Chapter 2: Hydrologic Needs: The Effects of Altered Hydrology on the Everglades

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Summary

This chapter is an overview of historic hydrologic patterns, the effects of altered hydrology on the ecology of the Everglades, and the tools needed to assess and predict the impacts of water management. This is an anthology of historical information and hydrologic studies conducted over the last 100 years, covering millions of hectares, and includes scientific studies of Everglades soils, plants, and animals. The synthesis of this information, for setting hydrologic targets for restoration, is the goal of the Central and South Florida (C&SF) Restudy (see **Chapter 10**). This ecosystem assessment of the Everglades in relation to only hydrology is difficult because hydrology is strongly linked to water quality constituents, whose utilization, mobilization, and degradation in the Everglades is in turn, linked to hydrologic events and management. Although this chapter disassociates water quality from hydrology, in an attempt to address water management needs, and to meet the obligations set by the Everglades Forever Act, it is important to understand these linkages for sustainable management and restoration.

Historic Hydrologic Change

Drainage of the Everglades began in 1880 and in some locations, reduced water tables up to nine feet, reversed the direction of surface water flows, altered vegetation, created abnormal fire patterns, and induced high rates of subsidence. Most of these changes were caused by four major canals (Miami, North New River, Hillsboro and West Palm Beach), constructed between 1910 and 1920. Other hydrologic alterations of major significance include the levee around Lake Okeechobee and construction of the Tamiami Trail.

The initiation of the C&SF Project for Flood Control in 1947 created a system of levees and borrow canals, essentially complete by 1963, that continued to alter water tables and surface flows by creating a highly compartmentalized landscape. Compartmentalization induced ponding in the southern regions of each Water Conservation Area (WCA), increased the frequency and intensity of peat/muck fires in northern regions of WCAs, and disrupted overland “sheet flow” by creating a hydrologic environment dominated by flows along levee edges, in borrow canals, and through water control structures.

Historic and current seasonality of water depth (the hydrologic cycle) in the Everglades is basically the same. The wet season is typically from June to October and the dry season is from November to May. However, canals and water control structures have altered the duration and spatial extent of hydroperiods. The South Florida Water Management Model (SFWMM) for the current managed system, shows that typical dry season water depths (1965-1995) in northern Shark Slough in Everglades National Park (the Park) ranged from 1.0 ft to -2.0 ft below ground. According to the Natural Systems Model

(NSM), pre-drainage water levels would have ranged from 3.0 ft. to -1.0 ft. Similar trends of decreased water depth and reduced hydroperiods were observed following construction of the C&SF Project.

Isotopic analysis of coral cores suggests that Florida Bay salinity in this century has been higher and less variable than it was during the last century. This shift in salinity patterns may have occurred as a result of several factors. The completion of the Flagler Railroad in 1910 closed a number of tidal inlets in northeast Florida Bay and may have increased hydrologic residence times by altering circulation patterns and reducing tidal exchanges in northeast Florida Bay. This shift in Florida Bay salinity patterns may have also occurred due to reduced surface and ground water flows discharged from the Everglades. The dredging of the Miami, New River, Hillsboro and West Palm Beach canals from 1906 to 1920 diverted large amounts of surface water flows east towards the Atlantic Oceans thus decreasing freshwater flows toward Florida Bay and the Gulf of Mexico.

Effects of Altered Hydrology

Low water tables, drainage, and droughts have altered the balance between peat accretion and peat oxidation - a balance that maintains wetland elevation. An increase in microbial oxidation and frequency of peat fires as a result of drainage has contributed to peat subsidence and lowered ground level elevations. In some locations the peat is completely gone, leaving only the underlying mineral material. Decreased wetland elevation has made the WCAs more vulnerable to excessive ponding and the Park more vulnerable to salt water intrusion from rising sea levels.

Calcareous periphyton communities are well adapted to seasonal dry-downs and quickly recolonize upon reflooding. However, continuous flooding may cause a shift toward a non-calcareous periphyton community that may in turn, alter phosphorus (P) cycling. It is not completely clear how depth, hydroperiod, light, temperature, and nutrients all interact to sustain healthy calcareous periphyton mats, although it is clear that excess nutrients alone can have a significant effect (see **Chapter 3**).

Hydrology can influence the success of invasive and exotic vegetation establishment by affecting growth and survival of seedlings. Cattails spread into areas of prolonged ponding, if sediment P concentrations are relatively high. Cattails are competitive in deep water environments because they can actively transport oxygen to their roots. Brazilian pepper, a woody shrub, has become established in areas of disturbed soil horizons where water tables have been lowered and inundation is now less than 4-6 months per year. The newest invader, Old World climbing fern, invades the same habitats as Brazilian pepper forming a mat that covers every plant. Raising the inundation frequency and depth to eliminate Brazilian pepper and the climbing fern from tree islands has been proposed in some areas. However, the biological affects of such an alteration are unknown and long inundation of tree islands may be fatal to native tropical hardwood species.

Animals are also affected by altered hydrology. The vulnerability of fish to predation by wading birds is directly affected by water depth. Even when fish densities are high, water depths greater than 28 cm, during February, March and April, can decrease foraging and the feeding of fledglings by Tricolored Herons, White Ibis, Snowy Egrets and Wood Storks. Altered hydrology can also have a direct impact on fish. However, there are two contradictory ideas of how hydrology affects fish populations. One hypothesis is that fish densities are highest when the marsh is managed for frequent dry-downs, while the other stipulates that fish densities are lowest when the marsh is managed for frequent dry-downs.

Nesting and foraging by Snail Kites and endangered Cape Sable Seaside sparrows have conflicting hydrologic requirements that call for different habitats and marsh elevations. Dry-downs to less than 10 cm during March and April impede the movement of apple snail, the exclusive food source for snail kites, thus interfering with peak snail reproduction behavior and the production of fertile egg clusters. In contrast, if water levels are not less than 10 cm by April, the seed and insect-eating Cape Sable Seaside Sparrow will not initiate breeding. The effects of altered hydrology on other animals populations, particularly amphibians and reptiles, are less well understood. However, it appears that alligator nests fail if during the 60-65 day spring incubation period, water levels get so low as to allow raccoons and other predators access to the nest, or so high (20-30 cm above spring water levels) as to flood the nest.

Tools for Hydrologic Restoration

Florida Statute 373.042(1) requires that all water management districts establish minimum flows and levels (MFLs) for surface waters. For the Everglades, the MFLs were proposed to prevent the occurrences of long-term low water levels that impact hydric (organic peat and marl) soils. To prevent the loss of peat soil, "water levels within wetlands overlying organic peat soils should not fall 1.0 ft or more below-ground level for more than 30 days duration, at return frequencies ranging from 1 in 5 years to 1 in 7 years depending on location." For marl soils, "water levels should not fall more than 1.5 ft below ground for more than 90 days no more frequently than once every 5 years."

Tools to synthesize and predict the effects of water management and restoration in the Everglades include a complex variety of hydrologic (e.g., Natural Systems Model), water quality (e.g.,: Everglades Water Quality Model), and ecologic (e.g., Everglades Landscape Model) computer models. Some of these tools are still under development but have already increased our general understanding of the importance of hydrology in the Everglades. The NSM found historic hydroperiods greater than 330 days/year and historic flow rates of high magnitudes in areas that are now no longer part of the Everglades. The ELM found that drainage and a low water table can increase soil decomposition and P availability by as much as 300%. These models are currently being used to evaluate USACE Restudy alternatives (see **Chapter 10**).

Conclusions

The hydrology of the Everglades has been fundamentally altered. Drainage from 1880 until 1946 (pre-C&SF) was a period of extensive changes in surface water flows, water tables, and soil subsidence. Drainage from 1947 to the present (post-C&SF) was a period of further landscape fragmentation, reduction in sheet-flow, and extensive habitat loss. The entire pre- and post-C&SF era was a period of higher and less variable salinity in Florida Bay.

Altered hydrology has caused major losses of wetland soils and is fostering the spread of invasive species, such as Brazilian pepper, cattail, melaleuca, and the Old World climbing fern. Drainage has shortened natural hydroperiods, increased soil decomposition, and enhanced the probability of peat fires, which in some places destroyed all peat, leaving only sand or rock. All three lower wetland elevations and increase soil nutrients. There is an imbalance between peat accretion and peat subsidence for the maintenance of wetland elevation.

Wildlife have hydrologic requirements for foraging and reproduction that change with time and species. As a result, sustainable wildlife diversity may require a diverse hydrological landscape. A better understanding of wildlife biology as a function of habitat and hydrologic diversity will help set restoration targets.

Models, both conceptual and numeric, have been developed to assist in the establishment of minimum flows and levels, and evaluate hydrologic impacts. The Natural System Model (NSM) and South Florida Water Management Model (SFWMM) are the best available hydrologic models for evaluating plans for restoration and management of the Everglades. Estimates of pre-drainage hydrology using the NSM, compared with estimates of managed hydrology using the SFWMM, are significantly different. Biological and biogeochemical models will soon be able to evaluate the ecological significance of this difference and thus, predict the hydrological needs of ecological restoration.

Introduction

Drainage of the Everglades changed south Florida from a subtropical wetland to a human-dominated landscape with a strong retirement, tourism and agricultural economy. As a result, the Everglades is half its original size, water tables have dropped, hydroperiods have been altered, flows have been diverted, wetlands have been impounded, wildlife has been reduced, water quality has degraded, and habitats have been invaded by non- indigenous plants. All of these impacts are caused directly or indirectly by altering the hydrology. Previous reviews of the ecological impacts of altered hydrology in the Everglades (Davis, 1943; Loveless, 1959; Craighead, 1971; McPherson et al., 1976; Gleason, 1984; Tropical BioIndustries, 1990; Gunderson and Loftus, 1993; Davis and Ogden, 1994; Sklar and Browder, 1998) have done much to increase public and scientific awareness of problems associated with altered hydrologic regimes and drainage. The District’s review will update this natural history by taking an ecologically comprehensive approach, highlighting current scientific studies, and introducing computer simulations as tools for landscape management.

Even though hydrology is a primary component of wetlands and estuaries, it is not always easy to show direct cause-and-effect relationships between altered drainage and ecosystem disturbance. It is difficult because one, there needs to be a long period of record in order to filter out changes due to climatic variability and two, there are a large number of factors associated with an altered hydrologic regime. Factors, such as water quality can make the impacts associated with a change in hydrology imperceptible. The goals for this chapter are to: 1) review scientific understanding of historical hydropatterns (i.e., hydrologic durations and depths) in the Everglades; 2) summarize research documenting the impacts of altered hydrology on the ecological structure and function of the Everglades; 3) describe computer models that are being used as management tools for hydrologic assessments; and 4) summarize the criteria for minimum flows and levels in the Everglades as required by the Act.

To help conceptualize the intricacies of hydrologic impacts, consider water as having four components of influence: source, timing (frequency), duration and depth. The source affects water quality. For example, the chemistry of agricultural runoff is very different from precipitation. Timing affects biological rhythms and annual cycles. For example, heron chicks hatch at a time of receding water tables when fish and invertebrates are most exposed to predation: no recession, few or no chicks (Frederick and Spalding, 1994). The duration of flows affect community structure. For example, cypress seedlings require one to two months of dry conditions to become healthy saplings. Prolonged hydroperiods can mean no seed germination, thus no new trees (Conner et al., 1986). If prolonged hydroperiods are accompanied by deep water conditions for many years, then trees may drown and wetlands may act more like ponds where grasses and sedges are replaced by submerged and floating vegetation, aquatic insects are replaced by zooplankton, and wading birds are replaced by ducks.

It is recognized by wetland ecologists around the world that source, timing, duration and depth of water will influence biogeochemical processes in soils and water, physiological processes of plant growth and decomposition, and reproduction and migration of fauna (Sharitz and Gibbons, 1989; Patten, 1990; Mitsch and Gosselink, 1993; Mitsch 1994; to name a few). Soils, plants, and animals can, in turn, affect the evolution of a wetland. This evolutionary process can be cyclical or unidirectional and is often called succession. Usually, environmental restoration programs are attempts to redirect an altered rate or direction of succession. For the Everglades, succession is also affected by the available gene pool, climate, and antecedent conditions (Light et al., 1995). This means that society may not be able to fully restore the Everglades ecosystem. Rising sea levels combined with urban sprawl and 1,500 miles of canals have set the stage for the Everglades to never be what is was 200 hundred years ago. However, scientists have a better understanding of the current system than they ever had of the pre-drainage Everglades.

This chapter should be viewed as an anthology of many works. It is not a synthesis for setting hydrologic targets for restoration. The synthesis for restoration lies within the ongoing USACE's integrated "Restudy" program (see **Chapter 10**). This chapter in divided into four sections: 1) past and present hydrologic change; 2) the effects of altered hydrology on Everglades ecology; 3) techniques for hydrologic management; and 4) information gaps and future research needs. The hydrology section will examine the sequence of events that have lead up to the current water management system and will present historical accounts of the ecological affects associated with this sequence. The second section, on the impacts of altered hydrology, will examine current accounts of ecological impacts of altered hydrology in the Everglades gleaned from experiments and ongoing research programs. The third section, on techniques, will summarize the conceptual and numerical models used or being developed for Everglades restoration. The final section is a recommendation for adaptive management and new experiments as a way to assess the influence of water management on soils, plants, and animals in the Everglades.

Historic Hydrologic Change

Pre-C&SF Project

The first major efforts to drain the Everglades began in 1880; yet the earliest comprehensive and systematic depictions of the system were not produced until the 1940s. By that time, however, the system was already substantially altered by preceding drainage activities. Between 1880 and 1940, water tables declined as much as nine feet, large areas of organic soils decomposed and subsided, topographic changes of one to five feet actually reversed the direction of surface water flow, and in more than half of the Everglades, the vegetation communities were substantially altered (McVoy et al., in prep.). The extent of these changes in the Everglades is impressive given that they all preceded the construction of the extensive C&SF Project for Flood Control and Other Purposes, beginning in 1947.

The first drainage projects were initiated by developer Hamilton Disston in 1880 with the construction of canals connecting the Kissimmee chain of lakes and construction of the 13-Mile Canal[1] extending south-southwest from Lake Okeechobee into the Sawgrass Plains of the northern Everglades

(Light and Dineen, 1994). As these drainage efforts had little effect on water levels in Lake Okeechobee, there were no significant changes in hydrology south of Lake Okeechobee; lake overflows into the Everglades continued as before.

In contrast, the next wave of drainage activity, from 1906 to approximately 1930 (**Table 2-1**), unquestionably affected the Everglades. Three of the four major canals, the North New River, Hillsboro and Miami, were begun in the 1910s and opened by 1915. The fourth, the West Palm Beach Canal, was likely finished within the following five years. By the late 1920s, water levels in Lake Okeechobee were being lowered by the St. Lucie and Caloosahatchee canals. A levee constructed around the southern shore

Table 2-1. Approximate dates of initial construction and open for service of major hydraulic works affecting the Everglades. Opening dates are less well-defined as improvements, redredging, widening etc. of canals often continued for numerous years (from McVoy et al., in prep.).

Canal	Initiated	Opened	Citation
Small, local truck farming canals related to railroad	>1896	1897	Jones et al., (1948)
North New River Canal	1906	1912	Interbureau Committee (1930) Clayton (1936)
South New River Canal	1906-1909	1913	Marston et al., (1927) Fla. Everglades Eng. Comm. (1914)
Miami Canal	1910	1913[a]	Marston et al., (1927) Fla. Everglades Eng. Comm. (1914)
Hillsboro Canal	1910	1915	Marston et al., (1927) Jones et al., (1948)
West Palm Beach Canal	1913-1917	1920	Marston et al., (1927)
St. Lucie Canal	1916	1926	Marston et al., (1927) Marston et al., (1927)
Caloosahatchee Canal	1915	1925[b]	Marston et al., (1927) Herr (1943)
Lake O. South Shore Levee[c]	1921	1926	Marston et al., (1927) Parker et al., (1955)
Lake O. Levee[d]	1932	1938	Parker et al., (1955) Parker et al., (1955)
Tamiami Trail & Canal	1916	1928	Tamiami Trail Commission (1928)

a. Dupuis (1954b), a doctor who settled in the Lemon City area north of Miami in 1898, notes an earlier date for the first opening of the Miami Canal locks: “However, when the Miami Canal locks were opened in the early part of 1911, garden vegetables in the edge of the Everglades died and some of the driven wells, 25 feet deep, went dry as far east as the Florida East Coast Railway, a distance of four miles.”
b. According to Herr (1943), Chief Engineer of the Okeechobee Flood Control District, 1929-1944: “The Caloosahatchee Canal had been in existence prior to that time (1925), but its capacity was small and it had little effect on the lake elevations.” A second project, increasing its capacities, was completed in 1938.
c. This was a low muck levee. It was seriously breached during the hurricanes of 1926 and 1928.
d. This is a much more solid levee constructed by the U.S. Army Corps of Engineers with a top elevation of 32 to 34 feet above m.s.l. (Herr, 1943).

1. The Miami canal later branched off of this canal.

further isolated the lake from the Everglades. The lake's last natural overflow into the Everglades occurred around 1925. At about the same time as the separation of Lake Okeechobee from the northern Everglades, Tamiami Trail was being constructed -- in effect, separating the southern Everglades from the northern Everglades and connecting Miami to the Gulf of Mexico.

