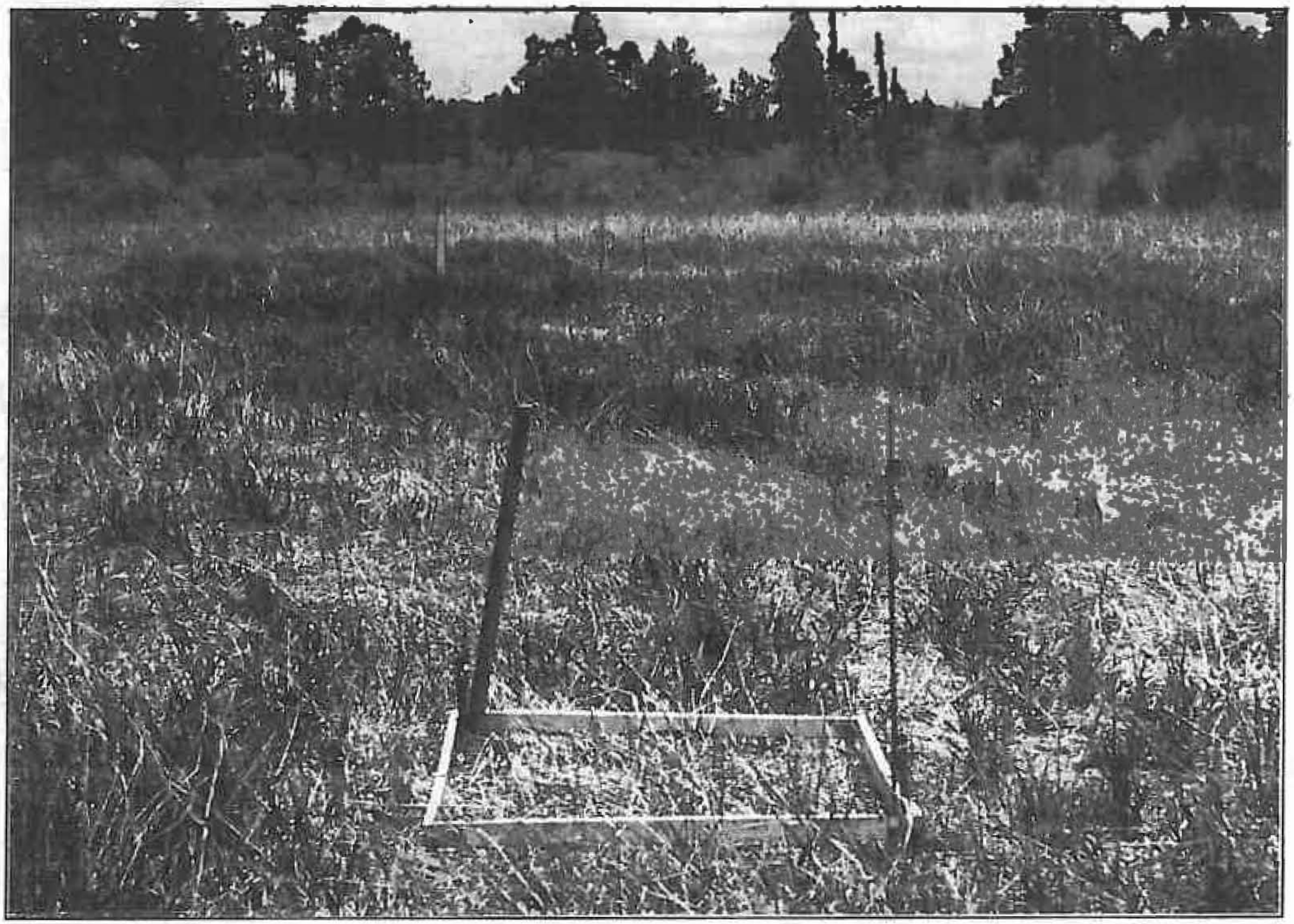


Figure 5. Wetland "D" in Cypress Creek wellfield on 6/24/85. Early wet season photo showing maidencane as the dominant species and elimination of pickerelweed. No standing water occurs in the area. Vegetation growth partially obscures the stakes marking the monitoring plots.

Figure 6. Wetland "D" in Cypress Creek wellfield on 6/18/91. Early wet season photo showing maidencane as the dominant species and elimination of pickerelweed. No standing water occurs in the area. Vegetation growth partially obscures the stakes marking the monitoring plots.

survive in areas without saturated soils or standing water. It is important to note that classification of wetland species in the U. S. Fish and Wildlife Service's (USFWS) indicator index (Reed, 1988) is based on the likelihood of finding that plant in a naturally occurring, undrained wetland. The index does not consider the range of water levels or hydroperiods that the species can naturally occupy or the ability of a particular species to tolerate adverse changes in water level and hydroperiod conditions induced by human activities.

Starkey Wellfield. The SWFWMD has monitored the Starkey Wellfield since the mid-1970's and presently collects quantitative vegetation data from 15 sites, qualitative data from 60 sites and records from 35 staff gauges. In addition to on-site monitoring, aerial overflight and historic aerial photographic surveys were conducted. The Green Swamp was used as a control site for hydrobiological comparisons. All water production from 1974 to 1983 occurred from the northwestern part of the wellfield. The average pumpage rate was 3.0 MGD during the period from 1980 to 1982. Comparison of modeled water withdrawals with data collected by SWFWMD biologists indicated that adverse impacts (increased fires, soil subsidence and changes in plant species composition) occurred within areas that the model indicated should have experienced a 0.6-foot to 2.0-foot drawdown from the late 1970's to the early 1980's.

Most of the water production was shifted to the central portion of the wellfield in 1983. By 1991, the wellfield was producing 13 MGD; 77% came from the central wells, 20% from the eastern wells and 3% from the western wells. Analysis of wetland hydrographs for the study period indicated that most of the wetlands in the western and central portions of the wellfield experienced a pattern of "declining seasonal maximum water levels and abbreviation of yearly hydroperiods." Adverse biological impacts observed at these sites included a change in species composition to extensive dog fennel (*Eupatorium spp.*) and broomsedge (*Andropogon spp.*) invasion, destructive fires, abnormally high treefall, excessive soil subsidence and fissuring.

Rochow (1994), citing reports by Henigar and Ray (1992) and CH_2M Hill (1991), indicated that more than 150 sites were monitored for ecological changes (including about one third located outside the wellfield), and that 14 sites that were monitored for quantitative vegetation changes. Rainfall analysis by Henigar and Ray (1992) showed that although rainfall during water year 1991 averaged about 10.8 inches above the long term average for the area, 27% of the monitored sites in the western portion of the wellfield remained dry (no standing surface water). Comparison of average water levels for water years 1991 and 1983, showed that water levels in western area wetlands averaged 2.1 feet lower, central area wetlands averaged 2.2 feet lower, eastern area wetlands averaged 1.0 feet lower and external wetlands averaged 1.5 feet lower in 1991 than in 1983. Henigar and Ray (1992) identified 16 "wetlands of specific interest" that had lowered water levels, shortened hydroperiods, severe fire damage, soil subsidence and vegetation changes.

Rochow (1994) also cited work by Environmental Sciences and Engineering, Inc., indicating that mean water levels of wetlands located within the 1-foot drawdown contour of the Starkey Wellfield were lower than water levels in wetlands located outside this contour. Thirteen wetlands of special concern were identified, located within or near the 1-foot contour. Impacts observed included vegetation changes, chronically reduced hydroperiods and water levels, fire damage, loss of canopy, and treefall. Rochow (1994) and others monitoring this wellfield are in agreement that adverse impacts occurred to wetlands in western and central portions of the

wellfield and that these impacts were attributable, in part or whole, to wellfield operation.

Cross Bar Wellfield. Wetland monitoring in the Cross Bar Wellfield began in 1977, before water production was initiated (Biological Research Associates 1992a). Eight transects were monitored for quantitative vegetation changes (four on-site and four off- site) and 20 sites were monitored for qualitative changes, in and around the wellfield. By 1991, water production averaged 22 MGD. During 1991, although total rainfall was 6.12 inches above normal for the wellfield, Biological Research Associates (1992a) reported that this area experienced the lowest groundwater levels observed over the period of record. Monitored water levels ranged from 0.4 feet above ground to 12 feet below ground. Groundwater levels at many sites dropped below the bottom of the monitoring wells. Observed effects of these reduced water levels included the establishment of plant species that were more characteristic of upland areas. In some cases, open water system plants were replaced by more drought resistant species such as maidencane. Although wildlife was not studied extensively, Biological Research Associates (1992a) noted that gopher tortoise (*Gopherus polyphemus*) burrows were common in a previously wet area and remains of 400 turtles (*Chrysemys* sp. and *Trionyx ferox*) were found at Big Fish Lake, which was completely dry.

Modeling of groundwater levels, based on an allowable average annual withdrawal of 30 MGD and a maximum withdrawal of 45 MGD, created a 1-foot drawdown contour that covered the majority of the site (Rochow 1994). Rochow (1994) indicated that the surface water levels and vegetative patterns of monitoring sites within the modeled 1-foot drawdown contour "strongly suggest that wetlands are being adversely affected by water withdrawal." Monitoring by Biological Research Associates (1993) also showed that wetlands outside of the 1-foot (modeled) contour were exceptionally dry and had experienced vegetation changes. Rochow (1994) notes that further investigations of the modeling efforts, undertaken by the Southwest Florida Water Management District, indicated that drawdowns that occurred during wellfield development were much greater than anticipated.

Rochow (1994) (citing Biological Research Associates 1994), discussed monitoring efforts in the Cross Bar Wellfield for water year 1993 and noted that the monitored wetland plots had less surface water than in 1985, when water production increased. Many wetlands within the 1-foot modeled contour were dry since the latter half of the 1989 water year. Water levels in 1992 were significantly lower than water levels at the beginning of the monitoring period. Also, statistical analysis of the vegetation data showed a significant increase in the abundance of upland plants in almost all monitoring plots. Biological Research Associates (1994) found that several transects through wetlands that were located within the modeled 1-foot contour, had experienced shorter hydroperiods and had altered vegetation. Wetland plants such as floating hearts (*Nymphoides* spp) and fragrant water lilies (*Nymphaea odorata*) were replaced by dog fennel (*Eupatorium spp.*), blackberry (*Rubus spp.*), and blue maidencane (*Amphicarpum muhlenbergianum*). Cypress trees had exposed roots and some trees were leaning, indicating soil subsidence. Biological Research Associates (1994) also noted invasion of wetlands with upland plants within and near the outside of the 1-foot modeled contour. In their opinion, species composition and water level changes correlate more strongly with wellfield production than with rainfall for sites within and adjacent to the modeled 1-foot contour.

Eldridge-Wilde Wellfield. Although water production from this wellfield began in 1956, biological monitoring did not begin until the early 1970's (Rochow 1994). A biological survey performed by Rochow in the early 1980's reported that the vast majority of the wetlands in the Eldridge-Wilde wellfield were adversely impacted. Based on a detailed examination of historical aerial photographs dating back to the 1940's (SWFWMD 1982), it was inferred that most impacts occurred during the period of wellfield operation prior to 1971 (Rochow 1994). Adverse impacts to Eldridge-Wilde wetlands included soil subsidence, leaning trees, invasion of upland plants and the occurrence of destructive fires. Many of the impacted wetlands occurred within the modeled 3-foot water table drawdown contour and others were found in the area between the modeled 3-foot and 1-foot contours.

Morris Bridge Wellfield. This wellfield has been monitored by SWFWMD since 1977 (Rochow 1994). Average annual withdrawals increased from 13 MGD, when pumping began in 1978, to 16.8 MGD in 1983, with a peak withdrawal of 24.7 MGD. In 1983, modeling studies conducted for a Water Use Permit, using 18 MGD average and 30 MGD maximum withdrawals, indicated that the 1-foot contour extends beneath most of the wellfield. Rochow (1994) noted a set of conditions, termed "dry wetland" trends, that results from altered hydroperiods and include gradual and permanent loss of obligate aquatic and semi-aquatic plants and a gradually increasing coverage by upland and facultative plants suited to prolonged dry periods. The 1990 Water Use Permit, which included data from 1983 to 1989, indicated that most of the "dry wetland" trends continued during 1985 and in most cases were still observed in 1989. Cypress tree mortality was also observed, in one case depleting canopy cover by 45%. A recent 40% reduction in overall average annual wellfield pumpage appears to have stabilized the transition from wetland to upland plant species (Rochow 1994).

Biological Research Associates, Inc. began a monitoring program at Morris Bridge wellfield in 1985. In their 1991 water year report, which was reviewed by Rochow (1994), Biological Research Associates, Inc. (1992) indicated that, for the period from 1978 to 1991, rainfall was 10 inches above normal and the average daily pumping rate for water year 1991 was 8.9 MGD. Wetland water levels were lower on-site than off-site. In areas where models predicted a 1-foot contour, the wetlands remained dry until late June to mid July. Rochow (1994) states the opinion that monitoring by both the SWFWMD staff and Biological Research Associates indicates that wetland effects within the 1-foot contour are moderate compared to other wellfields. The moderate impacts observed at this particular wellfield are the likely result of a general reduction in overall wellfield pumpage since 1986 in combination with variable monthly pumpage that allows for some degree of water level recovery in wellfield wetlands at certain times.

Northwest Hillsborough Regional and Section 21 Wellfields. The Southwest Florida Water Management District has not conducted monitoring programs within these wellfields, but has reviewed the Consumptive Use Reports that were submitted by consultants (Rochow, 1994). Although the Section 21 Wellfield occupies a large tract of publicly-owned land, the Northwest Hillsborough Regional Wellfield wells are scattered among moderately to heavily urbanized areas. Therefore, in the area of the regional wellfield, wetlands that are influenced by well pumpage may also be influenced by ditches, impervious surfaces and other land uses that are unrelated to groundwater withdrawals. In addition, significant water production in at least one northeast Hillsborough County area began as early as 1930, thereby making it difficult to determine which uses or alterations caused adverse impacts to wetlands.

Water and Air Research, Inc. (1992) has monitored ecological conditions at 22 sites located in wetlands within the northwest region of Hillsborough County. Monitoring included sampling of vegetation and water levels at each site and measurement of soil subsidence at five sites. Water levels fluctuated between 8.05 feet and 0.03 feet. Ecological monitoring indicated that the wetlands were healthy and were not significantly impacted by wellfield production (Water and Air Research,1992).

Wellfield Impact Studies in Dade County, Florida. A wellfield impact study was conducted by the USGS and partially funded by the SFWMD in Dade County, Florida. Water levels in areas surrounding a Miami wellfield were above the ground 25% to 50% of the time before pumpage began in May of 1983 (Sonenshein and Hofstetter 1990). After the wellfield operations began, water levels within the cone of influence were above the land surface for less than 1% of the time in some areas (Figure 7). In the study area of 65 square miles, 20 square miles of wetland around the wellfield were adversely affected. The dewatering has completely dried out about 10 square miles and lowered groundwater levels in approximately another 10 square miles to the point that these areas are no longer considered wetlands.

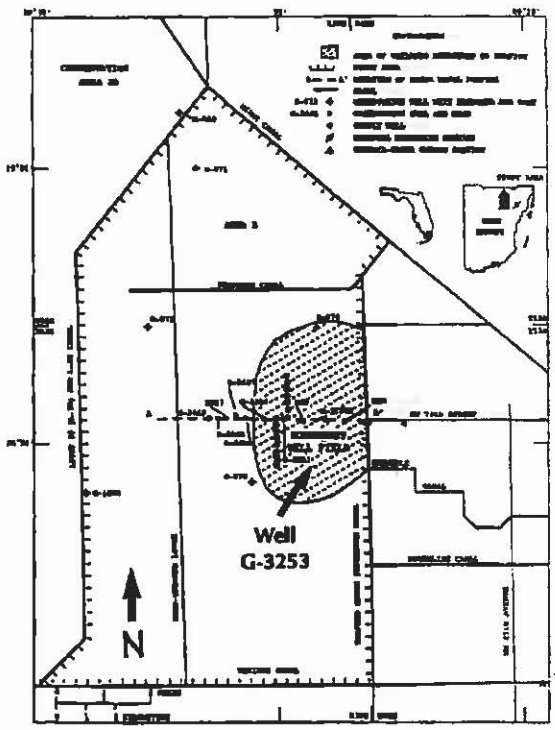
Hofstetter and Sonenshein (1990) reported that vegetation at sites surrounding the wellfield significantly changed between 1978 and 1986, as characterized by a "reduction in the relative frequency of herbaceous vegetation and an increase in the relative frequency of woody vegetation." Also, associated with the lowered water table and shortened hydroperiods was a change in dominance of those herbaceous species that are typical of a transition from wetland to upland. These transition areas became invaded by the exotic plant species, melaleuca (*Melaleuca quinquenervia*). The authors indicate that aerial photographs could not be used to document the impacts of wellfield operations because insufficient time had passed from the start of wellfield operations (May 1983) to when the photographs were taken (January 1986) to see detectable changes at that scale. The authors observed significant vegetation differences on-site that were not visible on the photographs and were indicative of future trends (Hofstetter and Sonenshein 1990).

Sonenshein and Hofstetter (1990) observed that in 1983 groundwater levels (Figure 7) were above land surface 60% of time, reaching a maximum height of 0.75 feet above the surface approximately 2% of the time. During this same year, the groundwater reached a maximum drawdown of 2.5 feet below land surface. In the period from 1984 to 1987 (after wellfield pumpage began), the maximum groundwater levels declined from 0.9 feet below land surface to 8.5 feet below land surface. Hydroperiods (water levels above land surface) went from 60% in 1983 before pumpage began to 0% after pumpage began.

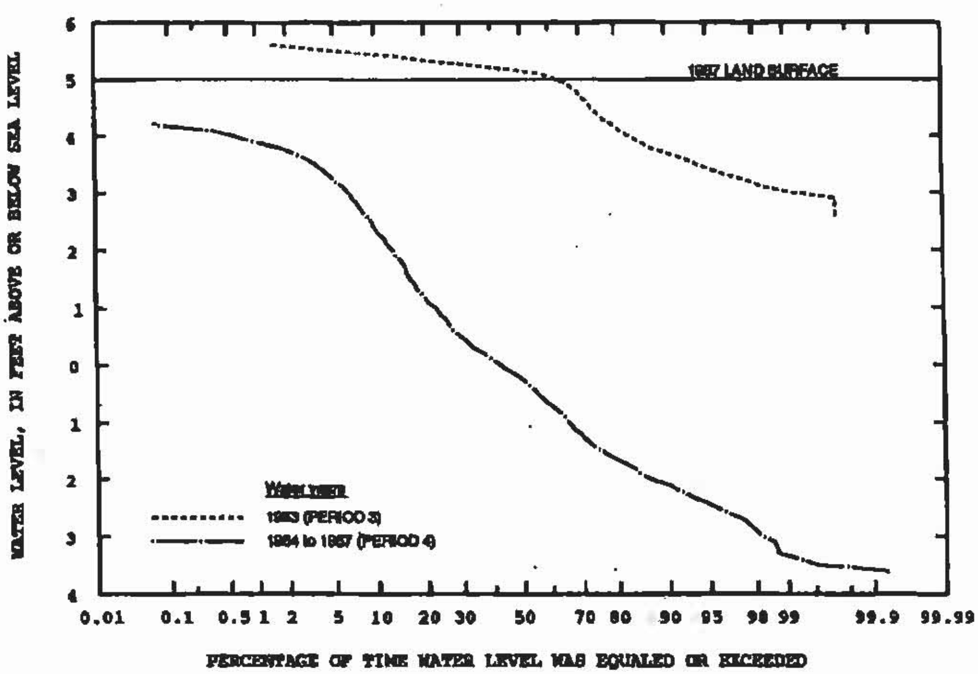
Hofstetter and Sonenshein (1990) inferred that local wellfield drawdowns were not the only source of wetland degradation. Lowering of regional surface water levels due to drainage canals has profoundly affected wetlands and their associated flora and fauna. Both local and regional effects of this nature have been documented within both the SFWMD (Hofstetter and Sonenshein, 1990) and the Southwest Florida Water Management District (Hancock 1993; Rochow 1994).