The hydrologic isolation of the Everglades from Lake Okeechobee, completion of the four major canals and construction of the Tamiami Trail all strongly affected Everglades hydrology. Water tables were lowered throughout the Everglades basin. **Figure 2-1** depicts water levels adjacent to the New River Canal from February-March, but measured 25 years apart. Comparison of the two time periods reveals that water levels declined dramatically, from just one foot below-ground in 1915, to some five feet below-ground surface by 1939.

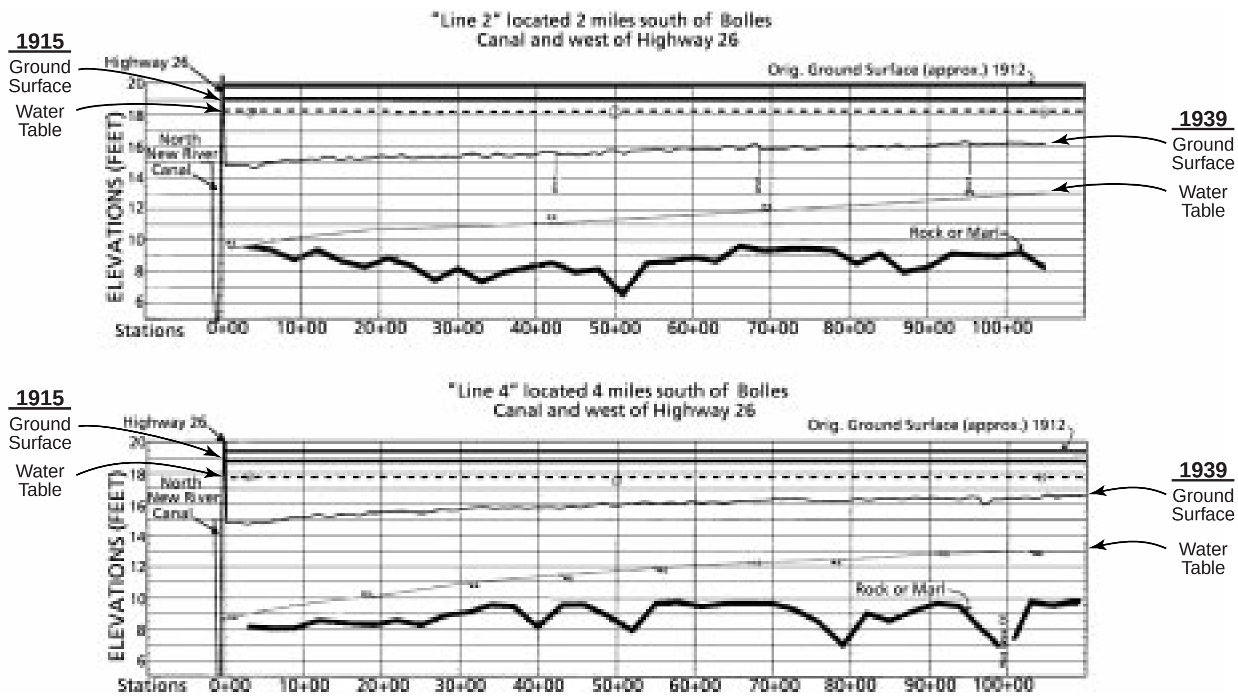

Figure 2-1. Cross-sectional views of two transects adjacent to the northern portion of the North New River Canal, showing elevations of bedrock, water table and ground surface. February-March 1915 water table data measured by Baldwin and Hawker (1915). March 1939 data measured by Clayton et al. (1942). From McVoy et al. (in prep.).

These drops in water level, though drastic, are less surprising when one considers the changes in the annual water budget of the Everglades caused by the four major canals. Modeling (SFWMD, 1998) and discharge measurements (Parker et al., 1955) suggest that these four canals collectively discharged on the order of 1.5 million acre-feet per year, and drained approximately 1.5 million acres. The average removal of water was therefore one foot (12 in.). The magnitude of this removal can be put in perspective by comparison with net annual precipitation (total precipitation minus evapotranspiration) in the Everglades. Assuming 50 inches of total precipitation and 45 inches of evapotranspiration (SFWMD, 1998) leaves an average of 5 inches of net annual precipitation. This means that more than twice (12 in. divided by 5 in., or 240%) of the net annual precipitation formally available to the Everglades was now being removed by these canals. It is not surprising that water tables dropped precipitously.

The hydrological and ecological effects of the canals became apparent shortly after canal completion. John King worked in the early 1900s as a civil engineer and surveyor for Miami developer Capt. Jaudon, accumulating several years of field experience in the Lower Glades west and southwest of Miami (Larned, 1917; Anonymous, 1926). In early 1917, just a few years after completion of the first major canals, King already noticed definite changes in the Everglades:

> "...the drying up of the 'Glades, due to the various canals, is playing havoc with the birds here. The finer ones are fast disappearing. They lack feeding grounds. There are, occasionally, in the southern portion, a few green leg white herons as well as small blue and Louisiana blues, but five years has made a marked change. Of the food birds, the limpkin are found only occasionally. A guide told me his record was two in a season...." (Larned, 1918).

As the northern and central portions of the Everglades were being drained by the four major canals, the canal and levee associated with the Tamiami Trail were draining the southern Everglades. Captain Jaudon and other promoters of the Tamiami Trail had extensive interests in several townships of Everglades land south of the proposed Tamiami Trail and intended to drain the lands for farming (King, 1917c; 1917d; 1917e; 1917g; 1917h). Blockage of southward flow of Everglades water and diversion to the sea appears to have been an explicit goal of the Tamiami Trail promoters:

> "The idea actuating the Dade County Commissioners was that the drainage of the Everglades would be promoted by the construction of the proposed road, because it was the plan to dig a canal and use the rock excavated from the canal for the road bed. The canal would constitute a waterway of value in draining the adjacent lands and the drainage thus affected would enhance their value to the State." (Tamiami Trail Commissioners 1928).

There was public opposition to this Tamiami Trail because of a concern about flooding upstream from the proposed road. These concerns were well-founded. Only a few years after the initiation of dredging and levee construction in 1916, flooding due to blockage of southward flow across the Tamiami Trail was noted. In a written response to a 1923 complaint by the Pennsylvania Sugar Company (Pennsuco), F. C. Elliot, Chief Engineer of the Everglades Drainage District, agreed that the Tamiami Trail,

> "... act[ed] as a continuous dam across the Everglades preventing the natural flow of water and jeopardizing [by flooding] the lands East and Northwest along the Tamiami Trail and Miami Canal." (June 23, 1923 letter from F. C. Elliot; in Graham 1951).

As early as 1915, vegetation changes due to drainage were already apparent:

> "The drainage of the Everglades has proceeded sufficiently to induce noticeable changes in the character of the vegetation in certain places. In the interior of the glades, along edges of the sloughs which once supported a luxuriant growth of water lilies the lowering of the water table is accompanied by the invasion of saw grass and Sagittaria on the lower ground. Two or three miles south of the lake willows are gradually encroaching upon ground which under former conditions of poorer drainage supported a heavy growth of saw grass. In the 'lower glades' saw grass is giving way to myrtle, maiden cane and fennel." (Baldwin and Hawker 1915).

As water levels dropped under the influence of drainage, organic soils (peats) of the Everglades were exposed to air for progressively longer periods each year. Prior to drainage, these soils had been protected from aerobic decomposition by a year-round or nearly year-round covering of surface water. With drainage, the surface elevation of the soils of the Everglades began to subside, partly due to physical compaction and actual burning, but mostly due to oxidation (Clayton, 1936). Few understood the implications. Forty years after drainage began, a comment by Stephens and Johnson (1951) gives a sense of the enormity of the peat loss due to the lack of early understanding of peat subsidence:

> "In making plans for the original drainage of the Everglades, apparently the main causes of subsidence were misunderstood. The original shrinkage of the peat due to drainage was considered, but the continuing losses by slow oxidation were not taken into account. Had the true nature and causes of subsidence losses been fully understood in the earlier days, the original plans might have been modified so as to have saved a large portion of the waste which has occurred since that time." (Stephens and Johnson 1951).

Soil subsidence has been well-documented along several subsidence lines set up in 1916 by the U.S. Dept. of Agriculture in the northern Everglades (Clayton, 1936; Clayton et al., 1942; Stephens and Johnson, 1951; Shih et al., 1979a; Shih et al., 1979b; Shih et al., 1979c). These subsidence lines consisted of regularly resurveyed transects (**Figure 2-2**). Exponential declines in soil surface were typical[1]. Between 1912 and 1940, as much as 6 to 7 feet of soil were lost in the Lake Okeechobee area. (Stephens and Johnson 1951). Across the northern Everglades as a whole, the average subsidence rate during this period was approximately one inch per year. As a result of regional drainage in the northern Everglades, by the 1940s, the originally flat or convex surface of these wetlands had become more of a concave, sunken basin (McVoy et al., in prep). A third to nearly half the depth of the original 10 to 12 feet of peat soil in the area directly south of Lake Okeechobee was lost. So much so, that by 1940 the original slope of the land was reversed, descending northward and toward rather than away, from Lake Okeechobee (Stephens, 1942).

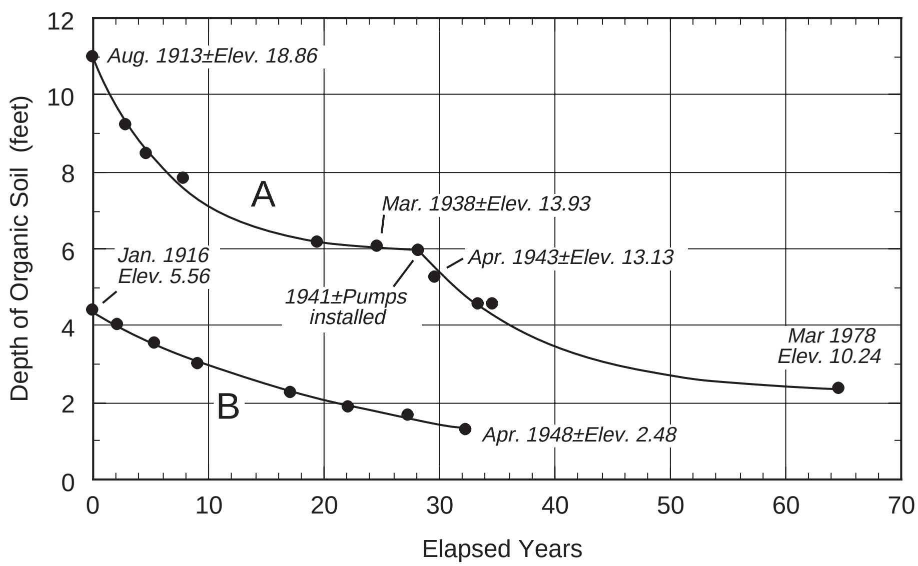

Figure 2-2. Subsidence of organic soils along lines established 1913-1916 by the U.S. Dept. of Agriculture, in the northern (A) and eastern (B) Everglades. Data from Stephens and Johnson (1951) and Shih et al. (1979).

1. The rate constant was found by Clayton (1936) and by Stephens and Johnson (1951) to be a linear function of depth of the water table. Inflection points such as the one seen in **Figure 2-2** reflect a change in water table, often due to a switch from gravity-driven to pumped drainage.

Table 2-2. Approximate peat thickness (in feet) at different points in time: shortly after initial drainage, in the 1940s, and post 1940s. (Township (T) and Range (R) locations shown on **Figure 2-9**.) (From McVoy et al., in prep.)

Location		Approx. peat thickness (in ft) at different points in time		
		1918	1940s	1986
Tamiami Canal	R 37	4.6	3	3
	R 38	5.3	4.3	2.9
	R 39	3.6	3.0	1.9
	R 40	3.7	1.0	--
Snapper Creek Ext. (4 miles south of Tamiami Canal	R 37	4.4	2.2	--
	R 38	3.1	2.5	--
	R 39	0.9	0.9	--
		1911	1940s	1954
Miami Canal, southern part		6	3	2
		1916	1940s	
T50 R41 Sec 34 (Line at Davie; Eastern Everglades)		4.4	0.4	
		1912	1940s	
T 51 R 41 (Eastern Everglades)		4.0	0.5	
T 53 R 40 (Miami Canal Area)		2.8	0.7	
T 54 R 39 (Eastern Tamiami Canal)		1.9	1.4	

Changes in peat thickness in the central and southern Everglades have not been measured as systematically as they have in the northern Everglades. The only U.S. Dept. of Agriculture subsidence line for the eastern Everglades was established in Davie in 1913. Time series measurements are lacking for the rest of the Everglades, particularly the uncultivated areas. However, various measurements from original engineering drawings of peat thickness recorded shortly after the onset of canal drainage were compared with 1940 estimates of peat thickness (Noble et al., 1996). **Table 2-2** shows peat thickness measured close to the onset of canal drainage, again in the 1940s and where available, at a post-1940 date.

With a few exceptions, **Table 2-2** indicates that peat thickness in the central and southern Everglades were less in the 1940s than in the period just after drainage (1911 to 1918). The most severe peat losses occurred along the eastern edge of the Everglades. The severity of losses is in part because pre-drainage peat thickness were less here than in the northern Everglades and in part, because the underlying sand allowed water tables to be drawn down below the peat horizon. Depending upon the initial soil thickness, some locations experienced almost a 100% loss of the original organic soil.

Post-C&SF Project

The 1940s mark an important second phase in the evolution of the Everglades. Life was getting harder in south Florida due to a series of very wet years, two major hurricanes, and economic recession. Repairs on the four major canals were needed. Throughout the country the USACE were taking on more responsibilities and more projects (Barry, 1997). The C&SF Project, authorized by Congress in 1948, gave the USACE the funds to greatly expand the canal network of the 1920s, and gave the Central and Southern

Florida Flood Control District (now known as the South Florida Water Management District) the authority to manage it.

The first major earthworks of the C&SF Project was to construct a 100-mile-long series of levees and borrow canals from Palm Beach to Dade counties (**Figure 2-3**). These levees were completed during 1952 to 1954 and became the eastern boundaries of what would become the WCAs, effectively stopping Everglades sheetflow from advancing on urban coastal areas. The next step during the period 1954 to 1959 entailed construction of levees 5, 6 and 7, which formed the northern and western boarders of the WCAs. Construction of additional levees (1 through 4 and 28) completed the partitioning off of 700,000 acres (283,290 ha) of deep muck lands that became known as the Everglades Agricultural Area (EAA). Flood protection for the EAA was provided by construction of large-capacity pump stations. Other flood protection activities during the 1954 to 1959 period included the deepening of the Hillsboro, North New River and Miami canals in the EAA and construction of water control structures (S-11A, S-11B and S-11C) that moved water from WCA-2 to WCA-3, thereby diverting it away from coastal areas. Pump stations (S-9 and private pump stations) were also constructed to move water west from urban areas into the WCAs.

During the period 1960 to 1963, additional levees and structures were constructed, completing substantial portions of the project that impounded the Water Conservation Areas (**Figure 2-3**). WCA-2 and WCA-3 were divided in “A” and “B” sections during this period in order to prevent water from draining too rapidly into the Biscayne Aquifer. The borrow canal of the L-67A levee not only served to prevent seepage into the porous WCA-3B area, but also became an important route for conveying water to Everglades National Park. Also during this period, levee 29 and four water control structures (S-12A, 12B, 12C and 12D) were constructed at the northern edge of Everglades National Park. While the structures conveyed water west of the original Shark River Slough, no structures were built to convey water east of the L67 extension, the pre-drainage location of the Shark River Slough. Additional structures were built along the Miami Canal (S-151 and S-31) that improved discharge capacity to coastal areas and structures S-7 and S-8 were constructed to provide flood control for western portions of the EAA. Finally, the construction of two sections of L-28 was completed, which served as the western boundary for WCA-3A. A gap was left in L-28, which allowed a natural eastward flow of water from the Big Cypress watershed into WCA-3A.

During 1965 to 1973, parts of the C&SF Project were reworked or added in order to satisfy water requirements of Everglades National Park (**Figure 2-3**).These water requirements were codified by Congress in 1970 and were designed to meet minimum monthly deliveries that would have been expected in the 1940s and 1950s. Minimum water deliveries, defined for Shark River Slough, Taylor Slough and the eastern panhandle of the Park, necessitated enlarging the L-67A canal and extending it several miles south of the Tamiami Trail into the Shark River Slough. Also during this period, the Everglades National Park - South Dade Conveyance System was authorized to provide water not only to the Park but also to provide water for expanding agricultural and urban needs of Dade County. As part of this system, S-332 furnished water to the headwaters of Taylor Slough, while S-18C delivered water via the C-111 canal to the Park panhandle area.