3.6. Effects of Changing Ground Water Withdrawals. Groundwater withdrawals from public wellfields tend to be permanent in nature. Generally, the demands for potable water increase over time. Public water supply wellfields rarely close completely and, if they are closed, this is generally caused by a reduction in treatability (saltwater intrusion, trihalomethane production) or manmade

Figure 7. Study area map and percentage time water levels were equaled or exceeded (Sonenshein and Hofstetter, 1990)



Study area showing data-collection sites, section A-A', and region of wetlands dewatered by pumping.



(After USGS 1990)

Water-level duration curves for well G-3253.

contamination (SFWMD 1991). Large public water supplies pump on a continuous basis, resulting in continual, extended or permanent dewatering of the aquifer in the vicinity of the wells. This has been documented as far away as 2.25 miles from an existing wellfield located in Dade County (Sonenshein and Hofstetter 1990) where water was withdrawn from the surficial aquifer system.

Pumpages from existing wellfields have occasionally been cut back, but wellfields are rarely shut down completely because of wetland impacts. Several wellfields within the SFWMD have had their pumpages reduced based on field data combined with a site-specific stress model (James M. Montgomery Consulting Engineers 1988; SFWMD 1991). SFWMD (1995) documented that the overall health of some adversely impacted wetlands within the SWFWMD did not improve when groundwater withdrawals from the Starkey wellfield were reduced. The author further stated that a reduction in wellfield pumpage did not return the original hydroperiod to the wetlands but merely decreased the drawdown underneath the wetland. SFWMD (1995) also noted that, "given enough rain, almost all impacted wetlands will become inundated, but the hydroperiods have become short and biological functions have been over stressed." The author attributed changes in the inundation period to lowering of the regional water table in the North Tampa Bay area.

3.7. Surface Water. Surface water features such as drainage ditches, canals, lakes and ponds can affect both local and regional surface and groundwater hydrology depending on their location, size and magnitude of water diversion. Drainage ditches and canals lower surface waters by diverting water that would otherwise pond, run off or percolate slowly to groundwater and by draining groundwater from the adjacent aquifers. Under other conditions, ditches and canals may provide recharge to adjacent groundwater systems. Generally, gravity fed ditches and canals have a relatively constant effect on surface and groundwater hydrology, while pumped ditches and canals have a discontinuous and time-varying effect. The presence of natural or man-made standing water bodies such as ponds and lakes can buffer the effects of drainage systems on local or regional hydrology via spillover or recharge, depending on their area, depth and spatial distribution.

Impacts of Ditching. Ditching of a wetland can result in significant lowering of the water table and reduction of the hydroperiod. CH_2M Hill (1988) studied the effects of ditching on wetlands in Sarasota County and reported that the average hydroperiod of 21 unaltered wetlands was 313 days, whereas the average hydroperiod of 5 wetlands that were affected by ditching was 173 days. During the period of study, they also observed that average dry season water levels were 1 to 2 feet lower in ditched wetlands than in unditched wetlands, but that seasonal high water levels were not significantly different. At the beginning of the rainy season in 1986, water levels in ditched wetlands did not rise above ground level until 2 to 4 weeks later than in the unditched wetlands. CH_2M Hill (1988) classified the plants that occur in these systems into four groups that respond to declining water levels as follows: 1) invasive species that are not generally associated with unaltered wetlands and that increase in abundance; 2) facultative wetland species that increase in abundance; 3) wetland species that maintain viable populations or decrease slowly; and 4) obligate wetland species that rapidly decline in dominance.

Impacts of Drainage Canals on Cypress Communities. Lowered water tables may adversely affect wetlands at substantial distances, due to changes in surface water and groundwater availability. Swayze and McPherson (1977) studied the effects of declining water levels in the Fakahatchee Strand caused by the

construction of the Faka Union Canal. Results showed that a water level decline of 2 feet at a distance of 6,000 feet from the canal caused a reduction in cypress head productivity. A decline in the water table beneath a wetland can have sublethal effects on vegetation by reducing plant vigor and productivity. Burns (1984) studied the relationship between water levels and productivity of two cypress strands in the Fakahatchee Strand located in Collier County, Florida. The swamps were located 0.2 km (660 ft) and 2 km (6600 ft) from a newly constructed drainage canal. There was a two-fold decrease in biomass and net productivity in the cypress swamp nearest the canal. The water table in the vicinity of this wetland declined an average of 50 cm (1.6 feet). He attributed net productivity loss in the drained swamp to the diversion of energy from leaf canopy maintenance to below ground production. Burns (1984) also noted that the site nearest the canal experienced a loss of vegetative ground cover with the exception of some patches of *Baccharis* and that the more remote wetland supported a dense cover of ferns. The author suggested that "cypress forests may be strongly dependent on regional water storage during the first few months of the growing season." These observations are supported by Carter et al. (1973) who documented that a 1-foot drawdown beneath a cypress swamp was caused by construction of drainage canals in the Golden Gate development in Collier County. This reduction in water levels produced observable alterations in hydroperiod, soil moisture content and structure, and a 40% reduction in cypress tree production.

Effects on Wetland Flora and Fauna. In addition to direct effects on plant survival, lowered water tables may alter vegetation communities by changing reproductive cycles and subsequent seedling repopulation. Shorter hydroperiods may induce or inhibit flowering. Seeds of wetland species that are well adapted to germinate and survive in saturated soils may be outcompeted by seeds of more terrestrial species that grow faster in drier soils.

Wetlands also provide home, reproductive and forage habitat for many species of animals, including macroinvertebrates, fishes, amphibians, reptiles and birds. As the hydroperiod and vegetation characteristics of these systems are altered, these changes may adversely impact fauna that depend on specific water regimes for their survival. Harris and Vickers (1984) reported on the effects of lowered water tables on the fauna of cypress wetlands. In assessing herpetofauna in ditched and unditched cypress swamps, they observed that ditching caused a shift in species abundance from aquatic to more terrestrial species.

3.8. Hydrogeological Models. Various federal, state and local entities, including the USGS, Water Management Districts (WMDs) and many local governments, use hydrogeological models as tools to assess groundwater withdrawal impacts. Some of those agencies (USGS and WMDs) also use these models to assess hydrologic impacts on wetlands. The SFWMD uses numerical models (MODFLOW computer code written by the USGS) for their water supply plans and for the review of some permit applications. All models have errors associated with their numerical output. The accuracy and precision of the modeled results depend upon the information uncertainty and intrinsic uncertainty of the chosen numerical approach. Experts (Mitchell 1993; Cooley and Vecchia 1987; Dettinger and Wilson 1981; Harper and Clark 1989; Rafalko and Hawley 1989) indicate that to properly assess the intrinsic and information uncertainty, the modeler needs to conduct statistical analyses and generate confidence intervals in order to provide users and policy makers with an explicit degree of confidence or certainty in their decisions. The District has not generated uncertainty graphs or confidence intervals for existing groundwater models. The effect of cumulative errors is generally represented by a discrepancy in

the water budget of the model or by differences between maps constructed on the basis of the modeled groundwater levels versus maps based on the actual ground water levels.

Differences between Model Results and Field Measurements. Results of the literature survey (SFWMD, 1995; Rochow 1994) suggest that a modeled drawdown of one foot can be associated with an actual drawdown of significantly greater magnitude. Scientists from the SWFWMD compared model simulations with field monitoring data collected from seven regionally important wellfields (Rochow, 1989; 1994). The model stress parameters were as follows: a 90-day numerical model run, maximum monthly pumpage and no recharge. These studies documented adverse impacts to wetlands within a 0.6-foot modeled drawdown contour (Rochow 1994). The assumption that the hydrogeologic system will reach equilibrium within 30 days was also investigated by SWFWMD District staff. They concluded that, in some cases, equilibrium may never be reached or, if so, only after many years of constant pumping. It is important to note that areas within a modeled 1-foot water table drawdown, when compared to on-site hydrological data, showed varying degrees of stress. At some locations, little impact occurred to the water table and wetlands, while at others, the water table may have dropped several feet with immediate and profound impacts to wetlands (Rochow, 1989; 1994).

Rochow (1994) noted that biologists from the SWFWMD observed adverse ecological impacts in cypress swamps and freshwater marsh areas where models were predicting a 0.6-foot drawdown due to wellfield pumping. The percentage of each type of wetland within the 0.6-foot cone of depression that exhibited such effects and the severity of effects observed in each impacted wetland were not discussed in their report. Significant adverse impacts tend to occur in isolated cypress swamp and freshwater marsh areas where modeling studies predicted a lowered water table of one foot or more. When results of such modeling studies were compared with actual field measurements, it was observed that a 1-foot drawdown (estimated from a stress model) caused by municipal groundwater withdrawals from wells placed at various distances from isolated wetlands corresponded to actual drawdowns of several feet (Hancock 1993). These drawdowns, in turn, produced observable and adverse alterations in hydroperiod, fire characteristics, soil subsidence, plant community structure and wildlife use. Rochow (1994) cautions that impacts may become apparent where modeled groundwater level declines are of a relatively small magnitude and that withdrawals of small quantities may have impacts on wetlands given a long enough period of study.

3.9. Examples from Other Areas. Bernaldez et al. (1993) studied the effects of agricultural irrigation on water table levels in the Dours River Basin in Central Spain, and noted several types of impacts on local wetlands. The study area was divided into four zones and wetlands were categorized based on their relationship to the main aquifer. Within this region, irrigation has doubled since pumping began in the 1950's and lowered the water table substantially (average decline of 0.9 to 1.2m [3-4 ft] per year from 1970 to 1987). Wetlands connected to the main aquifer, wetlands linked to local flow systems on relatively steep slopes, and wetlands connected to intermediate or subregional flow systems were affected by water withdrawals. Wetlands that were not affected by groundwater withdrawals included recharge ponds and wetlands that were not connected to the main aquifer. Wetlands connected to regional systems, in almost all cases, were affected by drainage due to ditching. Bernaldez et al. (1993) determined that the decline in the water table, due

to either groundwater withdrawals or ditching, caused some wetlands to become noticeably drier, vegetation to shift, and wetland species to disappear.