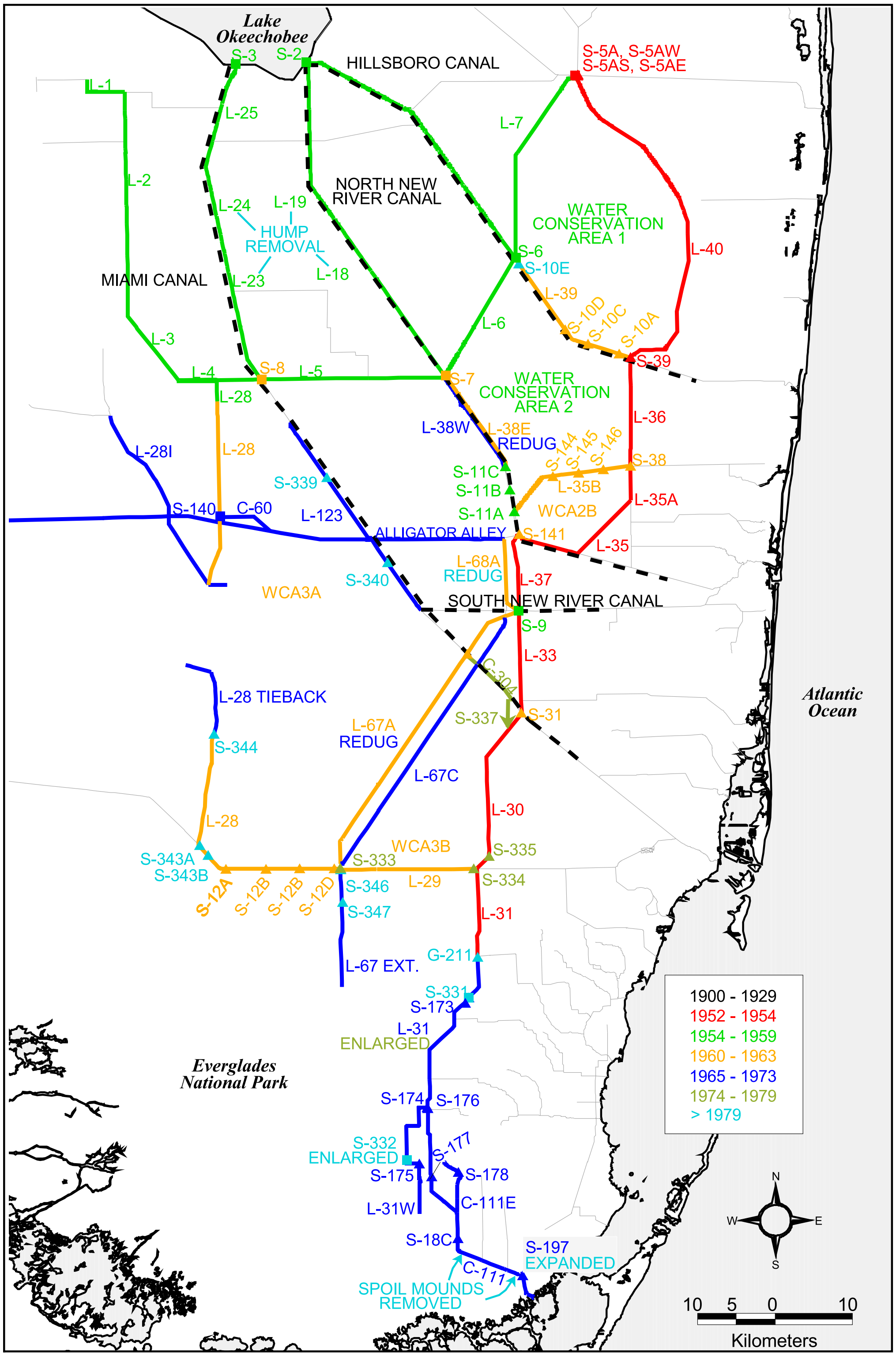

Figure 2-3. Construction sequence of canals, levees, and water control structures associated with the C&SF Project and the South Dade Conveyance System. From Light and Dineen (1994).

Water Conservation Areas (WCAs).

The C&SF Project lead to the establishment of six primary hydrologic units: Big Cypress, Lake Okeechobee, WCA-1, WCA-2, WCA-3, and the Park. The Water Conservation Areas are currently managed by a set of regulation schedules which determine when flood control releases are to be made and when water levels are to be maintained by limiting releases to meet downstream demands. The schedules attempt to establish bounds within which water levels fluctuate. The differences between natural and managed water level fluctuation are illustrated by comparing average and extreme water levels for both the NSM and the SFWMM for selected gauge locations (**Figure 2-4**). These two models will be described later in this chapter. Suffice it to say for now that both simulate water levels and flows, the NSM v4.5 represents pre-drainage conditions by excluding all 20th century modifications to the south Florida landscape, and the SFWMM v3.5 represents current 1995 hydrologic management (not historic management).

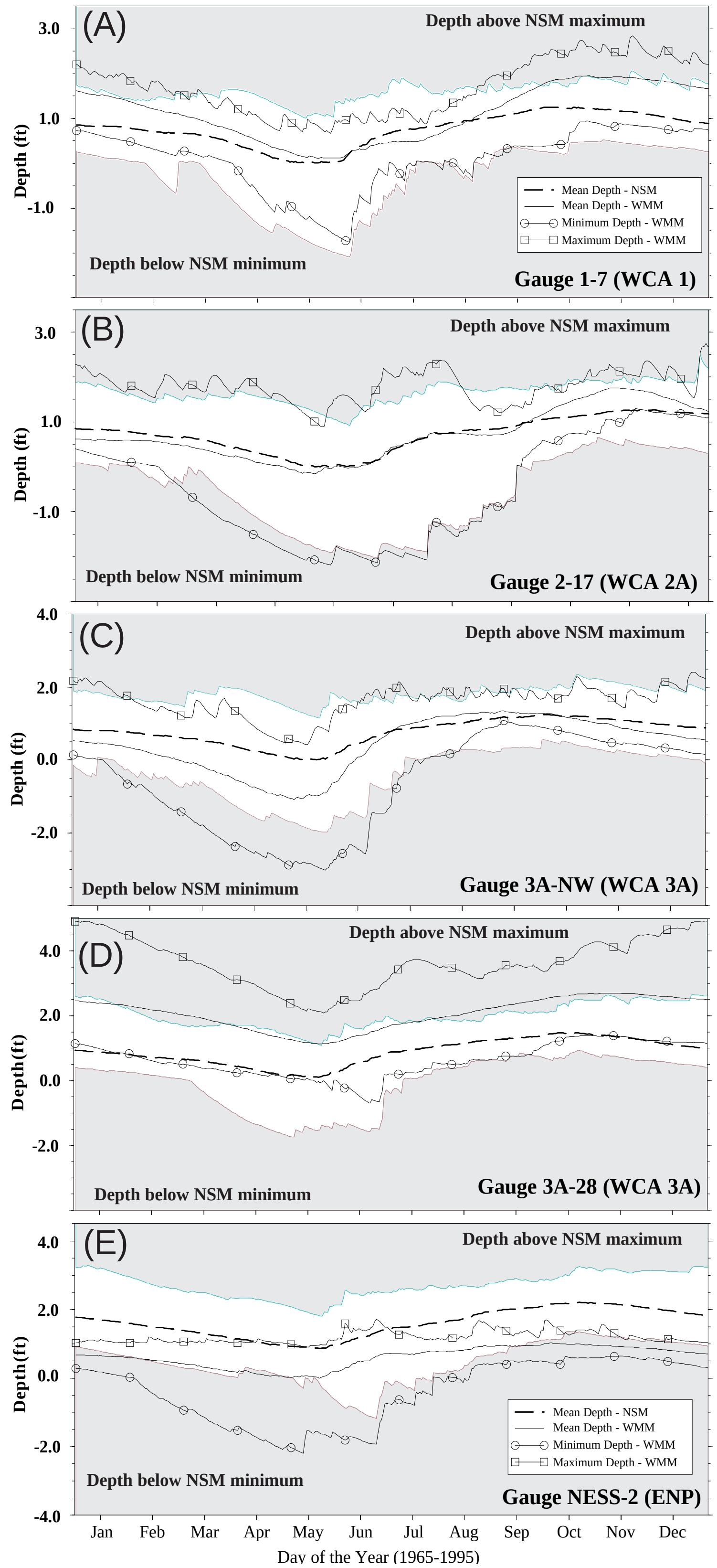

Figure 2-4. The difference between natural and managed water level fluctuations for a calendar year are shown as 30-year minimum, maximum, and average water levels for the Natural Systems Model (NSM) v4.5 and the South Florida Water Management Model v3.5 (SFWMM), respectively, at selected gauge locations (SFWMD, 1998). The SFWMM uses the regulation schedules and water control structure rules of 1995 to simulate 1965-1995.

Water Conservation Area 1 (WCA-1), an area of 221 square miles, is part of the Arthur R. Marshal Loxahatchee National Wildlife Refuge and is managed by the U.S. Fish and Wildlife Service (USFWS). The West Palm Beach Canal discharges agricultural drainage water into the peripheral canal at the north end of WCA-1 via pump station S-5A. The Hillsboro canal, via pump station S-6, discharges water into the southwestern portion. Historical data suggests that WCA-1 was originally wetter when it was part of the Hillsboro Lakes region of the Everglades (Davis, 1943a; Parker et al., 1955). Soils data (Gleason and Spackman, 1974), long-term vegetation studies (Alexander and Crook, 1984) and hydrologic models (Fenemma et al., 1994) also suggest that WCA-1 was wetter prior to the construction of drainage canals. Based on this information, in 1992, the USFWS proposed a change in the WCA-1 regulation schedule to provide deeper water, with longer hydroperiods. Under the former regulation schedule (1965-1982), the northern and central portions of the Refuge dried out almost every year, allowing terrestrial and exotic vegetation to invade. The NSM and SFWMM comparison (**Figure 2-4A**) indicates that this new management schedule is generally deeper or the same as natural water levels, particularly in October - February. During May - September mean water levels for both simulations are within 0.5 ft, with somewhat less variability in the SFWMM. An important difference between the new management schedule and pre-drainage conditions is the reduced rate of overland sheet-flow across the present landscape. The impacts of this new regulation schedule are not yet clear. Cattail along the edges of WCA-1 and sloughs and tree islands within the interior seem unaffected at this time (pers. obs.).

Water Conservation Areas 2 at 210 square miles, is the smallest of the three WCAs. In 1961, the L-35B levee divided the area into two smaller units, WCA-2A (173 sq. mi.) and WCA-2B (37 sq. mi.), in an effort to reduce seepage and improve the water storage capabilities of WCA-2A. In contrast to WCA-1 and 3, which receive most of their water from direct rainfall, WCA-2A receives the majority of its water (59%) from surface water inflows which includes drainage from the EAA and outflows from WCA-1 (SFWMD, 1992). Prior to drainage, WCA-2 was part of the extensive ridge and slough landscape. Except in very dry times, the sloughs supported aquatic species such as white water lily (*Nymphaea odorata*) and spatterdock (*Nuphar luteum*). With completion of the major canals much of the ridge and slough landscape was over-drained, leading to extensive, long-burning peat fires. Peat on many tree islands was burned, significantly lowering island ground surfaces. Vegetation of the landscape also changed, with wet prairie species filling in sloughs (Andrews, 1957; Loveless, 1959).

During the 1960s, after construction of the peripheral levees and canals, water levels rose again, creating “high water” conditions relative to what had been present in the 1950s. With higher water, the wet prairies reverted to sloughs but there was a destructive overtopping or “drowning” (Dineen, 1972; Worth, 1988) of those tree islands whose elevations had been lowered by the previous peat fires. There have since been a number of downward adjustments to the WCA-2A regulation schedule so that 1995 water management is now more similar to that predicted by the NSM (**Figure 2-4B**).

The largest of the WCAs, WCA-3 covers an area of 915 sq. mi. and is predominately a vast sawgrass marsh dotted with tree islands, wet prairies and aquatic sloughs. A cypress forest fringes its western border along the L-28 Gap and extends south to Tamiami Trail. In 1962, WCA-3 was divided into WCA-3A and WCA-3B (786 and 128 sq. mi., respectively) by the construction of two interior levees (L-67A and L-67C) so that water losses due to levee seepage and groundwater flows could be reduced. WCA-3A is bisected by several interior canal-systems. Major inflows include the Miami Canal which drains the EAA, the S-9 pump station which drains urban areas east of the Everglades, and the S-11 structures which drains agricultural areas and WCA-2A.

Creation and drainage of the EAA eliminated sheet-flow from the former sawgrass plains, causing an over-drainage of northern WCA-3A. This has resulted in a loss of tree islands and wet prairies due to soil subsidence and peat fires (Zaffke, 1983; Schortemeyer, 1980). Water level differences between the NSM and SFWMM in the northern WCA-3A are considerable (**Figure 2-4C**). Average SFWMM water levels at the 3A-NW gauge are nearly always below that of the NSM. Average and minimum NSM values are 1.0-1.5 ft higher than SFWMM values during the dry season.

The southern section of WCA-3 has experienced a quite different hydrologic regime. The construction of Alligator Alley and associated borrow canal may restrict overland sheet-flow to the south. Water discharged through the S-8 pump station moves south in the canal much more rapidly than historic sheet flow. The construction of the L-29 levee across the southern end of WCA-3 in 1962 interrupted the southerly flow of water to Everglades National Park causing water ponding and extended hydroperiods, conditions considered harmful to Everglades plant communities and wildlife habitat (Zaffke, 1983). Impoundment also prevents water levels from decreasing annually to dry season levels representative of pre-drainage conditions. Average water levels at the 3A-28 gauge in southern WCA-3A are much higher than the SFWMM (**Figure 2-4D**). Average SFWMM water levels are 0.75 – 1.75 greater than NSM average levels, and are nearly equal to maximum NSM water levels for the calendar year. Minimum SFWMM water levels are nearly equal to average NSM water levels from October to May.

Everglades National Park (the Park)

Everglades National Park encompasses some 2,200 sq. mi. of freshwater sloughs, sawgrass marshes, marl-forming wet prairies, mangrove forests and saline tidal flats. The topography is extremely low and flat, with large areas below 4 ft. NGVD. Everglades National Park is the second largest national park in the United States. It is also one of the nation's 10 most endangered parks. The decline in the Park's biological resources has been primarily linked to changes in the volume, timing and distribution of water inflows to the Park. Flows to the primary, original pre-drainage flow-way, Shark River Slough in the northern Park, first began decreasing as the Miami, North New River, Hillsboro and West Palm Beach canals diverted water from the Everglades to the ocean. Flows were further reduced by the completion in 1928 of the first east-west highway and accompanying borrow canal across the Everglades (Tamiami Trail).

Completion of the C&SF Project blocked flow into the eastern sections of the original Shark Slough flow path, pushed flow westward, and increased discharge through the reduced inflow cross-section between Levee 30 and the Levee 67 Extension (Leach, Klein and Hampton, 1971). Over the past several decades, these structures have been used to vary the Shark Slough hydrology. From 1970 to 1983, the period when flows to Shark Slough were governed by a minimum delivery schedule, annual flows averaged 430,000 ac.-ft, with all of the water passing into western Shark Slough via the S-12 (National Park Service 1995). From 1985 to 1995, under a Rainfall Plan, annual flows averaged 785,000 ac.-ft, but less than 35% passed into the northeast section of the Shark Slough basin (**Figure 2-5**). This is in contrast to natural conditions when more than half of the flows passed through Northeast Shark Slough. Note the higher flows into Northeast Shark Slough prior to 1960 when L-29 was completed. This shift in the relative volumes of water passing across the eastern and western Shark Slough flow sections have shortened hydroperiods and decreased water depths in the east while lengthening hydroperiods on the western side of Shark Slough. Thus, in Shark Slough, the proportion of area dominated by sawgrass stands has increased while the slough and aquatic communities have declined (Alexander & Crook, 1975; Davis and Ogden, 1994; Olmsted & Armentano, 1997). The effects of this altered and reduced inflow in the current system most impacts areas near L-31. Average NSM water levels at the NESS-2 gauge in Northeast Shark Slough

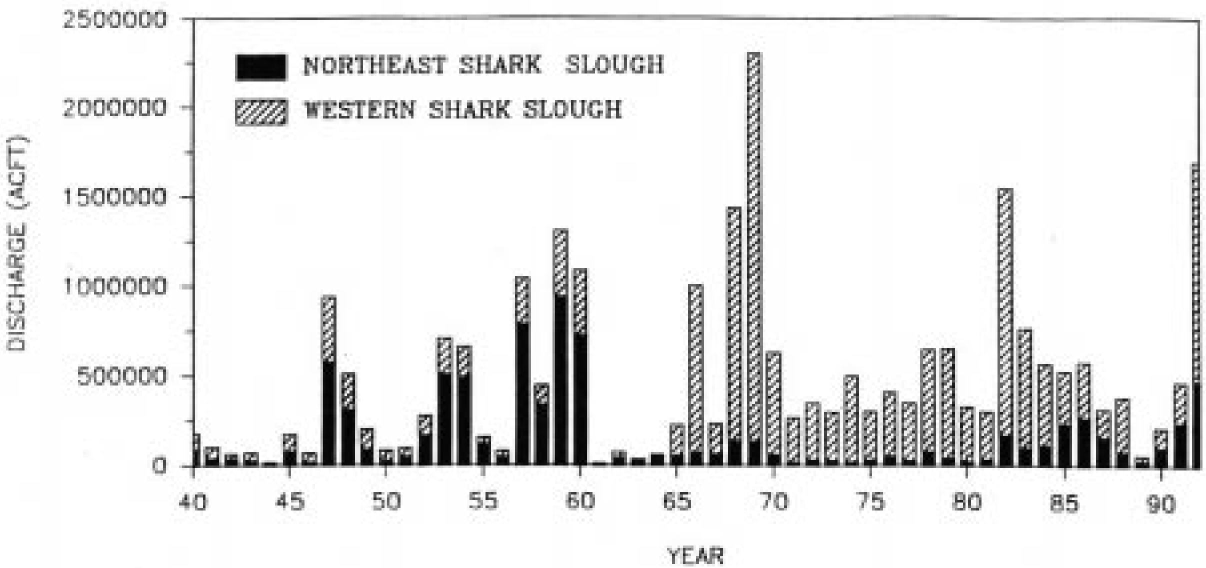

Figure 2-5. Annual surface water inflows to the northeast Shark Slough and western Shark Slough sections of Everglades National Park (1940-1993), based upon a hydrologic year of June through the following May (South Florida Natural Resources Center, 1994).

are 0.7 to 1.25 ft. greater than the average SFWMM water levels for most of the calendar year (**Figure 2-4E**). The present drier conditions were found to support fewer populations of fish and crayfish (Loftus et al., 1990), essential prey for wading birds.