Wilkie and Larson (1980) studied the effects of municipal wellfield water withdrawals on wetlands in Massachusetts, using aerial photographs, and found that wetland water levels were reduced between 18% to 100%. These authors also noted shifts in vegetation structure, from wetland to upland plant species. Kirschner et al. (1988) conducted a half-year study to compare conditions in a red maple (*Acer* sp.) swamp that had been ditched with conditions in a nearby unaltered red maple swamp. They noted that the ditched wetland no longer had standing surface water and had reduced wildlife usage compared to the unaltered wetland.

Lowering of the water table beneath a wetland by means of drainage tubes can change the vegetative structure of a wetland. Such studies conducted in a Danish fen by Hald and Petersen (1992) indicated that an increase occurred in the bulk density of vascular plants and a vegetative shift to a plant community that was more characteristic of drier conditions. Driver (1977) studied small, natural prairie ponds in Central Saskatchewan and discovered a linkage between hydroperiod and chironomid (midge) diversity and concluded that chironomids could be used as indicators of hydroperiods. The diversity of chironomid populations in small prairie wetlands with different water regimes (ranging from temporarily flooded to permanently flooded) increased as the duration of flooding increased.

3.10. Needs for Additional Information. The literature reviewed during this survey indicated that most studies and methods used could not determine a threshold of harm corresponding to a specific groundwater drawdown level (modeled or actual). Most authors provided quantitative and/or qualitative observations of changes in plant species composition of wetland communities or plant "condition" over time. However, these analyses did not consider the combined TDFM effects of drawdowns on the wetland.

More information is needed to determine when, and to what degree, wetland ecosystems and their component flora and fauna become impacted due to changes in water conditions. The responses of different types of wetlands to drawdowns must also be determined. Biological indicators that are sensitive to reduced hydroperiods and water levels need to be identified. Additional information is also needed to compare drawdowns predicted by models with actual drawdown conditions that occur at the site. Primary sources of such information are controlled field experiments and careful monitoring of existing or new facilities.

Two ways (in theory) to determine whether a wetland ecosystem is experiencing unnatural stress due to anthropogenic perturbations are to (1) compare a stressed site to reference sites in which the perturbing influence is absent or (2) evaluate a suite of sites under a gradient of increasing stress. Both types of studies require a relatively long study period or monitoring period (e.g., decades), because wetlands exhibit natural variabilities over the short term (seasons, years) and long term (e.g. extended droughts or wet periods) that may mask true trends. In addition, local variations in soils, plant community structure, geology, climate, drainage, geomorphology, etc. make it difficult to identify truly "comparable" sites.

The experimental or monitoring design must adequately measure ecosystem response to the stress. Significant manifestations of stress in response to a perturbation are often first observed at the population level and occur due to effects on the survival, health or reproduction of one or more species. Although there are

many potential symptoms of stress, it is not always possible to establish an exact cause. The amount of stress actually applied needs to be carefully measured or monitored. Manifestations of stress will tend to increase in significance, extent, and probability of irreversibility as a function of the TDFM of the perturbation. The changing ecosystem response to a particular stressor is specific to the site and antecedent conditions.

The experimental or monitoring program design also needs to consider plant, animal, microbial, geologic, hydrologic and geomorphologic aspects of the ecosystem. Vascular plants are not likely to be the most sensitive indicators of ecological stress. Periphyton and microbial species are critical components of the ecosystem that should also be considered and will often respond more quickly to environmental conditions. However, periphyton and microbial species may be more influenced by factors other than hydroperiods and water levels, such as temperature or changes in water quality. The timing of the consecutive days of water depth between a minimum and maximum level is especially critical for animal species. For example, aquatic insects and amphibians require a minimum depth of standing water for egg-laying and development for only a few months during their reproductive cycle. If this requirement is not met, the local amphibian and/or aquatic insect populations may be severely impacted. Such changes could occur even though the wetland hydroperiod has not changed.

In addition to understanding the ecological and hydrological aspects of a wetland, the geological and geomorphological features need to be more fully investigated. Currently, most freshwater wetland classification systems are based strictly on ecological or hydrological (surface water) features, or some combination of both. Geomorphological features are important regulating factors that also determine properties of wetland systems. Much of South Florida's topography is dominated by past sea level transgressions and regressions. Modern examples of such features include sea level terraces, paleo-karst, and erosional surfaces (eolian, fresh water or saltwater). The most recent major sea level regression, which has shaped the land surfaces evident in South Florida today, occurred more than 10,000 years ago.

Vegetation zonation patterns have developed in response to physical topography and sediments of a given location (Mitsch and Gosselink (1994). In addition to geomorphology, other important factors include the regional and local geology. In some cases, the effects of regional geology are greater than the effects of surface geomorphology and control the overall shape and type of the wetland system. The ability of the surface water and groundwater to interact within wetlands is also a function of regional and local geology. Investigations into classification and management of major wetland systems and isolated wetlands and determination of the effects of water withdrawals can only be complete when a detailed geomorphological and geological evaluation has been conducted.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. What is the relationship between the timing, duration, frequency and magnitude (TDFM) of the groundwater drawdown and the effects on the ecology of isolated wetlands?

- There is a limited amount of information in the scientific literature on the relationship between the TDFM of groundwater drawdowns and the nature, magnitude and extent of impacts on isolated wetlands. Approximately 24 of the 108 references were relevant to this issue.

- Reports on the effects of hydrologic perturbations on isolated wetlands focused either on the flora or fauna and most of these investigations dealt with effects on plants. Comprehensive studies that investigated flora, fauna and hydrogeological conditions have not been conducted in an ecological assessment framework .

- Some of the best information available was obtained from more than a dozen studies that were conducted by the SWFWMD on the effects of drawdowns on isolated wetlands, primarily cypress swamps and deep water marshes, over the past 20 years. Drawdowns beneath these wetlands have caused cypress tree mortality, changes in herbaceous community structure, soil subsidence, substrate collapse, and increased incidence of destructive fires.

- Although none of the studies provided sufficient data to quantify a relationship between the TDFM of groundwater withdrawals beneath isolated wetlands and observable adverse effects on wetlands ecology, at least six of the studies indicated that an extended modeled drawdown of from 0.6 ft to 1.0 foot, within seasonally to semipermanently flooded wetlands, corresponded to significant changes in plant community composition and structure.

Recommendations:

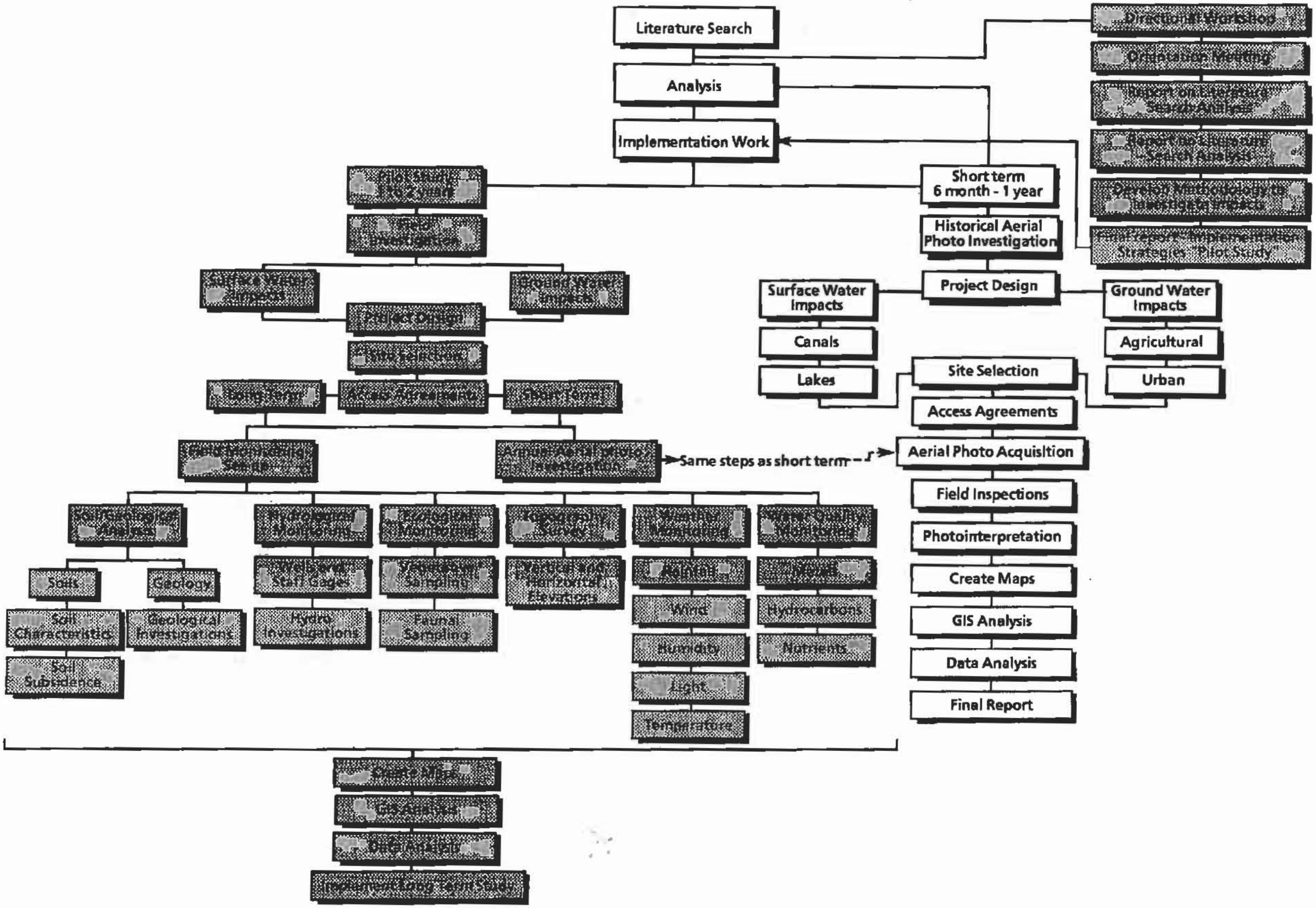
Additional studies will be required to determine effects of TDFM of groundwater drawdowns on isolated wetlands. It should be possible to confine additional studies to be cost-effective and most likely to produce directly applicable results in the shortest time-frame.