Construction of the South Dade Conveyance System, along the southeastern boundary of the Park, after the completion of the C&SF Project, added further hydrologic changes. It fostered agricultural and urban development in the east Everglades which resulted in a direct loss of marl- forming wet prairies. It compartmentalized the remaining marl prairie/Rocky Glades wetland system through a network of levees and canals, and it interfered with freshwater flows through the Park's second most important flow-way, Taylor Slough. **Table 2-3** shows the effects of the C&SF Project and the South Dade Conveyance System on the water levels in the headwaters of Taylor Slough (Van Lent and Johnson, 1993). Weekly average stages from 1957, the first year of monitoring, through 1989 are shown at Gauge-789. This site is located on the L-31N canal and is representative of water levels in the northern Taylor Slough basin. The record

Table 2-3. Summary of the water level and hydroperiod changes at Gauge 789 (elevation: 5.0 ft) in the Rocky Glades, the headwater region of Taylor Slough (Van Lent and Johnson, 1993; USACE, 1994).

Period	Average October Water Levels (ft)	Average April Water Levels (ft)
1957-1962	5.82	3.22
1963-1989	4.35	2.03

shows that peak water levels have been markedly reduced, resulting in loss of surface water, fundamentally altering the wetlands hydrological regime (National Park Service, 1995). In addition, minimum levels have been raised, reducing the range in water level fluctuations. (**Figure 2-6**).

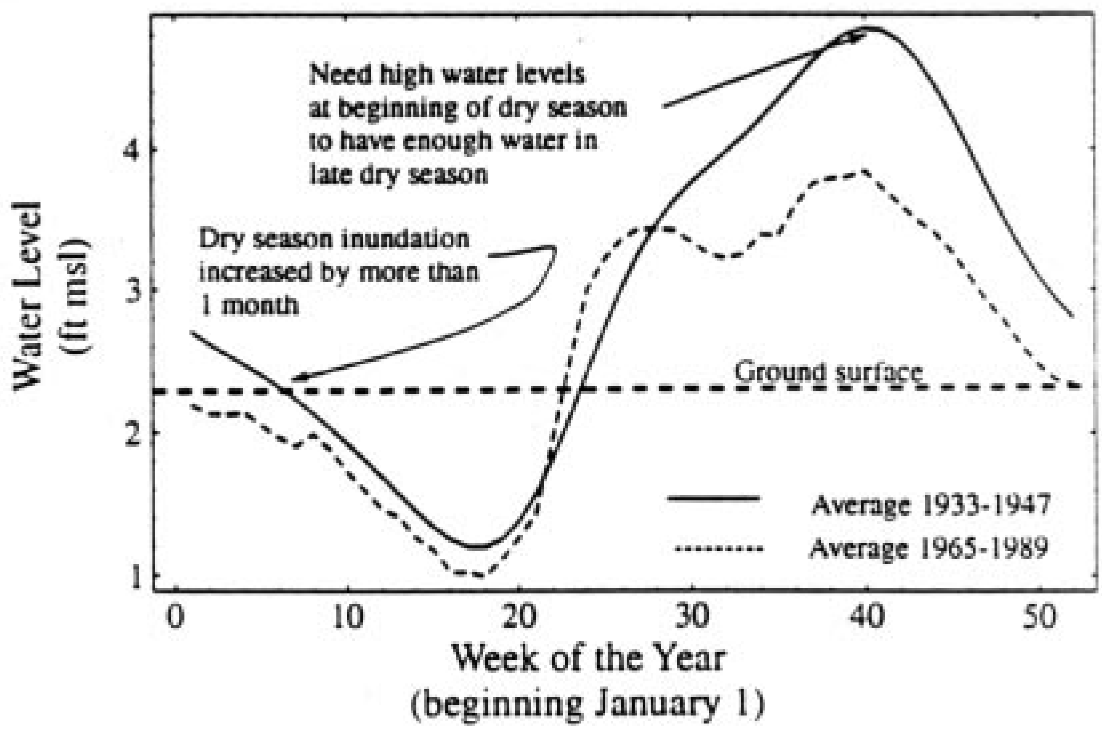

Figure 2-6. Water levels at the Taylor Slough Bridge in Everglades National Park (Van Lent and Johnson, 1993). The 1933-1937 water levels are representative of conditions prior to the C&SF Project and are considered targets for restoration by Park hydrologists. From 1965-1989, water levels exceeded pre-C&SF levels half the time and fell short the other half of the time.

Water Budget Comparisons

The average annual water movement, in and out of the Park and WCAs from 1965 through 1995 that would have occurred under natural conditions (simulated by NSM v4.5) and under the 1995-base managed conditions (simulated by SFWMM v3.5), are summarized in **Figures 2-7** and **10-1**, respectively. Differences between natural and managed surface and ground water flows are striking. Beginning with Lake Okeechobee at the top, the first most obvious hydrologic alteration is the complete elimination of overland flows to the EAA and Caloosahatchee Basin due to the construction of the Lake Okeechobee levee and water-control structures. In place of some 868,000 ac-ft of overland outflow that would have flowed south and west had the system not been altered, 989,000 ac-ft of channelized outflow to the south, west, and east occurs for urban and agricultural supply and flood control. In addition, 216,000 ac-ft is discharged back into Lake Okeechobee to prevent regional flooding adjacent to the Lake. The second most obvious hydrologic alteration to Lake Okeechobee is discharge of 149,000 ac-ft to the St. Lucie Basins.

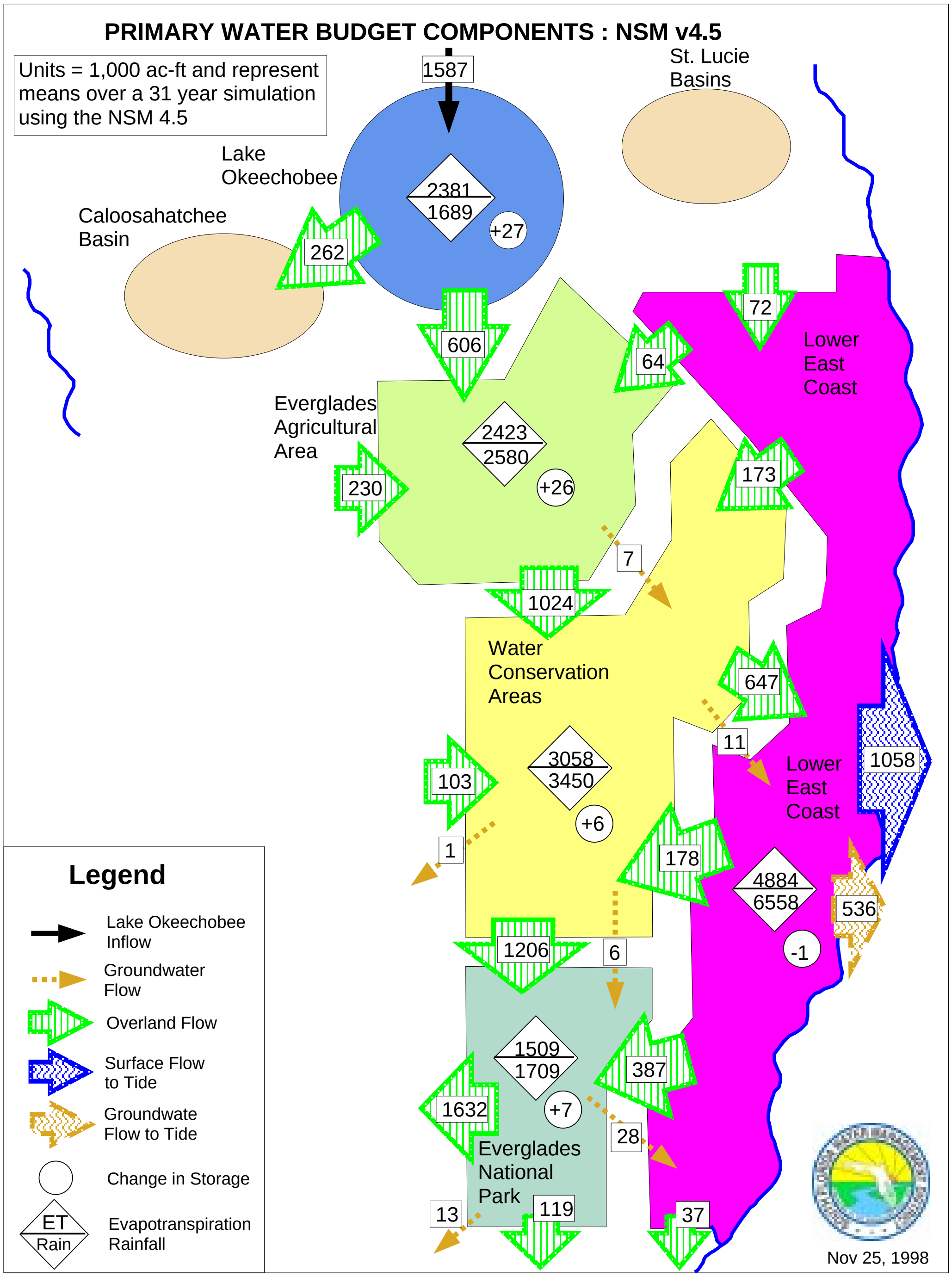

Figure 2-7. Primary water budget (V1.0) components that resulted from a 31-year simulation of the Natural Systems Model v4.5. Data are aggregated by major basins. All values are annual averages in thousand acre-feet. This figure will be included within the final version of the Central and South Florida Comprehensive Review Study and is subject to revision.

In the EAA south of Lake Okeechobee, which was once dense sawgrass and pond-apple forests, the NSM water budget (**Figures 2-7**) indicates that 157,000 ac-ft of net precipitation plus 900,000 ac-ft of surface water would have combined to form a southerly overland flow to the WCAs. The 1995-base managed condition (**Figure 10-1**) indicates that given the same climate, channelized flows to the WCAs deliver drainage (917,000 ac-ft), flood control discharge (62,000 ac-ft), and water supply to meet urban, agriculture, and environmental needs (205,000 ac-ft). Some of this water passes through the WCAs and is supplemented by Everglades water to meet urban and agricultural needs in the Lower East Coast (172,000 ac-ft), and some WCA water seeps back into the EAA as ground water (36,000 ac-ft). The vast majority of this water enters the WCAs as point-source inputs and not as overland flow as in the NSM water budget.

Downstream of the EAA and the Lake, the three Water Conservation Areas act, in part, as large reservoirs for Lower East Coast flood control and the storage of EAA drainage water (**Figure 10-1**). This storage helps create a large groundwater flow (677,000 ac-ft) to the Lower East Coast. This flow contributes to the huge movement of surface water (2,929,000 ac-ft) to the Atlantic Ocean. In the 1995-base case, water is pumped to the WCAs from the Lower East Coast (238,000 ac-ft) and the EAA (917,000 ac-ft) to prevent agricultural and urban flooding. Water also moves through control structures to meet the environmental needs of the Park (358,000 ac-ft) and to control WCA-3A flooding (421,000 ac-ft). The only remaining exchange of surface water in the WCAs is the inflow from Big Cypress Preserve along the western boundary of WCA-3A. This managed system is in sharp contrast to the NSM-predicted large exchange of surface water, the lack of groundwater movement, and the low amount of freshwater flow to the Atlantic Ocean (**Figures 2-7**).

Finally, in the NSM water budget, the vast majority of all inflows and outflows in the Park are overland flows (**Figures 2-7**). This is not true for the 1995-base SFWMM water budget (**Figure 10-1**). According to the 1995-base managed conditions, inflows from the Lower East Coast into the Park are only 18% of what was predicted to occur by NSM. As a result, Shark Slough outflow from the Park to the southwest is 48% of what was predicted to occur by the NSM. A big difference between the NSM and the 1995-base SFWMM is the amount of annual groundwater seepage to the Lower East Coast. In the NSM it is only 28,000 ac-ft but in the SFWMM, it is 306,000 ac-ft. Another difference is the amount of freshwater flow toward Florida Bay via the Park and the Lower East Coast. The NSM total average discharge is 156,000 ac-ft. However, the SFWMM average discharge is 249,000 ac-ft. This increase over NSM reflects an increase in the water supply to Florida Bay that was initiated in 1993 and incorporated into the 1995-base managed condition. Note that the 1995-base is a fixed Everglades infrastructure with stationary operational rules (circa 1995) and thus, is not indicative of the amount of actual freshwater delivered to the Bay by the C&SF Project from 1965 to 1995.

Groundwater

Previous geologic investigations provided only limited interpretations of groundwater/surface water interactions in the WCAs (Parker, 1942; Parker, 1955; FGS, 1991; Leach, 1972; Schroeder, 1958). Interactions between canals and aquifers in WCAs and groundwater flow beneath levees was addressed by the U. S. Army Corps of Engineers in several design memorandums (1951, 1968 and 1980). Few previous investigations addressed the impacts of the WCA compartmentalization on regional interactions between groundwater and surface water (regional recharge or discharge by vertical fluxes through wetlands). There also has been little attention given to groundwater geochemistry and the possible relation to ecological processes in the WCAs. The hydrogeological framework defined by Florida's Groundwater Quality Monitoring Program (FGS, 1991) shows large data deficiencies in the Everglades.

Although monitoring wells in the northern Everglades are limited in number and aerial coverage, these unpublished District data suggest that compartmentalization of the remnant Everglades has a significant effect on the groundwater hydrology. Compartmentalization of the WCAs has enhanced the driving forces that promote groundwater-surface water exchange. For example, WCA-1 is maintained at approx. 16 feet NGVD, while the adjacent WCA-2A is maintained at approx. 12 feet NGVD. This head difference of 4 feet across the levee causes subsurface leakage from WCA-1 beneath the levee and discharges into WCA- 2A. These horizontal and vertical flows enhanced by compartmentalization are not representative of the natural Everglades system that existed prior to levee and canal construction (Krupa et al., 1998).

South of this area, transmissivities (an index of hydrologic conductivity) of the upper aquifer can be approximately 2 orders of magnitude greater (SFWMD, 1997) and thus, subsurface flows take on even greater importance. Conservation Areas 2-B and 3-B were built in part, to reduce groundwater flows and levee seepage losses. Transmissivity is likewise high in the eastern Park down to the region of the C-111 canal system. In an attempt to reduce this unintended flow out of the managed system into urban areas, the C&SF Restudy is incorporating a variety of mechanisms to either impede these flows or return them back to the Conservation Areas and the Park.

A more thorough investigation is needed on the role groundwater/surface water interactions play in hydrologic budgets, chemical mass balances and ecological consequences in the Water Conservation Areas. For this reason, in 1996 the District undertook a study to characterize the hydrogeology and to quantify groundwater and surface water interactions in several wetland areas of the northern Everglades. These same types of studies are currently underway in the Everglades Nutrient Removal Area (ENR) and WCA-2A. Results of those investigations indicate that surface water management in WCA-1 and 2 and subsidence in the EAA primarily control the regional interactions between groundwater and surface water in the northern Everglades (Harvey et al., 1998c). Water in WCA-1 is a significant source of recharge to the aquifer. The highly transmissive upper part of the surficial aquifer is a conduit for groundwater flow. It discharges to wetlands and surface waters in the ENR and in WCA-2A (Harvey et al., 1998a,b,c; Krupa et al., in press). Operational and climatic effects on water and chemical mass budgets are currently under investigation.

Florida Bay

The development of south Florida and the associated alteration of regional hydrology has not only impacted the freshwater wetlands of the Everglades but also the coastal wetlands and estuaries of the region. Some of these coastal areas, such as the Caloosahatchee and St. Lucie estuaries, have been subject to large and unnatural increases in freshwater inputs from flood control structures. For the coastal areas of the Everglades, however, freshwater input has diminished. Much of the freshwater that naturally flowed through Taylor Slough and Shark River Slough to the coast has been diverted by canals to other coastal areas (Light and Dineen, 1994).

An important goal of Everglades restoration is to restore the hydrologic conditions and ecological characteristics of the coastal zone. Florida Bay restoration is of particular concern, because it has been subject to drastic ecological changes during the past 10-100 years (Boesch et al., 1993). These changes include increased seagrass mortality and algal blooms, and decreased water clarity. It is generally thought that decreased freshwater inflow from the Everglades and resultant increases in salinity, have contributed to these ecological changes.