A phased approach is proposed for obtaining short- and long-term information to fill critical data gaps most cost-effectively, with each successive phase building on the information and experience of the previous phases. This process, as shown in **Figure 8**, should be implemented immediately.

4.2 What are the differences between observed effects on isolated wetlands based on actual groundwater drawdowns vs. modeled groundwater drawdowns?

- A number of cases from the literature have documented adverse impacts on isolated wetlands that experienced a 1-foot modeled drawdown in the water table caused either by construction of drainage canals or by groundwater withdrawals. One study, in which results from the model were compared with field observations, indicated that a 0.6-foot modeled drawdown caused by municipal groundwater withdrawals corresponded to actual drawdowns of

Figure 8. Steps to Investigate Wetland Drawdown Impacts



unspecified magnitude, but produced observable and adverse alterations in plant community structure and wildlife use.

- Information from studies conducted in Florida suggests that a 1-foot decline in water levels due to wellfield operation, as predicted by a stress model, represents an initial estimate of the amount of drawdown that will cause adverse impacts on seasonally to semi-permanently flooded wetlands, such as cypress swamps and marshes.

- Although the SFWMD uses numerical and analytical models to evaluate water use permits for protecting wetland resources, there may be substantial uncertainty between actual and predicted groundwater levels. In some cases where SWFWMD used models to predict groundwater levels near municipal wellfields, there were significant differences between the actual and predicted water levels. This finding is not inconsistent with the degree of accuracy of the models used and reflects the difference between the simplifying assumptions that were used to build the model and the inherent complexity of natural environments.

Recommendations:

To determine and compare observed effects on isolated wetlands based on actual groundwater drawdowns with effects predicted from modeled groundwater drawdowns, the South Florida Water Management District should first implement the recommendations of the Modeling Advisory Committee. These include: (1) substitute the Penman-Monteith formula for the Blaney-Criddle Formula to calculate evapotranspiration water demands; and (2) initiate field studies to determine the effects of permitted groundwater withdrawals on isolated wetlands, both locally and regionally.

Local impacts from permitted groundwater withdrawals should be assessed by visiting a significant set of sites in each wetlands category that occurs within the SFWMD. Shallow wetlands, in particular, need investigation since these wetlands have not been adequately evaluated by SWFWMD or others and may very likely need a level of protection that is not taken into account by the 1-foot modeled drawdown criterion.

Regional impacts from permitted groundwater withdrawals should be assessed from historical aerial photographic data from the 1940's-1990's.

Follow-up aerial photography studies should focus on a subset of unimpacted, slightly impacted, moderately impacted, severely impacted, and destroyed wetland ecosystems, over a time period of several years, to establish correlations between the distance and magnitude of groundwater withdrawal and the nature and magnitude of the ecological impacts. The study should include local, as well as regional, control (unimpacted wetland) sites and compare modeled with actual drawdown conditions.

Decisions must be made to establish how much precision is required to adequately protect the resource. This information can then be used by the District to determine the optimum numbers and locations of groundwater monitoring wells needed to calibrate modeling tools and determine impacts of management decisions.

4.3 What is the appropriate TDFM groundwater withdrawal criterion for each distinct category of isolated wetland?

- None of the articles from the literature examined or addressed the actual or modeled impacts of local or regional groundwater withdrawals on isolated wetlands under specified conditions of timing, duration, and frequency with the desired scientific rigor.

- Wetlands studied were classified on the basis of dominant vegetation characteristics (cypress swamp, pickerelweed marsh, etc.) rather than on the basis of their water regimes (water levels and hydroperiods) or faunal components. The studies conducted in Florida appeared to be centered around seasonal to semi-permanently flooded cypress swamps and marshes.

- There does not appear to be sufficient information in the scientific literature to derive hydrologic criteria to protect each category of South Florida wetlands from adverse impacts. However, based on studies conducted by the Southwest Florida Water Management District that compared stress modeled groundwater levels with field observations of wetland conditions, there is evidence to suggest that significant impacts occurred in areas where the models estimated a 1.0-foot drawdown. These studies also indicated that in areas where the magnitude of a modeled groundwater withdrawal was 0.6 feet, with 90 days of no recharge, damage occurred to seasonally or semi-permanently flooded cypress swamps and marshes, based on the hydrological, geological and meteorological conditions that exist in the SWFWMD jurisdiction.

Recommendations:

Further studies need to be undertaken that address the effects of drawdown TDFM on various types of wetlands in the different hydrogeological regimes that occur within the District.

The modeled 1-foot drawdown criterion, for one month under conditions of 90-days no recharge (1/1/90), has been a *de facto* standard for several years. There is no assurance, from the literature, that this is adequate to protect all wetland systems in South Florida and, in fact, there is ample evidence to suggest that a criterion of less than one foot of drawdown may be appropriate in some areas (SWFWMD, 1995). No criterion should be considered that provides less protection than the 1/1/90 criterion.

A combined lake and wetlands management plan should be developed by the five water management districts that includes a common classification of natural water bodies and wetlands. Once such a plan and classification are developed, these guidelines could be used to assess the status of surface water resources and provide a basis to evaluate the relative effects of groundwater withdrawals on these aquatic resources (see SWFWMD 1994b).

4.4 What types of additional information and data need to be obtained to provide better answers to these three questions?

- Most of the studies and methods that were reviewed during this literature survey did not determine a threshold of harm corresponding to a specific groundwater drawdown level (modeled or actual), based on the timing,

duration, frequency and magnitude of a groundwater drawdown. Although a certain amount of quantitative monitoring is necessary to provide sound scientific evidence, the need to cover large geographic areas economically makes it desirable to develop valid, rapid sampling techniques.

- Detailed site evaluations for regional and local geomorphology, geology and hydrogeology should be conducted in conjunction with biological and soil evaluations. Understanding the geology of the wetland will assist the evaluator in assessing the ecological variations within the wetland system.

- Surface water levels in the wetlands should be compared to deep and shallow groundwater wells to determine "connectivity" or interactions between surface and groundwater systems and time lags associated with aquifer stresses.

- More information is needed to determine when, and to what degree, wetland ecosystems and their component flora and fauna become impacted due to changes in water conditions. The two primary sources of such information are controlled research and improved monitoring of existing or new facilities.

- Long-term research and monitoring studies are needed that adequately measure the amount of perturbation and stress applied, and ecosystem responses. Measures of ecosystem response need to be developed that consider microbial, periphyton, vascular plant, macroinvertebrate, fish, amphibians and other wildlife.

- The regulatory process requires that a workable, consistent definition of harm needs to be developed for ecosystems. Such a definition would provide a better means to assess and control impacts. Statistically significant results are required from well-designed, controlled, field experiments, and from improved monitoring and field surveys of existing impacted sites. These data could provide the weight of evidence needed to develop an administratively defensible hydrologic criterion that can protect isolated wetlands from an unacceptable risk of impairment or harm.

Recommendations:

The following steps are suggested as a means to derive hydrologic criteria to protect wetlands from an unacceptable risk of harm:

1) Adapt existing arrays of biological imbalance indices and their measures, tests, and procedures to wetlands ecosystems.

2) Identify the set of perturbing influences that, singly or in various combinations, have been associated causally with the observed physical, chemical, and biological manifestations of ecological stress.

3) Develop a set of evidentiary criteria with which to distinguish ecologically insignificant effects from significant effects at the individual organism, cohort, population, community, and ecosystem levels.

4) Develop a set of statistical criteria with which to discriminate the association between the nature, magnitude, extent, duration, and

frequency of recurrence of a perturbing influence and significant physical, chemical, and biological manifestations of ecological harm.

5) Apply the adopted array of indices and their measures, tests, and procedures to evidence gathered from quasi-controlled field studies, uncontrolled field surveys, and required monitoring.

6) Adopt combinations of meteorological, hydrological, and biogeochemical conditions of appropriately infrequent recurrence for each physiographic region as the design conditions for issuing permits.

7) Develop a consensus among management and permitting authorities to adopt hydrologic criteria to protect each distinct wetland category and physiographic region. An example of such a criterion would be the value that precludes the manifestations of hydrologic stress in 95 percent of the isolated wetlands, 95 percent of the time.

8) Verify the hydrologic criterion by inducing a gradient of ecological harm with a corresponding measurable gradient of hydrologic stress in a statistically significant number of isolated wetlands in each wetlands category.

5. LITERATURE CITED

Bernaldez, F.G., J.M. Rey Benayas and A. Martinez. 1993. Ecological impacts of groundwater extraction on wetlands (Dours Basin,Spain). Journal of Hydrology 141:219-238.

Biological Research Associates, Inc. 1992a. Cross Bar Ranch Wellfield ecological monitoring report - 1991 water year. Submitted to West Coast Regional Water Supply Authority, Clearwater, Florida.

Biological Research Associates, Inc. 1992b. Annual Report – Ecological monitoring of the Morris Bridge Wellfield, water year 1991. Prepared for the City of Tampa Water Department. (Reference obtained from Rochow 1994).

Biological Research Associates, Inc. 1993. Cross Bar Ranch Wellfield ecological monitoring report, SWFWMD water use permit no. 204290.02 -- water year 1992. Prepared for West Coast Regional Water Supply Authority, Clearwater, Florida.

Biological Research Associates, Inc. 1994. Cross Bar Ranch Wellfield ecological monitoring report, SWFWMD water use permit no. 204290.02 -- water year 1993. Prepared for West Coast Regional Water Supply Authority, Clearwater, Florida. (Reference obtained from Rochow 1994).

Burns, L.A. 1984. Productivity, and water relations in the Fakahatchee Strand of South Florida. In: Ewel, K.C. and H.T. Odum (Eds.), Cypress Swamps. Center for Wetlands, University of Florida, Gainesville. pp. 318-333.

CH_2M Hill. 1988. Hydroecology of wetlands on the Ringling-MacArthur Reserve. Technical Report No. 2, Vol. 1. Prepared for Sarasota County, Florida. various. pages.