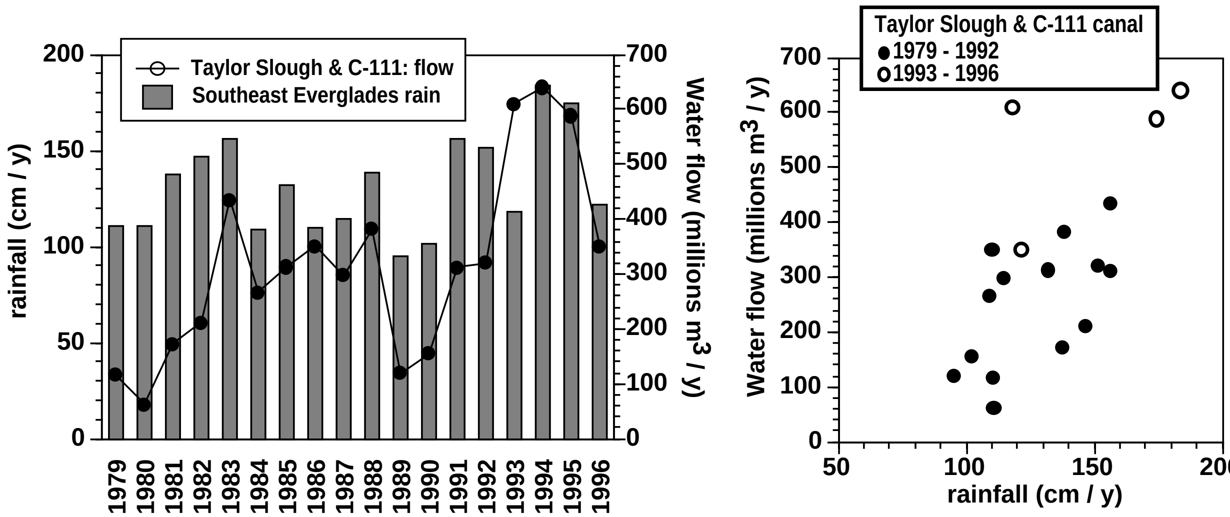

Figure 2-8. Annual regional rainfall and the annual discharge of water into Everglades National Park through its eastern boundary into Taylor Slough and the wetlands south of the C-111 canal. While water discharge generally increases with increasing rainfall, relatively more water has flowed into the Park since 1993.

Restoration of the southern Everglades and Florida Bay is currently under way. This restoration effort includes structural and operational changes in the water management system, combined with an interagency program of monitoring and research, to assess the response of these ecosystems to hydrological changes. Structural and operational changes that have been made during the past five years have been part of the C-111 project (a cooperative effort of the District and the USACE), Modified Water Deliveries to ENP Project, and the Experimental Program of Water Deliveries to the Park. One important change during this time has been the District's acquisition of the Frog Pond agricultural area adjacent to the eastern boundary of the Park in 1995. This acquisition has enabled the District, in cooperation with the USACE and the Park, to increase water levels in the headwaters of Taylor Slough and increase water deliveries through the Slough to Florida Bay. Another important change has been the removal of the levee on the south side of the lower C-111 canal. This entailed the removal of 660,000 cubic yards of spoil and was completed in 1997. This levee had impeded the flow of water through the southeast Everglades (Park panhandle) and to the northeast corner of Florida Bay.

With these changes in water management in the southern Everglades and high rainfall in the mid-1990s, more freshwater has been flowing toward Florida Bay. **Figure 2-8** shows that water discharged into Taylor Slough and the Park panhandle has, relative to rainfall, increased since 1993. From 1993 through 1996, average annual discharge was more than double the average annual discharge from 1979 through 1992. Average annual rainfall only increased 18% between these two time periods. Furthermore, with increased freshwater flow, salinity in northeastern Florida Bay has decreased (McIvor et al., 1994; Boyer and Jones, in press). When Everglades restoration is completed, the District will have greater operational capability to control the salinity regime of much of Florida Bay (northeastern and coastal regions).

Ecological Effects of Altered Hydrology

Soil Responses to Hydrology

One of the primary influences of drying on Everglades organic soils is the oxidation of organic matter with resultant subsidence. Drained Everglades agricultural soils are estimated to subside at 2.5 cm/yr (Snyder et al., 1978). Radiocarbon dating of peats near Belle Glade (McDowell et al., 1969) suggest a peat accretion rate during the last 1,000 years of about 16 cm/yr (0.16 cm/yr), less than one tenth the subsidence rate. Peat accretion reaches a maximum of 1.1 cm/yr in areas with extended hydroperiod and/or P enrichment, such as northern WCA-2A (Craft & Richardson, 1993; Reddy et al., 1993). Accretion rates are lowest (0.04-0.28 cm/yr) in areas of reduced hydroperiod, such as northern WCA-3A (Craft & Richardson, 1993; Reddy et al., 1993; Robbins et al., 1996).

Although Jones et al. (1948) is the first soil map of the entire Everglades, an earlier soil mapping effort described a six-mile-wide transect through the middle of the Everglades. The detailed work of Baldwin and Hawker (1915) mapped three miles on either side of the full length of the North New River canal, thus passing from the Atlantic Coastal Ridge to the Pond Apple Zone at the shore of Lake Okeechobee. **Figure 2-9** illustrates the principal soil profiles seen in 1915 and in 1940. In 1915, all organic soil present was uniformly a brown, fibrous, slightly decomposed peat. By 1940, between mileposts 47 and 54, the brown fibrous peat was completely gone, leaving only a trace of organic matter in the top portion of the remaining sand. Between mileposts 3 and 47, the upper layers of the original brown fibrous peat had decomposed into a black non-fibrous material. In addition to these changes, the soil surface had subsided and the vegetation had changed. In 1915, the North New River canal traversed 20 miles of ridge and slough landscape before reaching the Atlantic Coastal Ridge. By 1940, no ridge and slough landscape remained, having been completely replaced by expansion of the sawgrass plains and a short stretch of grassland toward the coast.

The widespread appearance of a new surface layer of black, finely fibrous peat is highly significant. All evidence points to oxidation as the cause of this layer: the loss of structure, the increase in density and mineral content, and the black coloration. Soil scientists and drainage engineers at the Everglades Agricultural Experiment Station in Belle Glade, who studied these soils during the 1930s, in fact clearly state that the oxidized surface layer was a result of lowered water levels (Clayton et al., 1942). The black surface layer visible in all the areas mapped by Jones et al. (1948) as Everglades Peats, reflects the widespread oxidation caused by lowered water tables throughout the Everglades.

The limited literature examining the effects of flooding and drying on natural Everglades soils suggests that during the dry period, some nutrients are made more available as a result of increased decomposition rates. These nutrients are subsequently released into the overlying water upon reflooding of the area (Worth, 1981; Worth, 1988). Preliminary laboratory studies show that naturally drained soil cores from WCA-2A had P fluxes into the overlying water column of 2.45 to 10.12 mg P /m^2/d in soils from an enriched site and 0.005 to 0.016 mg P /m^2/d in soil cores from an unenriched site (Newman and Reddy, unpublished data).

<u>Change in the nature of fire</u>

There is little doubt that fires occurred in the Everglades with some frequency even prior to drainage. Modern scientific studies confirm that the periodic occurrence of moderate surface fires would

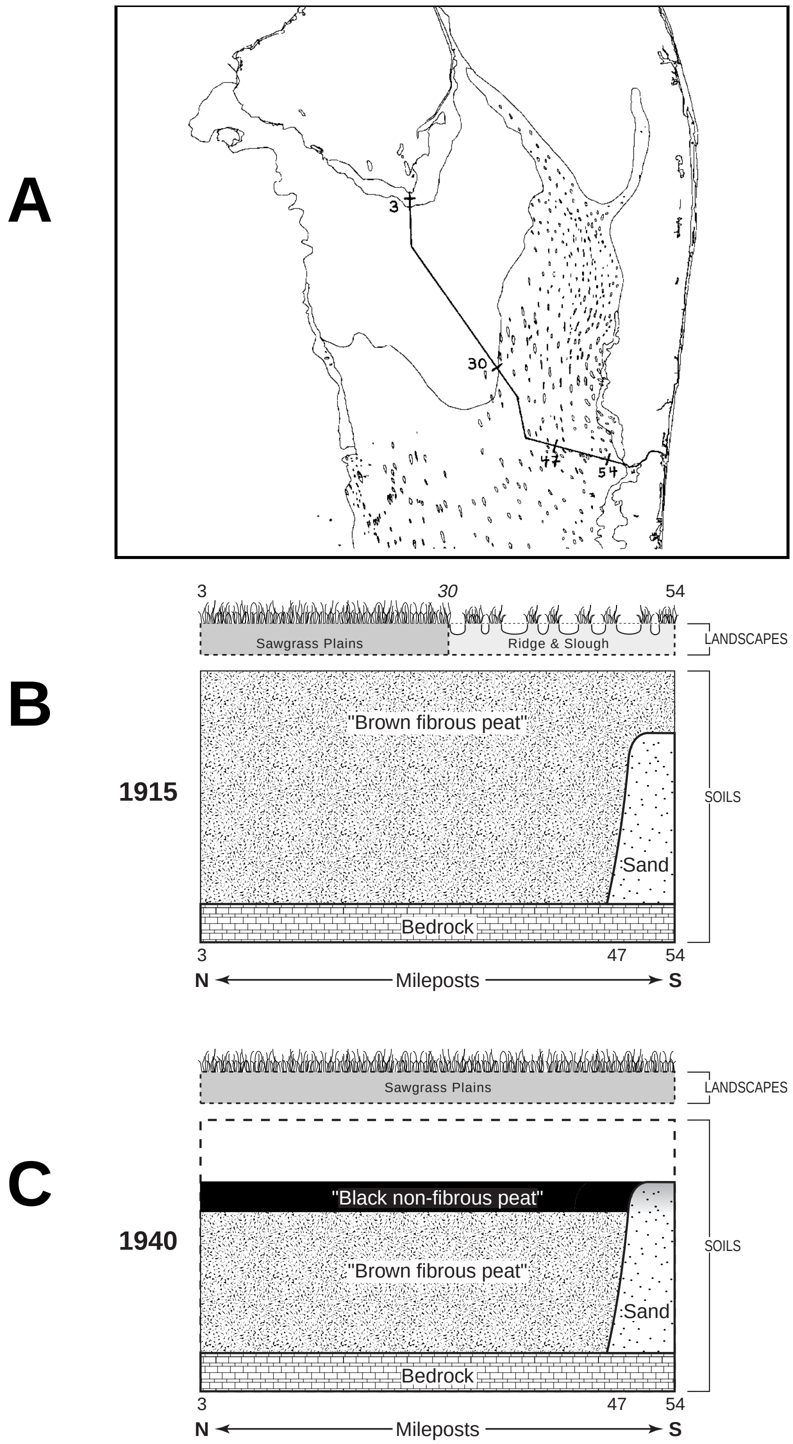

Figure 2-9. Soil profiles along the length of the North New River canal (A), as mapped in 1915 (B) and again in 1940 (C). Note southward expansion of the Sawgrass Plains landscape, elimination of the Ridge and Slough landscape, loss of elevation due to soil oxidation, and conversion of the surface layer from brown, fibrous peat to black, non-fibrous peat. From McVoy et al. (in prep.).

not have destroyed the sawgrass landscape. Loveless (1959) and Forthman (1973) found that sawgrass regenerates rapidly after fire, provided that the soil is sufficiently wet or inundated to prevent sawgrass culms from being killed. Hofstetter (1984) suggests that periodic fires may even be beneficial, reducing the build-up of flammable leaf litter. If water levels decline far enough below-ground to dry out the surface of the organic soils, a different type of fire, the so-called peat or muck fires, can occur. Extensive peat fires, covering tens to hundreds of square miles (Bender 1943), spread during dry periods beginning in the 1920s (Robertson, 1953).[1] Such fires could burn for months and even through the wet seasons of multiple years (Bender, 1943). Water tables in the peat, lower than the normal annual dry season minima of 4 to 6 inches below- ground surface, permit peat fires to occur (Cornwell et al., 1974). An increase in wildfire intensity and frequency is attributed by many investigators to overdrainage of Park wetlands (Wade et al., 1980; Craighead, 1971; Robertson, 1955). Davis (1943) described the effect of lowered water levels and burning on the Rockland Marl Marsh area:

> "Excessive artificial drainage has recently created drier conditions promoting these fires and also causing the shallow organic soils to become oxidized and subside until now some areas once soil covered are returning to rockland conditions." (Davis, 1943).

These fires affected not only the sawgrass, but the higher lying tree islands as well. Bay heads, one of the higher elevation vegetation types, dried sufficiently in the Park to suffer repeated burns (Robertson 1953). Further north in WCA-3, Loveless (1959) noted similarly drastic effects of fire on the higher lying communities:

> "These [early summer of 1956] fires completely destroyed many tree island communities by burning the peat substrate out from under the tree growth. Some of these areas are now open water ponds devoid of any type of emergent vegetation while others support sparse strands of sawgrass, water-lily, floating heart and other aquatic species."

Fire is an important ecological process in the Everglades and a primary factor shaping the Everglades vegetation patterns (Robertson, 1954; White, 1970; Cohen 1974; Duever et al., 1976; Wade et al., 1980; Wu et al., 1996). Fire is an important determinant of inland expansion of mangroves and tree island growth (Davis, 1940; Egler, 1952). Fire also plays an important role in preventing cypress trees from extending into marshes. However, without moderate fires, cypress domes in the Big Cypress Preserve can be replaced, perhaps permanently, by mixed hardwoods (Wade et al., 1980). Moderate fire is a natural process of leaf-burn with many vital functions (Wright and Heinselman, 1973). It influences nutrient recycling, stimulates net primary production and may even be the evolutionary process that selects for sawgrass and slough environments (Wade et al., 1980). The mean moderate fire interval for sawgrass marsh is about 9 years (Gunderson and Snyder, 1994; Wu et al., 1996). A hydrologic regime that prevents moderate sawgrass fires, can increase the amount of willow or other woody vegetation which, in turn, creates an environment that is more fire tolerant (Wu et al., 1996).

Altered hydroperiods, when combined with altered nutrient inflows, can also affect fire (Wu et al., 1996). When ponding and nutrients lead to the encroachment of cattail (Newman et al., 1998), the landscape is altered. The Everglades Landscape Fire Model (ELFM), developed to predict the effects of cattail on fire regimes in WCA-2A (Wu et al., 1996), found that moderate fire-spreading characteristics (i.e., fires that do not burn peat) were reduced due to the expansion of cattail within WCA-2A. A 30% increase in cattails reduced the average annual fire frequency by 21% and mean annual area burned by

1. These damaging peat fires continued into the 1950s (FGFWFC, 1956; Wallace et al., 1960)

23%. The ELFM predicted an average of 3.4 moderate fires a year in sawgrass marshes and only 2.7 moderate fires a year in marshes with a significant biomass of cattails.

The fragmentation of the Everglades has also altered the nature of fire by producing regions that tend to "pond" thus, reducing fire frequency, but also increasing the likelihood of larger, more intensive fires during droughts (Wade et al., 1980; Wu et al., 1996). When sawgrass remains unburned for many years due to ponding, the amount of dead fuel materials can accumulate to high and hazardous levels. When fire finally does occur, it is so intensive and destructive that it can lead to significant peat loss.

Vegetation Responses to Hydrology

The Everglades is composed of a heterogeneous mosaic of tree islands, shrubs, sawgrass, sloughs and open water (Kushlan, 1990). Water depth and hydroperiod, in this low nutrient environment, are considered to be the major mechanisms under which the unique vegetation patterns of the Everglades have evolved (Gunderson, 1994). Slight changes in the depth (± 10 cm) and period of inundation (± 90 days), over long periods of time (5-10 years), influences the presence of certain species and plant communities and results in shifts of the spatial distribution of the vegetation types. Shorter hydroperiods and reduced flooding depths in the Park has allowed woody species to encroach into marshes in the East Everglades, Taylor Slough (Olmsted et al. 1980), and Shark Slough (Kolopinski and Higer 1969). The woody species encroaching into the sloughs are mostly native but in the East Everglades (which includes margins of Northeast Shark Slough), much of the expansion is by invasive exotic trees (*Schinus terebinthifolius*, *Melaleuca quinquenervia* and *Causuarina equisetifolia*) that in some areas now dominate (DeVries 1995, Loope and Urban 1980,). Increased hydroperiod and depth for more than 10 years resulted in the expansion of the Ridge and Slough habitat and the elimination of much of the tree islands in WCA-2A (Dineen, 1974). Similarly, flooding in WCA-3A in the early 1980s resulted in a significant increase of some obligate wetland species such as *Sagittaria lancifolia* and some slough vegetation such as *Nymphaea odorata* and *Utricularia* spp. (David, 1997). Note that the presence of wet prairies within areas that were once Ridge and Slough may be an artifact of pre-C&SF drainage (McVoy et al., in prep). On the other hand, this flooding also reduced the extent and diversity of the wet prairies. Zaffke (1983) reported that wet prairies in southern WCA-3A were replaced by aquatic sloughs due to extended hydroperiods and increased water depth. Wood and Tanner (1990) did not find at least 13 species that Loveless (1959) encountered in wet prairies 30 years earlier in the same area. These observations suggest that many wet prairie species require an annual spring dry period to germinate (Goodrick, 1984).

Vegetative growth is the dominate mechanism of expansion for most Everglades sedges and grasses. However, long-term genetic diversity is preserved through sexual reproduction. Hydrologic factors limit population distributions by affecting the survival of seeds, seedlings and saplings (van der Valk and Davis, 1978). Seed germination of many wetland plants is inhibited by continuously flooded conditions (Brown and Bedford, 1997; Moore and Keddy, 1988). This is due to thousands of years of evolution under a regime of rain-driven hydroperiods selecting for species that are adapted to wet and dry seasons. As a result, hydrologic regimes play an important role for long-term survival and species expansion into "new" unvegetated areas via seed germination and seedling growth. Ponzio et al., (1995) found sawgrass seed germination was highest in water-saturated soil, intermediate in soil with 5 cm water above the surface, and lowest in the soil with 10 cm above the surface.

In the northeastern portion of WCA-2A, an expanding front of cattails (*Typha* sp.), invading and displacing sawgrass is well documented (Swift and Nicholas, 1987; Davis et al., 1994; Rutchey and

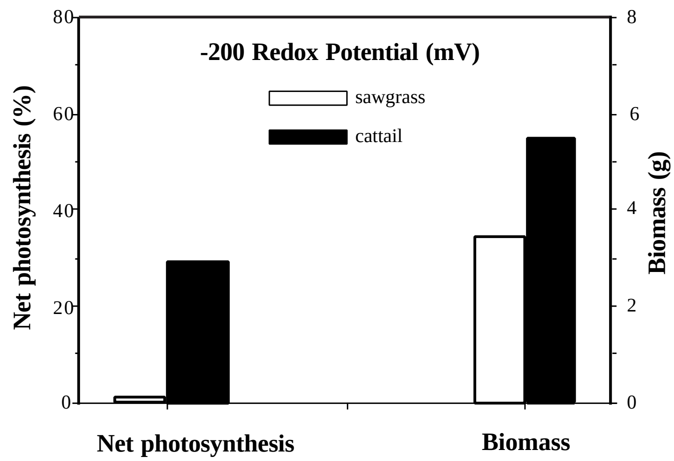

Figure 2-10. Changes in net photosynthesis and total biomass in sawgrass (open bars) and cattail (closed bars) in response to a soil redox condition of -200 mV (i.e., low-oxygen). Taken from Pezeshki et al., 1996.

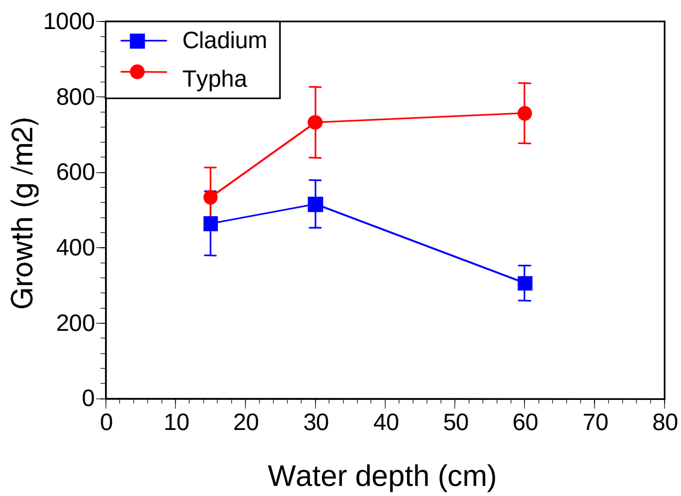

Figure 2-11. Growth of sawgrass (Cladium) and cattail (Typha) mixtures grown in outdoor tanks for two years (final-initial biomass). Taken from Newman et al., 1996.

Vilchek, 1994; Jensen et al., 1995). A six-year (1986 to 1991) study (Urban et al., 1993) in WCA-2A supports the idea that two factors led to the spread of cattail: nutrient enrichment and prolonged hydroperiods. Studies of cattail cover, soil nutrient concentrations, topography and fire history in the Holeyland and Rotenberger Wildlife Management areas located in the northern Everglades suggest that causal factors for cattail expansion are also site-specific. Cattail proliferation in the Holeyland management area has been found to be largely controlled by hydrology and elevated nutrients, whereas cattail distribution in Rotenberger is primarily determined by historic muck fires (creating new unvegetated areas) and elevated nutrients (Newman et al., 1998). It seems that shortened hydroperiods in Rotenberger have resulted in excessive soil oxidation and an increased frequency of wildfires, processes that mobilize P stored in the soils (Wade et al., 1980). This increase in bioavailable P can spur the colonization of cattails (Urban et al., 1993; Davis 1991).

Cattail and sawgrass have different hydrologic tolerance, because they have very different leaf morphology, anatomy and physiology. Sawgrass has coarse, gray-green, saw-toothed leaves with several xeromorphic characteristics such as a thick waxy cuticle, numerous bands of lignified fibers and marginal spines on the leaf surface (Miao and Sklar, 1998). On the other hand, cattail has wide, smooth, light-green and spongy leaves. Cattail plants can produce more adventitious roots (i.e., oxygen gathering structures), create more air spaces in the stems, and transport more oxygen to the soil rhizosphere than sawgrass grown under the same conditions (Kludze and DeLaune, 1996). Despite the stress of low-oxygen conditions, cattail net photosynthesis and biomass tends to be greater than sawgrass (Pezeshki et al., 1996; **Figure 2-10**). These differences are due to contrasting internal gas transportation systems (Grace, 1989). Cattail has a pressurized ventilation system that can actively transport oxygen to the roots when growing in deep-water habitats, whereas sawgrass has only molecular diffusion for oxygen transport (Brix et al., 1992; Chanton et al., 1993). The dominance of cattail with increased flooding levels has been demonstrated experimentally. When sawgrass, cattail and *Eleocharis* were grown in a low-nutrient, low-water, mixture, Newman et al., (1996) found no dominance by any species. However, cattail biomass was significantly greater relative to the other two species when grown in a low-nutrient, high-water, mixture (**Figure 2-11**). It should be noted that the observed cattail dominance did not result from a significantly increased growth of cattail plants but from significant decreases in the growth of sawgrass in deep water.

Periphyton

Periphyton is an important primary producer in the Everglades marshes, particularly in the deeper sloughs (Browder et al., 1994). Typically, the native periphyton exhibits a thick, calcareous (white, creamy) appearance with a layered structure (Gleason and Spackman, 1974; Browder et al., 1994). The calcareous periphyton community has high calcite content and is usually dominated by filamentous blue-green algae of the genera, *Scytonema* and *Schirothrix* (see **Chapter 3**). Periphyton communities require an aquatic environment to survive, grow and reproduce. They are adapted to cope with seasonal dry-downs and periodic droughts by either surviving under low metabolism or entering a state of dormancy. Individual species differ in their resistance to desiccation and ability to recolonize. Thus, periphyton community composition may respond to hydroperiod variations. Frequent and prolonged drying may promote dominance of calcareous periphyton while, year-round flooding may alter water quality and thus, favor noncalcareous periphyton (Van Meter-Kasanof, 1973; Browder et al., 1981, 1994).

There is some evidence that periphyton is also affected by high water depths. Swift and Nicholas (1987) found a statistically significant negative correlation between water depth and cell volumes for *Scytonema* and *Schizothrix*. Gleason and Spackman (1974) observed calcareous periphyton developed better in the upper 0.67 m of the water column. Some believe that calcareous periphyton mats will not develop in deep, open water environments. In Taylor Slough, bottom sediments of deep ponds have more organic material and less calcite mud than sediments in surrounding wet prairies (Browder et al., 1994). Studies conducted in the Park reported an average depth of 0.75 ft for about 7 to 10 months as the optimum depth and duration of flooding for marl producing periphyton communities (Biotropical Industries, 1990).

The effects of water management on periphyton are not clear. It is clear that P enrichment can affect periphyton community structure (see **Chapter 3**). However, hydrology and water chemistry probably interact to determine periphyton dynamics. A theoretical population model (Dong et al., in prep.) suggest that structural instability (i.e., high P sensitivity) is an inherent feature of the periphyton system. This means that a small shift in P concentrations may lead to a disproportionally large change in periphyton community structure. A better understanding of periphyton will result from designing P, hydrology, and macrophyte interaction experiments.

Tree Islands

Within the matrix of wetland types that makes up most of the greater Everglades are small topographical highs or tree islands, which historically have provided habitat for a wide variety of terrestrial plants and animals. Gawlik and Rocque (1998) found that tree islands support more species of birds than any other habitat in the central Everglades. Because the maximum elevations of the highest tree islands are only slightly above mean annual maximum water levels, tree islands with their less flood tolerant vegetation are the most sensitive component of the Everglades to changes in hydrology. In the 1960s, the number of tree islands in portions of WCA-2A and the northern portions of WCA-3A declined significantly (Shortemeyer, 1980). In WCA-2A (**Figure 2-12**), tree islands were lost because relatively high water levels were sustained for many years after prolonged drainage had caused subsidence of the tree island peat. The tree islands in WCA-2A lost their trees and shrubs between 1960 and 1970, a period of relatively prolonged high water levels (Dineen, 1974; Worth, 1988).

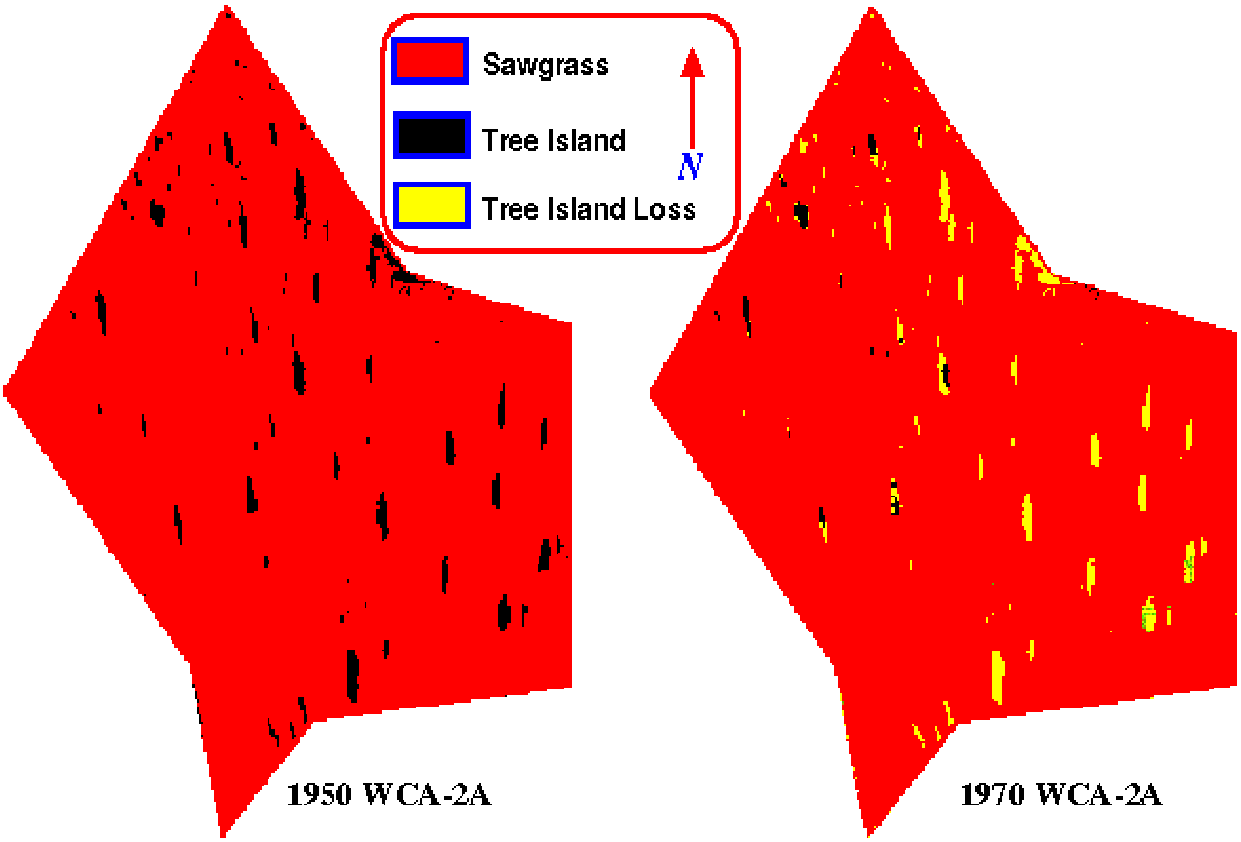

Figure 2-12. The loss of tree islands in WCA-2A between 1950 and 1970, due to conversion to marsh habitat. This 20-year period had relatively prolonged high water levels, and followed a thirty-year period of prolonged low water levels and high soil oxidation. The 1950 map was digitized by Worth (1988) from a Loveless (1959) survey. The 1970 map was taken from Dineen (1992, 1994).

Prolonged dry conditions can also result in a loss of tree islands. Prolonged low water levels in the northern section of WCA-3A resulted in tree island destruction because peat fires removed as much as 25 cm of their elevation (McVoy et al., in prep.). This later may result in flooding - water depths too great for shrub and tree recolonization - when surrounding water levels are returned to more normal conditions.

The conservation of diverse, healthy, functioning tree islands should be a goal of restoration and a criteria for determining appropriate water flows and levels in the Everglades. However, a review of the literature has provided little insight into what constitutes a healthy tree island. Studies on tree islands in the WCAs have been restricted almost exclusively to descriptions of their vegetation (Davis, 1943; Loveless, 1959; Alexander and Crook; 1974, McPherson, 1973; Zaffke, 1983). Almost no studies have been done to test the various hypotheses of tree island sustainability and development summarized by Loveless (1959). An unanswered question remains. If all tree islands have lost significant elevation, how can water managers restore the pre-drainage hydrology and preserve tree islands at the same time?

Muhly grass

Freshwater prairies of muhly grass (*Muhlenbergia filipes*) support the federally endangered Cape Sable Seaside Sparrow as well as a number of other birds species in the southern Everglades (Richter and Myers 1993). Increases in hydroperiod have caused shifts away from the muhly-dominated prairie, preferred by the sparrow, and toward a sawgrass-dominated community (Pimm et al., 1995). With a typical hydroperiod of only 1-5 months, muhly prairies have shorter inundation periods and shallower flooding depths than typical sawgrass marshes (Olmsted and Loope 1984). Hydrologic plans to reduce hydroperiods may reestablish areas once dominated by muhly grass. However, other than documenting the rates of biomass recovery (2-3 years) after annual prescribed fuel-reduction burns (Herdon and Taylor, 1986), little is known about the effects of hydrology on muhly grass ecology.

Invasive exotics

Hydrology can affect the ability of exotic or normally restricted plant species to expand into a variety of Everglades habitats. Austin (1976) reported that wet prairie sites, disturbed by fire, are particularly susceptible to invasion by *Melaleuca quinquenervia.* It was also observed that Brazilian pepper (*Schinus terebinthifolius*) is often a major component of postburn vegetation (Wade et al., 1980). In south Florida, exotic plants tend to establish in disturbed areas - abandoned farm land, along roadways, canals, and drainage ditches as well as, in wetlands that have been cleared or have been stressed due to hydroperiod changes.

Melaleuca (*Melaleuca quinquenervia*) is a pioneering Australian species that has been spreading since its introduction to south Florida in the early 1900s. It was thought to have very high transpiration rates and an ability to drain the Everglades. It did neither. Transpiration of melaleuca is no more than that of other forest types of the same density (Woodall, 1981, Woodall 1984), and theoretical models suggest that total evapotranspiration from melaleuca stands is likely to be only slightly larger than that of short canopy, native vegetation replaced by melaleuca invasions (Chin 1998). In its native range, it grows in low-lying flooded areas and is especially well-adapted to ecosystems that are periodically swept by fire. These are common conditions in South Florida, making it an ideal habitat for colonization. Melaleuca grows equally well in the deep peat soil of WCA-1 and the inorganic, calcareous soil of the Park. In general, wetland areas such as sawgrass prairie are more susceptible than drier, upland areas. However, increasing hydroperiod length in some wetlands can slow the spread of invasive plant species such as, melaleuca by limiting suitable germination sites.

Melaleuca is very responsive to fire. It forms dense stands with higher fuel loadings than a typical sawgrass marsh -- about 20 kg / m^2 (Conde et al., 1980) compared to 2.8 kg / m^2, respectively (Hofstetter, 1976). Heat value for the fuel is as high as 11,200 btu / lb compared to less than 8,000 btu / lb for herbaceous fuel (Huffman, 1980). As a result, fires in melaleuca stands burn very hot and intensive (Flowers, 1991). After a fire, melaleuca has vigorous regeneration of sprouts and prolific seed release (Mayers, 1970; Burkhead, 1991). Hydrologic management was not able to deter the spread of melaleuca. Before state and federal chemical control operations were initiated in 1990, melaleuca was distributed throughout South Florida. Today, large untreated monocultures of melaleuca are limited to WCA-2B and wetlands just east of the southern Everglades.

Unlike melaleuca, Brazilian pepper (*Schinus terebinthifolius*) is not a good fuel for fire and can function as a firebreak. It thrives on disturbed soils and is especially invasive in areas affected by drainage. It can not establish in deep wetlands and can rarely grow on sites inundated longer than three to six months. In the Everglades, Brazilian pepper is mainly restricted to levee berms and other areas of disturbance such as the rock-plowed “Hole in The Donut” in the Park. However, a large area in the eastern Ten Thousand Islands of the Park has Brazilian pepper and it has established itself on tree islands in northern WCA-3A. Some form of chemical and hydrologic management may reverse this trend.