CH_2M Hill, Inc. 1991. Ecological and hydrological monitoring, J.B. Starkey Wellfield, Pasco County, Florida. Annual Report, Water Year 1990. Prepared for West Coast Regional Water Supply Authority, Clearwater, Florida. (Reference obtained from Rochow 1994).

Carter, M.R., L.A. Burns, T.R. Cavinder, K.R. Dugger, P.L. Fore, D.B. Hicks, H.F.Revels, and T.M. Schmidt. 1973. Ecosystems analysis of the Big Cypress Swamp and estuaries. Ecological Report no. DI-SFEP-74-51. U.S. Environmental Protection Agency, Athens, Georgia. 375 pp.

Cooley, R.L. and A.V. Vecchia. 1987. Calculation of nonlinear confidence and prediction intervals for ground-water flow models. American Water Resources Association Water Resources Bulletin 23:4: 581-599.

Day, F.P., Jr., S.K. West and E.G.Tupacz. 1988. The influence of ground-water dynamics in a periodically flooded ecosystem, the Great Dismal Swamp. Wetlands 8:1-13.

Dettinger, M.D. and J.L. Wilson. 1981. First order analysis of uncertainty in numerical models of groundwater flow. Water Resources Research 17:1: 149-161.

Dooris, P.M., G.M. Dooris, T.F. Rochow, and M. Lopez. 1990. The effects on wetland vegetation and habitat value caused by altered hydroperiods resulting from groundwater withdrawals in central Florida. Env. Sec. Tech. Report, 1990-1. Southwest Florida Water Management District, Brooksville, Florida. 18 pp.

Driver, E.A. 1977. Chironomid communities in small prairie ponds: some characteristics and controls. Freshwater Biology 7:121-133.

Duever, M.J., J.E. Carlson, J.F. Meeder, L.C. Duever, L.H. Gunderson, L.A. Riopelle, T.R. Alexander, R.L. Meyers and D. Spangler. 1986. The Big Cypress National Preserve. New York: National Audubon Society. 444 pp.

Environmental Science and Engineering, Inc. 1991. Hydroperiods and water level depths of freshwater wetlands in South Florida: a review of the scientific literature. Environmental Science and Engineering, Inc., Tampa, Florida., for South Florida Water Management District. 39 pp.

Gee and Jensen Engineers-Architects-Planners, Inc. 1991. List of references on hydrologic data and environmental setting related to the Corkscrew Regional Ecosystem Watershed (CREW hydrologic and hydraulic study). Gee and Jensen Engineers-Architects-Planners, Inc., West Palm Beach, Florida., for South Florida Water Management District. 35 pp.

Hald, A. B. and P.M. Petersen. 1992. Soil and vegetation in two Danish fens following changes in water regime. Nordic Journal of Botany 12:707-732.

Hancock, M.C. 1993. Review of memorandum to the file of record concerning : "The effects of water table level changes on freshwater marsh and cypress wetlands in the northern Tampa Bay region." Memorandum to Ted F. Rochow, SWFWMD, Brooksville, Florida.

Harper, W.V. and I. Clark. 1989. Travel path uncertainty - two approaches to conditional simulation. Solving Ground Water Problems with Models: 149-162.

Harris, L.D. and C.R. Vickers. 1984. Some faunal community characteristics of cypress ponds and the changes induced by perturbations. In: Ewel, K.C. and Odum, H.T. (Eds.), Cypress Swamps :171-185.

Henigar and Ray, Inc. 1992. Water Year 1991 Annual Report, J.B. Starkey Wellfield, Pasco County, Florida. prepared for West Coast Regional Water Supply Authority, Clearwater, Florida. (Reference obtained from Rochow 1994).

Hofstetter, R.H. and R.S. Sonenshein. 1990. Vegetation changes in a wetland in the vicinity of a wellfield, Dade County, Florida. U.S. Geological Society Water Resource Investigation Report 89-4155. U.S. Geological Society. 16 pp.

James M. Montgomery Consulting Engineers, 1988. Evaluation of impacts of wellfield withdrawals in the vicinity of the North Martin County wellfield - Phase 1 Report. South Florida Water Management District, West Palm Beach, Florida.

Karr, J.R., K.D. Fausch, P.L. Angermeier, P.R. Yant, and I.J. Schlosser, 1986. Assessing Biological Integrity in Running Waters: A Method and its Rationale. Special Publication 5, Illinois Natural History Survey, Urbana Illinois.

Kirschner, B.A., R.W. Franzen, S. Palalay, and M. Olynyk. 1988. Groundwater drawdown in palustrine forested wetlands as a result of drainage and the use of water control structures to reduce adverse impacts. Proc.: National Wetland Symposium, Mitigation of Impacts and Losses. October 8-10, 1986, New Orleans, Louisiana. Publ. by Assoc. of Wetland Managers, Inc., Tech. Rept. No. 3, May, 1988. pp 153-155.

Lowe, E.F., S. Mortellaro, Mattson R., Flannery S., Rochow, T. and Epting, B. 1994. District Water Management Plan - Conventions Subcommittee on Impacts to Natural Systems. SJRWMD, Palatka, Florida. pp. 56-58.

Mazzotti, F.E., L.A. Brandt, L.G. Pearlstrine, W.M. Kitchens, T.A. Obreza, F.C. Depkin, N.E. Morris and C.E. Arnold. 1992. An evaluation of the regional effects of new citrus development on the ecological integrity of wildlife resources in southwest Florida. Final Report. South Florida Water Management District, West Palm Beach, Florida. 188 pp.

Mitchell, J.E. 1993. The influence of (*xy*) uncertainty on prediction error and contour lines from a three-dimensional surface. American Water Resources Association Water Resources Bulletin **29:5**: 863-870.

Mitsch, W.J. and J.G. Gosselink. 1986. Wetlands. New York: Van Nostrand Reinhold Company.

Mitsch, W.J. and J.G. Gosselink. 1993. Wetlands. 2nd Ed. New York: Van Nostrand Reinhold Company.

O'Brien, A.L. and W.S. Motts. 1980. Hydrogeologic evaluation of wetland basins for land use planning. Water Resources Bulletin, American Water Resources Association **16:5**: 785-789.

Osceola County v. St. Johns River Water Management District and South Brevard Water Authority. Case No. 91-1779. State of Florida, Division of Administrative Hearings. 1991.

Rafalko, L.G. and M.E. Hawley. 1989. Uncertainty in transport predictions. Solving ground water problems with models: 493-515.

Reed, P.B, Jr. 1988. National List of Plant Species that Occur in Wetlands: Florida. National Wetlands Inventory, U.S. Fish and Wildlife Service, St. Petersburg, Florida. 133 pp.

Rochow, T.F. 1982. Biological assessment of the J.B. Starkey Wilderness Park--1982 update. Environmental Section Technical Report 1982-9. Southwest Florida Water Management District, Brooksville, Florida. 58 pp.

Rochow, T.F. 1985a. Biological assessment of the Jay B. Starkey Wilderness Park--1985 update. Technical Report 1985-4. Environmental Section, Southwest Florida Water Management District, Brooksville, Florida. 105 pp.

Rochow, T.F. 1985b. Hydrologic and vegetational changes resulting from underground pumping at the Cypress Creek wellfield, Pasco County, Florida. *Florida Scientist*. 48(2): 65-80.

Rochow, T.F. 1989. Part II rule revision: water table levels necessary to maintain wetland vegetation in cypress domes and marshes. Memorandum to D.L. Moore. Environmental Section, Southwest Florida Water Management District, Brooksville, Florida.

Rochow, T.F. and P. Rhinesmith. 1991. Comparative analysis of biological conditions in five cypress dome wetlands at the Starkey and Eldridge-Wilde wellfields in southwest Florida. Tech. Report 1991-1. Environmental Section, Southwest Florida Water Management District, Brooksville, Florida. 67 pp.

Rochow, T.F. 1994a. The effects of water table level changes on fresh water marsh and cypress wetlands in the northern Tampa Bay region. Technical Report 1994-1. Southwest Florida Water Management District, Brooksville, Florida.

Sonenshein, R.S. and C.S. Hofstetter. 1990. Hydrologic effects of well-field operations in a wetland, Dade County, Florida. Water Resources Investigation Report 90-414. United States Geological Survey, Tallahassee, Florida.

South Florida Water Management District. 1991. Water supply policy document. Planning Department, SFWMD, West Palm Beach, Florida. 82 pp.

South Florida Water Management District. 1993. Management of water use permitting information manual, volume III. Regulation Department, SFWMD, West Palm Beach, Florida. various pages.

Southwest Florida Water Management District. 1978. Second Year Results of Vegetational Monitoring at the Cypress Creek Wellfield, Pasco County, FL, 1976-1977, Southwest Florida Water Management District, Brooksville, Florida. April, 1978

Southwest Florida Water Management District. 1979. Biological assessment of the Jay B. Starkey Wilderness Park -- 1979 Update. Technical Report 1979-7. Environmental Section, Southwest Florida Water Management District, Brooksville, Florida. 115 pp.

Southwest Florida Water Management District. 1995. Final Draft - North Tampa Bay Water Resources Assessment Project. Executive Summary, February 1995; Volume 1 - Surface Water/Ground Water Relationships, February,1995; Volume 2 - Water Quality and Saline Water Intrusion, May 1995 + Appendices. SFWMD, Brooksville, Florida.

Southwest Florida Water Management District. 1994b. Draft - Report of the subcommittee for the assessment of the hydrologic effects of ground water withdrawals on surface-water resources: March 18, 1994. Brooksville, Florida.

State of Florida. Chapter 17-40, Florida Administrative Code. State Water Policy.

State of Florida. Chapter 373, Florida Statutes. The Water Resources Act.

Swayze, L.J. and B.F. McPherson. 1977. The effect of the Faka Union Canal system on water levels in the Fakahatchee Strand, Collier County, Florida. Water Resources Investigations 77-61. Tallahassee, Florida.

Wang, F.C. and A.R. Overman. 1981. Impacts of surface drainage on ground water hydraulics. Water Resources Bulletin. Volume 17:971-977.

Water and Air Research, Inc. 1992. Northwest Hillsborough Regional Wellfield consumptive use permit #206676 regional monitoring plan, annual report - water year 1991. Hydrological and environmental conditions; wetland vegetation. Report prepared for the West Coast Regional Water Supply Authority, Clearwater, Florida. 5 pp.

West Coast Regional Water Supply Authority , 1989. Environmental monitoring and wetland vegetation report . Consumptive use permit # 206676 - Water Year 1988.

Watson, J., D. Stedje, M. Barcelo. and M. Stewart. 1990. Hydrogeologic investigations of cypress dome wetlands in wellfield areas north of Tampa, Florida. In: Proc. Focus Eastern Conference, National Water Well Assoc., Dublin, OH.:163-176.

Wilkie, D.S. and J.S. Larson. 1980. Municipal wells, land development and freshwater wetlands in Massachusetts. Publication No. 20. Water Resources Research Center, Amherst, Massachusetts.

Appendix - BIBLIOGRAPHY of REFERENCES REVIEWED

Bays, J.S. and Winchester, B.H. 1986. An overview of impacts associated with hydrologic modification of Florida freshwater wetlands. In: Managing cumulative effects in Florida wetlands conference proceedings, Mote Marine Laboratory, Environmental Studies Program, University of Florida. E.S.P. Publication #38: 125-152.

Bernaldez, F.G., J.M. Rey Benayas and A. Martinez. 1993. Ecological impacts of groundwater extraction on wetlands (Dours Basin,Spain). Journal of Hydrology 141:219-238.

Best, G.R., K.S. Clough and S.B. Everett. 1990. Wetland macrophyte production and hydrodynamics in Hopkins Prairie, Ocala National Forest, Florida. Center for Wetlands, University of Florida,Gainesville, Florida., for St. Johns River Water Management District. Special Publication SJ 90-SP7. 28 pp.

Best, G.R. and K.S. Clough. 1991. Wetland macrophyte production and hydrodynamics in Hopkins Prairie, Ocala National Forest, Florida, March 1989 - December 1990. Center for Wetlands, University of Florida, Gainesville, Florida., for St. Johns River Water Management District. Special Publication SJ 91-SP10. 87 pp.

Bethune, G. and V.R. Donthamsetti. 1990. Lake Lowry Basin Surface Water Management Study: Additional Evaluation of South Diversion of Lake Lowry Floodwaters. Technical Publication SJ 90-6. St. Johns River Water Management District, Palatka, Florida. 57 pp.

Bethune, G. and C.C. Tai 1987. Lake Lowery Basin Surface Water Management Study. Technical Publication SJ 87-5. Division of Engineering, Department of Water Resources, St. Johns River Water Management District, Palatka, Florida. 87 pp.

Bouten, W., M.G Schaap, D.J. Bakker and J.M. Verstraten. 1992. Modelling soil water dynamics in a forested ecosystem. I: a site specific evaluation. Hydrological Processes 6:435-444.

Brinson, M.M. 1993. Changes in the functioning of wetlands along environmental gradients. Wetlands 13:2:65-74.

Brock, J.H. 1987. I. Potential effects of partial water withdrawals from the Verde River on riparian vegetation. II. Structure of riparian habitats at selected sites along the Verde and East Verde Rivers of Central Arizona. Final Report to United States Bureau of Reclamation. Arizona State University, Tempe, Arizona. 111 pp.

Brown, M.T., C. Gettleson, J. Habercorn and S. Roguski. 1991. The role and importance of depth and duration of flooding in the maintenance and conservation of wetland functions and values: management implications and strategies. Center for Wetlands, University of Florida, Gainesville, Florida., for Southwest Florida Water Management District. 102 pp.

Chimney, M.J. and R. Helmers. 1990. A baseline study of the effects of wetland hydrology and water quality on the macroinvertebrate community of Hopkins Prairie, Ocala National Forest, Florida, June 1988 to November 1989. Normandeau

Associates, Inc., Aiken, SC., for St. Johns River Water Management District, Palatka, Florida. Special Publication SJ 90-SP8. 109 pp.

Cooley, R.L. and A.V. Vecchia. 1987. Calculation of nonlinear confidence and prediction intervals for ground-water flow models. American Water Resources Association Water Resources Bulletin 23:4: 581-599.

DeLaune, R.D., J.H. Whitcomb, W.H. Patrick, Jr., J.H. Pardue and S.R. Pezeshki. 1989. Accretion and canal impacts in a rapidly subsiding wetland: 1. ^{137}Cs and ^{210}Pb techniques. Estuaries 12:4:247-259.

Duever, L.C. 1984-1985. Natural communities of Florida's flatwoods. Palmetto 4: 6.

Duever, M.J. 1984. Environmental factors controlling plant communities of the Big Cypress Swamp. In: Gleason, P.J. (Ed.), Environments of South Florida: Present and Past II. Miami Geological Society, Miami, Florida. pp 127-137.

Duever, M.J., J.E. Carlson, and L.A. Riopelle. 1974. Water budgets and comparative study of virgin Corkscrew Swamp. In: Odum, H.T., K.C. Ewel, J.W. Ordway, M.K. Johnston and W.J. Mitsch (Eds.), Cypress wetlands for water management, recycling, and conservation. First Annual Report to National Science Foundation and Rockefeller Foundation, Center for Wetlands, University of Florida, Gainesville, Florida. pp 595-634.

Duever, M.J., J.E. Carlson, and L.A. Riopelle. 1975. Ecosystems analysis at Corkscrew Swamp. In: Odum, H.T., K.C. Ewel, J.W. Ordway and M.K. Johnston (Eds.), Cypress wetlands for water management, recycling and conservation. Second annual report to National Science Foundation and Rockefeller Foundation, Center for Wetlands, University of Florida, Gainesville, Florida. pp 627-725.

Duever, M.J., J.E. Carlson, L.A. Riopelle, L.H. Gunderson, and L.C. Duever. 1976. Ecosystems analysis at Corkscrew Swamp. In: Odum, H.T., K .C. Ewel, J.W. Ordway and M.K. Johnston (Eds.), Cypress wetlands for water management, recycling and conservation. Third annual report to National Science Foundation and Rockefeller Foundation, Center for Wetlands,University of Florida, Gainesville, Florida. pp 707-737.

Duever, M.J., J.E. Carlson, L.A. Riopelle, and L.C. Duever. 1978. Ecosystems analysis at Corkscrew Swamp. In: Odum, H.T., and K.C. Ewel (Eds)., Cypress wetlands for water management, recycling and conservation. Fourth annual report to National Science Foundation and Rockefeller Foundation, Center for Wetlands, University of Florida, Gainesville, Florida. pp 534-570.

Duever, M.J., J.E. Carlson, J.F. Meeder, L.C. Duever, L.H. Gunderson, L.A. Riopelle, T.R. Alexander, R.L. Meyers and D. Spangler. 1979. Resource inventory analysis of the Big Cypress National Preserve. Final report to the U.S. Department of Interior, National Park Service, Southeast Regional Office. Volumes I and II. First printing published by: Center for Wetlands, University of Florida, Gainesville, Florida and the Ecosystems Research Unit, National Audubon Society, Naples, Florida. 1225 pp.

Ehrenfeld, J.G. and J.P. Schneider. 1993. Responses of forested wetland vegetation to perturbations of water chemistry and hydrology. Wetlands 13:2:122-129.

Ewel, K.C. and H.T. Odum. 1984. Cypress Swamps. University of Florida Press, Gainesville, Florida.

Fjeld, R.A., B.L. Sill, and B.B. Looney. 1987. Presented at the DOE/AECL 87 Conference on Geostatistical Sensitivity and Uncertainty Analysis for Groundwater Flow and Radionuclide Transport Modeling. 18 pp.

Gee and Jensen. 1992. Corkscrew H and H Study - Environmental element report. South Florida Water Management District, West Palm Beach, Florida.

Geraghty and Miller, Inc. 1979. Water-management alternatives for the Anclote River water storage area: Jay B. Starkey Wilderness Park. Geraghty and Miller, Inc., Tampa, Florida, for Southwest Florida Water Management District. 194 pp.

Gerla, P.J. 1992. The relationship of water-table changes to the capillary fringe, evapotranspiration, and precipitation in intermittent wetlands. Wetlands 12:2: 91-98.

Gottgens, J.F. and C.L. Montague. 1987. Orange, Lochloosa and Newnans Lakes: a survey and preliminary interpretation of environmental research data. Department of Environmental Engineering Sciences, University of Florida, Gainesville, Florida, for St. Johns River Water Management District. Special Publication SJ 87-SP3. 82 pp.

Gottgens, J.F. and T.L. Crisman. 1992. Newnans Lake, Florida: removal of particulate organic matter and nutrients using a short-term drawdown [phase I]. Department of Environmental Engineering Sciences, University of Florida, Gainesville, Florida, for St. Johns Water Management District. Special Publication SJ92-SP23. 43 pp.

Grumbles, B.H. 1991. Wetlands, drainage ditches, and the Clean Water Act. Journal of Soil and Water Conservation May-June:174-177.

Hall, G.B. 1987. Establishment of minimum surface water requirements for the Greater Lake Washington Basin. Technical Publication SJ 87-3. St. Johns River Water Management District, Palatka, Florida. 78 pp.

Harbor, J.M. 1994. A practical method for estimating the impact of land-use change on surface runoff, groundwater recharge and wetland hydrology. American Planning Association Journal: 60:1:95-108.

Harper, W.V. and I. Clark. 1989. Travel path uncertainty - two approaches to conditional simulation. Solving Ground Water Problems with Models: 149-162.

Harris, L.D. and C.R. Vickers. 1984. Some faunal community characteristics of cypress ponds and the changes induced by perturbations. In: Ewel, K.C. and Odum, H.T. (Eds.), Cypress Swamps :171-185.

Hollands, G.G. 1985. Assessing the relationships of Groundwater and Wetlands. In: Kuslar, J.A. and P. Riexinger (Eds.), Proceedings of the National Wetland Assessment Symposium: 55-57.

Huff, D.D. and H.L. Young. 1980. The effect of a marsh on runoff: I. a water budget model. J. Environ. Qual., 9:4:633-640.