The newest of the invasive exotics is Old World climbing fern (*Lygodium microphyllum*). It is an exotic twining fern that was first found near the Loxahatchee River in the late 1950s. It is now spreading rapidly throughout the southern part of the state. Old World climbing fern overtops and smothers Everglades tree islands, pinelands and cypress swamps, and spreads across open wetland marshes. It also forms dense mats of rachis plant material. These thick, spongy mats are slow to decompose, exclude native understory plants and can act as a site for additional fern colonization. Significant infestations have been recently spotted in WCA-1A, Lake Okeechobee, and Big Cypress National Preserve. Increased hydroperiod does not seem to have an effect on this species as it has expanded greatly in areas that have experienced higher than normal water levels over the last few years. This plant also alters fire ecology. Burning mats of the light-weight fern break free during fires and are kited away by heat plumes, leading to distant fire-spotting. Additionally, the plant acts as a flame ladder -- carrying fire high into native tree canopies.

Finally, there is the potential problem of torpedograss (*Panicum repens*). The origin of torpedograss is uncertain. Its tolerance to desiccation (Wilcut et al., 1988), its ability to store high levels of carbohydrate in rhizomes (Manipura and Somaratne 1974), and its survival in 2 to 4 feet of water (Tarver, 1979) made torpedograss an easy forage plant for early Florida farmers to establish. It now occurs in 70% of Florida's public waters and has displaced 14,000 acres of native marsh plants in Lake Okeechobee (Schardt, 1994). Stormwater treatment areas will need to be monitored to prevent torpedograss from becoming a serious weed problem. Unfortunately, most herbicides for torpedograss are indiscriminate for grasses and can damage non-target woody plants (Langeland et al., in review). The control of torpedograss requires the destruction of the below-ground rhizome system (Chandrasena 1990).

Vegetation mapping

Vegetation maps are needed to define boundaries, detect change, and understand large-scale, ecological processes. The first complete vegetation map of the Everglades was produced by Davis in 1943. **Figure 2-13**, digitized from Davis (1943), suggests a zonation that might be expected as water levels progressively lower

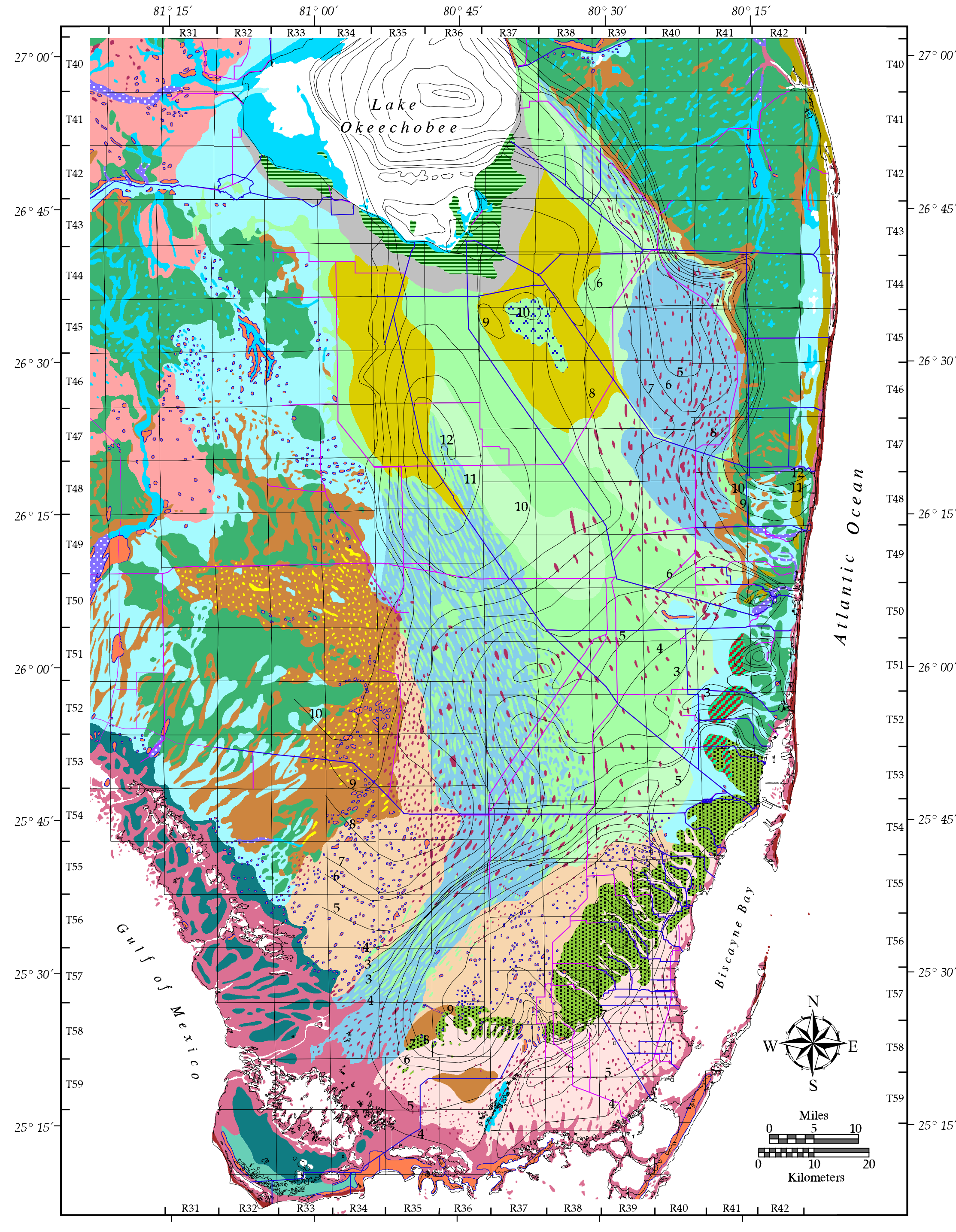

Figure 2-13. Vegetation map of Southern Florida, circa 1940. Overlain with contours of bedrock floor of Everglades and with 1990 canals. Vegetation polygons digitized from Davis (1943b); bedrock floor digitized from Parker et al. (1955); canals from South Florida Water Management District digital map coverage. From McVoy et al. (in prep.).

within a basin: a pattern of drier vegetation types encroaching inward from the edges of the basin. The encroaching vegetation types tend to occur in sequential bands parallel to the edges. Along the western and eastern borders of the Everglades the sequence passes from wet prairies to sawgrass (with wax-myrtle thickets) and then to sawgrass marshes (Davis, 1943). Although this map is still the only complete map of the Everglades, its spatial accuracy is poor. There are several ongoing projects and recent projects (**Table 2-4**) that define and map the current vegetation communities of the Everglades with much greater accuracy. These mapping projects use various mapping procedures including digital imaging processing (i.e., satellite data) and conventional photo interpretation (i.e., aerial photography). A new vegetation map for the entire Everglades is expected to be completed in the year 2000.

Table 2-4. Vegetation mapping projects for the Everglades Protection Area.

Region	Technique	Accuracy	Reference
WCA-1	SPOT image w/ Loran C 1940 photograph (tree islands)	Unknown N/A	Richardson, 1990 Brandt, 1997
WCA-2A	SPOT image w/ GPS Color infrared photography w/ GPS	70.9% 95.0%	Rutchey & Vilchek, 1994 Rutchey & Vilchek, in press
WCA-2B	None	-	-
WCA-3 (A&B)	Color infrared photography w/ GPS	On-going	District
The Park	Color infrared photography w/ GPS	On-going	US Park Service
C-111 Basins	Color infrared photography	Unknown	Dade County Planning Department, 1979
Holeyland & Rotenberger	Aerial point-sampling from a helicopter	Unknown	Florida Game & Fresh Water Fish Commission

Wildlife Responses to Hydrology

Avian Dynamics -Wading Birds

Changes in wading bird populations are often cited as evidence that the Everglades ecosystem is degraded. The recovery of these birds has been identified as a key component of a successful Everglades restoration (Walters et. al., 1992). Wading birds are used as landscape bioindicators of restoration because of their high mobility over large areas, rapid response to changes in lower trophic levels upon which they feed (Weller, 1995), and because of the long record of data available for the Everglades (Ogden, 1994). Beyond their role as indicators, wading birds function as nutrient transporters (Bildstein et al., 1990; Frederick and Powell, 1994) and regulators of prey populations (Kushlan, 1976a; Feunteun and Marion, 1994; Trexler et al., 1994). Three of the most notable changes in the historic (i.e., 1930's) wading bird community of the Everglades are: (1) a decrease of approximately 90% in the abundance of breeding wading birds; (2) a shift in the spatial distribution of colonies from coastal locations to interior sites in the WCA's; and (3) a late nest initiation for Wood Storks.

Causes for the observed changes in wading bird populations are not thought of as mutually exclusive. It is generally accepted that the observed changes are all symptoms of the same problem -- a degraded ecosystem that can no longer support the large populations of wading birds it once did. Three generalizations emerge from a review of Everglades wading bird literature from the last 20 years. First, good foraging conditions for wading birds usually translate into good reproductive output. Second, many aspects of wading bird reproductive and foraging ecology are influenced by water depth and water recession rate. Shallow receding water levels are associated with good reproductive and foraging success, whereas a reversal in water recession, especially late in the nesting cycle and an associated increase in water depth have a negative effect. Thirdly, the critical water recession rates and water depths vary with the species of bird. The two species that have shown the greatest change in the timing of the initiation of nesting have been White Ibis and Wood Storks (Ogden, 1994; Ogden et al., 1997). During the 1986-1995 base period, White Ibis initiated nesting, on average, about 1.5 months later than during the period 1931-1946. The months when Wood Storks throughout the Park and Big Cypress initiate colony formation has shifted in response to water level patterns from November-December in most years prior to 1969, to January –March in the 1970s and 1980s (Ogden 1994, 1996). This “late” nesting has been associated with reduced numbers of nesting birds and reduced nesting success (Gawlik, 1997).

These generalizations represent a considerable body of knowledge; however, they do not identify the mechanism by which receding water leads to good foraging conditions. Hypothesized mechanisms have focused either on the mechanical concentration (i.e., redistribution) of prey whereby they are easier to capture (Frederick and Collopy, 1989; Bancroft et al., 1990), or on the increased abundance of prey due to their release from predation (Kushlan,1976b; Kushlan 1987). It is tempting to conclude that even without a mechanistic model, restoring populations of wading birds could be achieved through frequent uninterrupted water recessions. However, even the basic relationship between fish populations and hydroperiod has recently come into question (Loftus and Eklund, 1994). New evidence suggests that frequent dry-downs decrease the density of fish, thus reducing the abundance of wading bird prey (Loftus and Eklund, 1994), in contrast to earlier work that indicated fish density increased with frequent dry-downs (Kushlan, 1976b). Such conflicting information suggests that as conditions in the ecosystem change, generalized relationships may no longer hold true. Despite recent, relatively wet years, compared to the drier year during the late 1980s and early 1990s, the percentage of the total number of nesting birds for the five species nesting in traditional ecotones continues to decline. The shift of nesting birds out of the mainland Park has been at a dramatic pace (Ogden, 1991). The upshot is that without a mechanistic understanding of how water-level dynamics affect the feeding success of wading birds, water managers will not have the flexibility to make sound management decisions under changing conditions.

The most direct way that water dynamics can affect the food acquisition of wading birds is by changing the availability of their prey. It has been suggested that food availability is the single most important factor limiting populations of wading birds in the Everglades (Frederick and Spalding, 1994). Food availability is determined by the abundance of prey and vulnerability of prey to capture. The vulnerability of prey can be affected by water depth. An analysis of this was conducted in experimental ponds, where the use of feeding sites by wading birds was measured in response to water depth (10 cm, 19 cm, 28 cm) and fish density (3 fish/m^2, 10 fish/m^2) treatments (Gawlik, 1996). Wood Storks and White Ibis, in this experiment, were unable to exploit all the ponds due to the wide range of depths and left the ponds early. In contrast, Great Egrets persisted because of their ability to forage at greater depths. There were noticeable differences among treatments in the rate of fish consumption and giving-up densities (fish densities at which bird species left the ponds). The results of this experiment as they pertain to hydrology of the Everglades, suggest that water depths, in the ranges examined, influenced the selection of foraging sites for 7 of the 8 species examined. Only the Great Blue heron was unaffected by a water depth of 28 cm. Although leg length appeared to constrain the use of deep water by most species, leg length did not equate to maximum foraging depth as previously reported. The temporal dynamics and foraging behaviors exhibited by birds in this experiment indicate that species most likely to be impacted by events like the high water conditions in the Everglades during 1994-1995 include the Wood Stork, White Ibis and Snowy Egret, which were constrained by both water depth and fish density, and the Tricolored Heron, which was most constrained by water depth alone.

The effects of hydrology have also been observed in the wading bird distribution and abundance data of the Systematic Reconnaissance Flight (SRF) program (Porter and Smith 1984; Bancroft et al., 1992; Bancroft et al., 1994; Hoffman et al., 1994), developed during the 1980's. Transects of the SRF program are laid across a 2-km grid and divided into 4-km^2 blocks or cells. The abundance of Great Blue Herons, Great Egrets, Wood Storks and White Ibises in response to water depth and vegetation across the northern Everglades were studied for two years (1988 and 1989) with dissimilar water levels, for WCA-2A and WCA-1. These analyses showed that water depth and the vegetation community in a 4-km^2 area influence the distribution and abundance of wading birds. In 1988, a wet year, there was a water depth threshold above which bird abundance was predicted to decline. The depth threshold varied among species and ranged up to 76 cm for the Great Blue Heron. In 1989, when water was shallower, the relationship between bird abundance and water depth was positive and linear.

Avian Dynamics -Cape Sable Seaside Sparrow

The Cape Sable Seaside Sparrow is a small, secretive bird that inhabits short-hydroperiod, freshwater prairies in the southern Everglades, particularly those dominated by the bunchgrass muhly (*Muhlenbergia filipes*). Sparrow populations occur both east and west of Shark River Slough, south of Tamiami Trail. The bird is classified as a federally endangered species and populations have declined dramatically between 1992 and 1997 (Lockwood et al., 1997).

Two factors that appear to limit breeding potential are suitable vegetation and water levels. Observational data suggests that water levels must be below 10 cm in order for the birds to breed (Pimm et al., 1995, Lockwood et al., 1997). If water levels are not less than 10 cm by April the birds will not initiate breeding. Likewise, a water level rise to depths over 10 cm usually marks the end of the breeding season, typically in July. Nott et al. (1998) report that the potential nesting areas in western Shark Slough were submerged during the March to May nesting period in several successive years, preventing many of the birds from constructing nests and decreasing the local sparrow population by approximately 80%. In addition to the obvious role of hydrology via water depths during the breeding season, hydrology affects the plant community and therefore the presence of suitable breeding habitat. In drained areas NE of Shark River Slough, shrubs have increased and severe fires have burned away peat, thus rendering the habitat unsuitable (Pimm et al., 1995). It should be noted that the role of fire in maintaining suitable habitat is not fully understood, and it is likely that some amount of burning is essential. It has been suggested that increases in hydroperiod, particularly west of Shark River Slough, have caused shifts in the vegetation away from the muhly-dominated prairie, preferred by the sparrow and toward a sawgrass-dominated community, which they do not (Pimm et al., 1995). Hydrologic management recommendations for the sparrow issued in a biological opinion (Pimm et al., 1995) were to increase water flows to northeast Shark River Slough and reduce flows west of Shark River Slough.

Fish

There are two contradictory ideas of how hydrology affects the Everglades' freshwater fish community. The first hypothesis suggests that fish density in the southern Everglades is highest when the marsh is managed for frequent dry-downs (Kushlan, 1976b). Data collected from 1965-1972 using pull-traps (described in Higer and Kolipinski, 1967) indicated that under a regime of frequent dry-downs small 2-cm omnivorous fishes (Kushlan, 1976b) dominated the fish community. As the length of time without a dry-down increased, the community shifted and became dominated by larger carnivorous sunfishes and catfish. The results suggested a shift in the structure of the community as a result of hydroperiod.

The second hypothesis suggests that both small and large fish densities increase during periods without dry-downs and there is no shift in community dominance toward large fishes as a function of increased hydroperiod (Loftus and Eklund, 1994). This hypothesis is based on data collected with throw-traps (described in Kushlan, 1974) during 1977 to 1985, an 8-year period without a dry-down. Throw-traps do not disturb the sampling site as much as pull-traps with repeated sampling and, therefore, throw-traps do not produce biased data inherent with pull-traps. Loftus and Eklund (1994) argued persuasively that the first hypothesis is without merit, because it is based on biased data.

Historically, freshwater flowed to Florida Bay via Taylor Slough. The northern mangrove fringe of Florida Bay experienced reduced freshwater flow and increased salinity levels because of the construction of a canal network upstream in the 1960s. Based on fish samples taken from 1991 to 1996 in this area, fish density was negatively correlated with increasing salinity (related to freshwater flow) and to a lesser degree, positively correlated with water depth (Lorenz, 1997).

Apple snails

The Florida apple snail (*Pomacea paludosa*) is a critical food web component in Florida, and is the primary food source for endangered snail kites (*Rostramus sociabilis*). Water resource managers and the U.S. Fish & Wildlife Service have identified apple snail research as a high priority in central and south Florida wetland restoration efforts (Darby et al., 1997). It is generally accepted that increased frequency and duration of dry-downs beyond natural levels negatively influences snail kite populations. It is assumed that the negative impact manifests itself through depressed apple snail populations, although no data other than Darby et al. (1997) exist.