Ingram, D.W. 1983. Hydrologic and engineering study for extreme drawdown of Lake Griffin: part 2 executive summary. Technical Publication SJ 83-6. St. Johns River Water Management District, Palatka, Florida. 15 pp.

Ingram, D.W. 1983. Hydrologic and engineering study for extreme drawdown of Lake Griffin: part 1. Technical Publication SJ 83-6. St. Johns River Water Management District, Palatka, Florida. 78 pp.

Johnson Engineering, Inc. 1990-92. Six Mile Cypress watershed plan. Volumes I-III. Prepared for the Board of County Commissioners of Lee County. Johnson Engineering Inc., Ft. Myers, Florida.

Johnson, R.A. and R.J. Fennema. 1989. Conflicts over flood control and wetland preservation in the Taylor Slough and eastern panhandle basins of Everglades National Park. Wetlands: Concerns and Successes, American Water Resources Association September 1989:451-462.

Kirschner, B.A., T.E. Davenport, R.T. Smith and S.L. Griffith. 1989. Use of water control structures in drainage channels to restore lost wetland values. Wetlands: Concerns and Successes. American Water Resources Association, September 1989: 331-333.

Kite, G.W. 1977. Frequency and Risk Analysis in Hydrology. Fort Collins: Water Resources Publications.

Kurimo, H. and A. Uski. 1988. Short-term changes in vegetation on pine mires after drainage for forestry. In: Proceedings of the International Symposium on the Hydrology of Wetlands in Temperate and Cold Regions 1: 256-269.

Kurimo, H. 1984. Simultaneous groundwater table fluctuation in different parts of virgin pine mires. Silva Fennica 18:2:151-186.

Kushlan, J.A. 1976. Wading bird predation in a seasonally fluctuating pond. The Auk 93:464-476.

Kusler, J.A., M.L. Quammen and G. Brooks (Eds.). 1986. Mitigation of impacts and losses. Proceedings: National Wetland Symposium. Association of State Wetland Managers, Inc. Berne, New York. 460 pp.

Marella, R.L. 1988. Water withdrawals, use and trends in the St. Johns River Water Management District. Technical Publication SJ 88-7. SJRWMD, Palatka, Florida. 131 pp.

Marois, K.C. and K.C. Ewel. 1983. Natural and management related variation in cypress domes. Forest Science 29:627-640.

McKnight, K.S. 1992. Transplanted seed bank response to drawdown time in a created wetland in East Texas. Wetlands 12:2:79-90.

Meeks, R.L. 1969. The effect of drawdown date on wetland plant succession. Journal of Wildlife Management 33:4:817-821.

Mendelssohn, I.A., K.M. Flynn and B.J. Wilsey. 1990. The relationship between produced water discharges and plant biomass and species composition in three Louisiana marshes. Oil and Chemical Pollution 7:317-335.

Mills, S.L., M.E. Soule and D.F. Doak. 1993. The keystone species concept in ecology and conservation: management and policy must explicitly consider the complexity of interactions in natural systems. BioScience **43**: 219-223.

Mitchell, J.E. 1993. The influence of (*xy*) uncertainty on prediction error and contour lines from a three-dimensional surface. American Water Resources Association Water Resources Bulletin **29:5**: 863-870.

Molnar, G. and F. Bernardino. 1988. The potential impact of the proposed Dade County west wellfield on the vegetational communities of Northeast Shark River Slough. Dade County Department of Environmental Resources Management. 93 pp.

Montgomery Consulting Engineers, J. 1988. Evaluation of impacts of wellfield withdrawals in the vicinity of the North Martin County wellfield - Phase 1 Report. South Florida Water Management District, West Palm Beach, Florida.

Mooney, H.A. and M. Godron (Eds.). 1983. Disturbances and Ecosystems. Springer-Verlag, New York, New York. 292 pp.

Panday, S., P.S. Huyakorn and J.B. Robertson. 1990. Two- and three- dimensional numerical analysis of the effects of groundwater development in the Geneva area, Seminole County, Florida: Final Report. HydroGeoLogic, Inc., Herndon, VI., for St. Johns River Water Management District. Special Publication SJ 90-SP10. 326 pp.

Pandey, R.S., A.K. Bhattacharya, O.P. Singh and S.K. Gupta. 1992. Drawdown solutions with variable drainage porosity. Journal of Irrigation and Drainage Engineering **118:3**:382-396.

Pittman, R.A. 1991. Conventional storm drainage which recharges the groundwater. In: Hydraulic Engineering. Proceedings of the 1991 National Conference, American Society of Civil Engineers: 1032-1037.

Price, J.S. 1992. Blanket bog in Newfoundland. Part 2 hydrological processes. Journal of Hydrology **135**: 103-119.

Rafalco, L.G. and M.E. Hawley. 1989. Uncertainty in transport predictions. Solving Ground Water Problems with Models: 493-515.

Rochow, T.F. and P.M. Dooris. 1982. Photographic survey of the Jay B. Starkey Wilderness Park. Technical Memorandum 4/27/82. Environmental Section, Southwest Florida Water Management District, Brooksville, Florida.

Rochow, T.F. 1983. 1983 Photographic survey of the Jay B. Starkey Wilderness Park. Technical Memorandum 4/27/83. Environmental Section, Southwest Florida Water Management District, Brooksville, Florida.

Rochow, T.F. 1984. Photographic survey of the Jay B. Starkey Wilderness Park. Technical Memorandum 4/27/84. Environmental Section, Southwest Florida Water Management District, Brooksville, Florida.

Rochow, T.F. 1985a. Biological assessment of the Jay B. Starkey Wilderness Park -- 1985 update. Technical Report 1985-4. Environmental Section, Southwest Florida Water Management District, Brooksville, Florida. 105 pp.

Rochow, T.F. 1985b. Hydrologic and vegetational changes resulting from underground pumping at the Cypress Creek wellfield, Pasco County, Florida. *Florida Scientist*. 48(2): 65-80

Rochow, T. F. 1985c. Vegetational monitoring at the Cypress Creek well field, Pasco County, Florida: 1985 Update. Technical Report 1985-5. Environmental Section, Southwest Florida Water Management District, Brooksville, Florida. 139 pp.

Rochow, T.F. and M. Lopez. 1984. Hydrobiological monitoring of cypress domes in the Green Swamp Area of Lake and Sumter Counties, Florida, 1979-1982. Environmental Section Technical Report 1984-1. Southwest Florida Water Management District, Brooksville, Florida. 79 pp.

Roulet, N., S. Hardhill and N. Comer. 1991. Continuous measurement of the depth of water table (inundation) in wetlands with fluctuating surfaces. Hydrological Processes 5:399-403.

Rowell, T.A. 1986. The history of drainage at Wicken Fen, Cambridgshire, England, and its relevance to conservation. Biological Conservation 35:111-142.

Schoof, R. 1980. Environmental impact of channel modification. Water Resources Bulletin, American Water Resources Association 16:4:697-701.

Schot, P.P., A. Barendregt and M.J. Wassen. 1988. Hydrology of the wetland Naarderemeer: influence of the surrounding area and impact on vegetation. Agricultural Water Management 14:459-470.

Scott, M.L., W. Slauson, C. Segeluist and G. Auble. 1989. Correspondence between vegetation and soils in wetlands and nearby uplands. Wetlands 9:41-60.

Shiklomanov, I.A. and S.M. Novikov. 1988. Drainage effect on the environment. In: Proceedings of the International Symposium on the Hydrology of Wetlands in Temperate and Cold Regions 2: 66-71.

Slocombe, D.S. 1993. Implementing ecosystem based management: development of theory, practice, and research for planning and managing a region. BioScience 43:9: 612-622.

Skaggs, R.W., J.W. Gilliam and R.O. Evans. 1991. A computer simulation study of Pocosin hydrology. Wetlands 11:Special Issue: 399-416.

Southwest Florida Water Management District. 1982. Historic impact on wetlands within the Eldrige-Wilde wellfield, Work Order Number 238, April 13, 1982. Memorandum by Rock G. Taber.

Southwest Florida Water Management District. 1994. Northern Tampa Bay Water Assessment Project. SWFWMD. 479 pp.

Spangler, D.P. 1984. Hydrogeologic variability of four wetland sites in North Central Florida. :27-55.

State of Florida. 1991. Osceola County, Triple E Corporation and East Central Florida Services versus St. Johns River Water Management District and Brevard County. Case No. 91-1779,91-1780 and 91-1781. Tallahassee, Florida.

Turner, R.E. and S.R. Yeleswarapu. 1990. Relationships between wetland fragmentation and recent hydrologic changes in a deltaic coast. Estuaries 13:3:272-281.

U.S. Environmental Protection Agency. 1976. Impacts of construction activities in wetlands of the United States. EPA-600/3-76-045. April 1976. U.S. Environmental Protection Agency, Corvallis, Oregon. 420 pp.

U.S. Geological Survey. 1978. Impact of Potential Phosphate Mining on the Hydrology of Osceola National Forest, Florida. Water Resources Investigations 78-6. Water Resources Division, U.S. Geological Survey, Tallahassee, Florida. 159 pp.

U.S. Geological Survey. 1979. Summary of U.S. Geological Survey investigations and hydrologic conditions in the Southwest Florida Water Management District for 1978. Open-File Report 79-1257. United States Department of the Interior Geological Survey, Tallahassee, Florida. 124 pp.

United States Department of Agriculture 1987. Farm drainage in the United States: history, status, and prospects. Miscellaneous Publication Number 1455. Economic Research Division, U.S. Department of Agriculture. 179 pp.

Welling, C.H., R.L. Pederson and A.G. Van Der Valk 1988. Recruitment from the seed bank and the development of zonation of emergent vegetation during a drawdown in a prairie wetland. Journal of Ecology. 76: 483-496.

Wharton, C.H., H.T. Odum, K. Ewel, M. Duever, A. Lugo, R. Boyt, J. Bartholomew , E. DeBellevue, S. Brown, M. Brown and L. Duever. 1977. Forested wetlands of Florida: their management and use. Center for Wetlands, University of Florida, Gainesville. 348 pp.

Wilkie, D.S. and J.S. Larson. 1980. Municipal wells, land development and freshwater wetlands in Massachusetts. Publication Number 20. Water Resources Research Center, Amherst, Massachusetts