Data on snail movements (Darby et al., 1997) revealed that apple snails do not seek out deep-water refuge during a dry-down. Apple snail reproductive ecology drives the movement patterns of snails more so than hydrology. Water depth does, however, influence snail movements. An approximate depth of 10 cm appears to be a threshold level at which snail movements become impeded. At this point snails settle in one spot and, as residual water recedes, they become subjected to dry down conditions. They do not burrow, but they do conserve moisture through the tight closure of their operculum.

Lab and field studies (Darby et al., 1997) both indicated that desiccation during the dry season is not necessarily a predominate cause of mortality. Regardless of hydrologic conditions, post-reproductive adult size snails reach the end of their life span (estimated at 12 to 18 months) and die, usually within a few weeks after reproducing. Snails that did survive dry-down conditions for 8 weeks (laboratory snails) and 12 weeks (observed in the field) tended to be juvenile-size snails. It is hypothesized that snail tolerance to desiccation is a function of snail size and/or reproductive status.

The timing of dry-downs affects snail reproduction (Darby et al., 1997). Peak egg cluster production by apple snails in central and south Florida consistently occurs between March and July with a peak in April. Dry downs, which encompass the time period of peak reproduction, may reduce or eliminate recruitment in the affected area. Dry-downs occurring later in the reproductive season (i.e., after peak reproduction) likely pose significantly less harm to snail populations than those occurring during peak reproduction. Young-of-the-year snails can survive at least 2 to 3 months in dry-down conditions. Rapid early growth enables snails hatched in March and April (typically a substantial portion of the total hatch) to reach sufficient size to survive a mid- to late spring dry down. Thus, a slight shift in the timing of dry-downs has the potential to have a large impact on snail recruitment.

Alligators

Alligators are dependent on marsh hydrology for many aspects of their life history. Nesting success is probably more closely linked to water levels than any other parameter. Nests will often fail if during the 60 to 65 day incubation period, water levels get so low as to allow raccoons and other predators access to the nest, or so high as to flood the nest (Mazzotti and Brandt, 1994). Alligators adapt to fluctuating water levels by adjusting the height of their nest cavity at egg-laying time to spring water levels, which historically were good predictors of maximum water levels. However, water management practices such as late-season regulatory water releases have reduced the predictability of water level rise and, thereby, increased nesting losses (Kushlan and Jacobsen, 1990). The once large nesting alligator population of Grossman's Slough, at the southern end of Northeast Shark Slough in the Park (National Park Service, T. Armentano, pers. comm.), may have declined due to this unpredictably of water management.

Responses of Nutrients and Salinity in Florida Bay to Changing Hydrology

The hydrological conditions of watersheds strongly influence the ecological characteristics of estuaries. For the coastal areas of the Everglades, decreases in historical supplies of freshwater changed the salinity regime of the areas and also changed the movement of nutrients and sediments through these areas. The District, in cooperation with the Park and Florida International University, has monitored changes in salinity and water quality in these areas since 1991. Furthermore, through a cooperative interagency science program, there has been support for seagrasses and fish monitoring during this time. Finally, since enactment of the Act, the District has funded research to assess the impact of changing water management on the ecology of Florida Bay and the mangrove wetlands that constitute a salinity "transition zone" between the Bay and the Everglades. These projects are assessing how water quality, seagrasses, wetland plants in the transition zone, and fish are affected by changing freshwater flow and salinity.

One research project, on P and nitrogen (N) inputs to Florida Bay from the Everglades, has shown that increased freshwater inflow from the transition zone is unlikely to cause any ecological damage in Florida Bay because of increased P loading. A preliminary estimate of total nutrient loads to northeast Florida Bay from it's primary watershed (Taylor Slough and the C-111 canal basin) was based on measurements in Taylor River, McCormick Creek and Trout Creek (Rudnick et al. *in press*). Assuming other creeks that flow into Florida Bay have similar nutrient concentrations as these three creeks, creeks contributed about 2.8 metric tons of total P and about 230 metric tons of total N to the Bay in 1997. This P input is probably insignificant to the Bay, because it is probably far less than P inputs from other sources, including the Florida Keys and the atmosphere (each with inputs of about 40 metric tons per year, as estimated by Rudnick et al. *in press*). However, the total N input from the coastal creeks of Taylor Slough and the C-111 basin is probably significant to the Bay, being similar in magnitude to N inputs from the

Keys and the atmosphere (respectively, about 200 and 800 metric tons per year, as estimated by Rudnick et al. *in press*). These calculations do not include indirect nutrient inputs from the Shark River Slough, which flows to the Gulf of Mexico. Nutrient inputs to Florida Bay from the Gulf of Mexico, which includes some of the nutrients that passed through Shark Slough, may greatly exceed all other inputs to Florida Bay. At this time, nutrient inputs from the Gulf cannot be accurately estimated. Measuring these inputs is a high priority of the interagency Florida Bay science program.

Based on these preliminary results, it appears unlikely that changing freshwater flow to Florida Bay, as part of the restoration of the EPA, will significantly affect the input of P to Florida Bay. However, it does appear that N inputs to the Bay could increase with increased freshwater flow. The consequences of N inputs are not certain. These areas are generally much more sensitive to P inputs. However, in western Florida Bay and in adjacent ocean waters, both N and P concentrations are low. Increased N inputs to these regions could stimulate productivity, including the production of algal blooms. At this time, however, it is premature to conclude that efforts to restore Florida Bay by increasing freshwater flow will cause any harm to any part of the Bay or adjacent waters.

Changing salinity conditions can change the structure of important habitats such as seagrass beds and wetlands. An ongoing project is researching how different seagrass species are affected by salinity change. Initial results from northeastern Florida Bay and saline ponds along the northern coast of the Bay indicate that salinity fluctuations do indeed have a strong influence on the growth and death of different seagrasses (Chipouras et al., 1998). Increases in widgeon grass (*Ruppia maritima*) and the alga, *Chara*, have been associated with increasing freshwater flow into these areas during the past two years. Furthermore, experiments on the salinity tolerance of the dominant seagrass of Florida Bay, turtle grass (*Thalassia testudinum*), have shown that it is surprisingly tolerant of salinity changes (Montague et al., 1993, Jones et al., 1998). While results from ongoing studies are too preliminary to present in great detail, initial results indicate that increased freshwater flow to the Bay will not result in the sudden mortality of turtle grass beds, which are thought to have become more dominant in the Bay in recent decades because of decreased freshwater flow (Zieman et al., 1989).

Historic Changes in Salinity

Since the enactment of the Act, the District has funded three research projects to help determine targets for salinity restoration in Florida Bay. In these studies, a variety of chemical and biological measurements within the sediments and skeletons of corals have been made to reconstruct the variations of the Bay's salinity during the past 100 to 200 years. Such reconstructions are possible using corals because when corals grow, they deposit skeleton layers in annual rings that can be counted and dated, much like that with tree rings. Since the age of a ring can thus be determined and the chemistry of the skeleton in this ring reflects the chemistry of water at the time it was deposited, the past salinity of Florida Bay can be inferred. Using this approach, it has been determined that the salinity of Bay waters was more variable, with more frequent periods of low salinity during the 1800s than during the 1900s (**Figure 2-14**). Perhaps the most striking finding to date has been that an abrupt change in the salinity regime of the Bay coincided with the construction of the Flagler railway around 1910, prior to major canal construction in south Florida. With railway construction, passes between the Keys were filled, changing the circulation patterns of the Bay and apparently also changing the Bay's salinity.

In a second study, historical reconstructions of Florida Bay salinity have been made from sediment analyses. These reconstructions are also possible because sediments in a few areas of the Bay were deposited and remain in undisturbed layers that can be dated using several different techniques. Finding

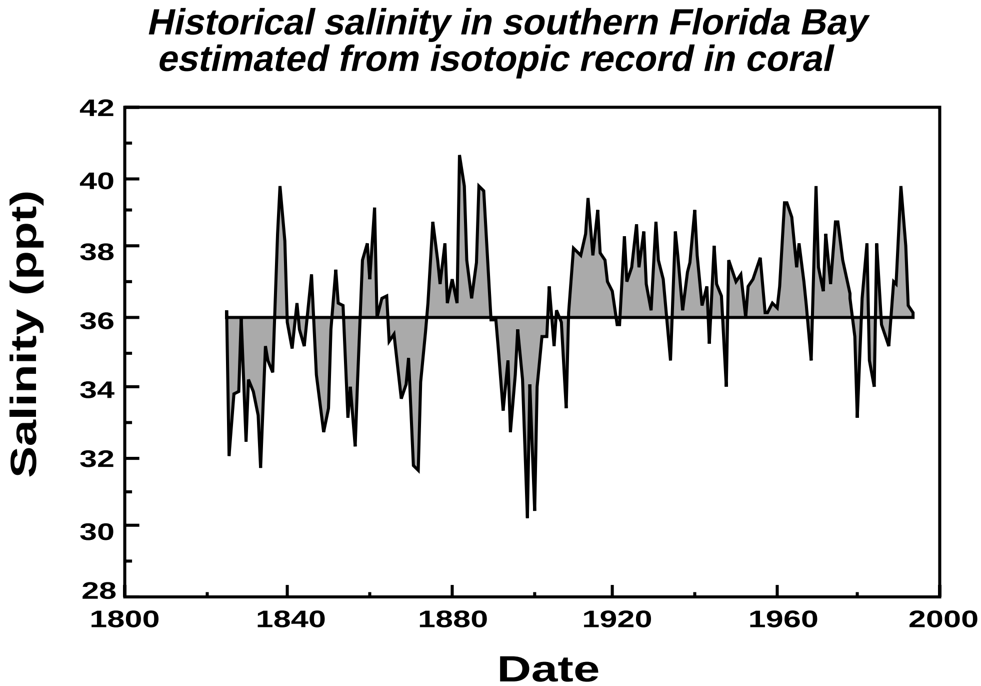

Figure 2-14. Historical salinity of southern Florida Bay for the last 150 years, as estimated by Swart et al. (in press) from the isotopic record of a coral skeleton. This record shows that southern Florida Bay was strongly influenced by the construction of the Flagler Railway around 1910. Salinity in this century has been higher and less variable than during the last century.

these undisturbed areas and confirming the dates of sediment layers required about two years of collecting and analyzing sediment cores from throughout the Bay. An analysis of a suite of environmental indicators of historical salinity is in progress, but preliminary results seem to confirm the results from the coral study. Salinity appears to have increased because of the construction of both the canal system and the Flagler railway.

While these first two studies are estimating past salinities in Florida Bay, a third study (Meeder et al., 1996) has estimated the rate at which freshwater marshes of the southeastern Everglades have become saline marshes. This intrusion of Florida Bay waters into the wetland has been caused not only by a decrease in freshwater inflow, but also by rising sea level. During the past 100 years, the interface of freshwater and saline zones north of Joe Bay and Long Sound have moved northward between 3 and 4 km, while this interface has moved only about 0.5 km into Taylor Slough (**Figure 2-15**). This intrusion of saline waters may be responsible for the decline in Roseate Spoonbill nesting and feeding since the early 1980s (Bjork and Powell, 1993). With Everglades hydrologic restoration, this loss of freshwater marshes is expected to slow or reverse.

Summary of the Ecological Effects of Altered Hydrology

Historical alterations and large-scale development have isolated large segments of original Everglades from the natural system. Davis and Ogden (1994) estimate that more than half of the original Everglades system has been lost to drainage and development. Today, these developed areas support a

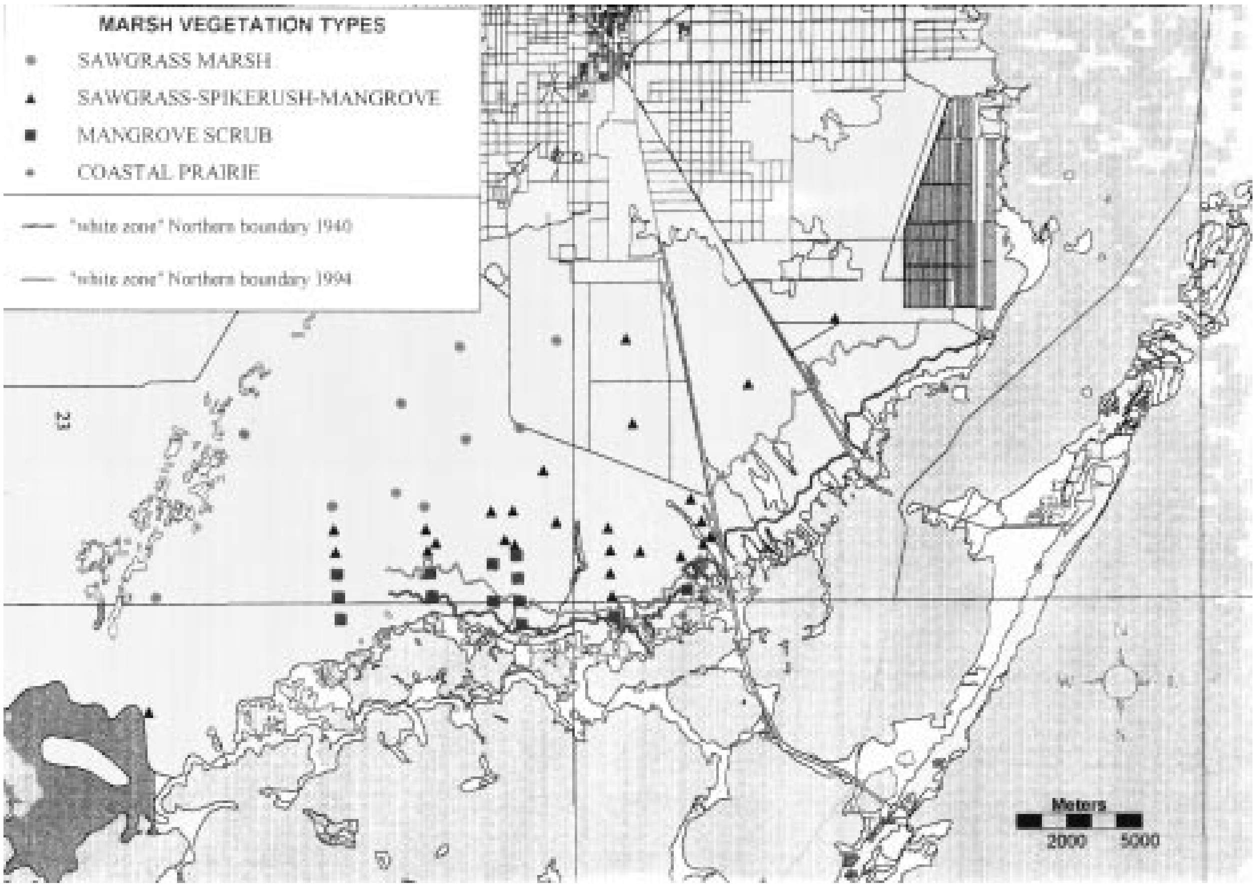

Figure 2-15. Evidence of salt water intrusion into the southern Everglades wetlands, from historical aerial photographs and vegetation surveys. A "white zone" of high reflectance, which is dominated by dwarf mangrove tress, now covers an area that in 1940 had been freshwater marsh, dominated by sawgrass (From Meeder et al., 1996).

variety of land uses, ranging from intensively managed agriculture in the EAA to rapidly spreading urban areas adjacent to WCAs. Together, their impacts on Everglades hydrology have been dramatic and include:

- **Loss of water storage, overland sheet-flow, and spatial extent:** A loss of over 50 percent of the original ecosystem has reduced the water storage capacity of the ecosystem considerably. A loss of the ability to store large volumes of water that slowly moved as sheet flow across the Everglades landscape increases the system's susceptibility to the effects of flood and drought. A reduction of the original ecosystem by half as a result of land development activities has placed a fundamental limitation on its capacity to support populations of wading birds, alligators and panthers that once used the area in much greater numbers (Davis and Ogden, 1994; Science Subgroup 1994; USACE, 1994).
- **Fragmentation of the Everglades:** The historical system has been subdivided by the construction of canals, levees, roads and other facilities and has resulted in the loss of connections between the central Everglades and adjacent transitional wetlands. Everglades wildlife communities and the long-term sustainability of the ecosystem may be impaired by this separation and isolation. Compartmentalization has significantly altered the amount of

sheet-flow. The construction of canals and levees and impoundment of the WCAs have caused overdrainage of some areas and excessive flooding in other areas (USACE, 1994).

- **Changes in timing, distribution and quantity of water:** Altered discharges into, within, and between freshwater wetlands and estuaries have led to the destruction, loss or degradation of native Everglades plant communities and associated wildlife habitat (District, 1992; Davis et al., 1994; Davis and Ogden, 1994) and the timing of Wood Stork nesting (Ogden, 1994; Ogden et al., 1997).
- **Water quality:** (see **Chapters 3** and **4**)
- **Altered fire regimes:** Fire is a natural process (Wright and Heinselman, 1973) that can influence the spread of exotics (Austin, 1976), prevent encroachment of emergent vegetation into sloughs (Forthman, 1973; Hofstetter, 1984), restrict the spread of herbaceous groundcover, (Wade et al., 1980) and influence the expansion of hardwood species into marsh habitats (Duever et al., 1976; Koch, 1996). Fires can be rejuvenating or destructive.
- **Invasion of native plant communities by exotic species:** Species such as melaleuca, Australian pine, and Brazilian pepper have displaced native plants (Bodle et al., 1994) and degraded or destroyed wildlife habitat.
- **Freshwater Discharge to Estuaries:** The quantity, timing and distribution of water discharged from the freshwater areas of the Park and the WCAs downstream to Florida Bay and Biscayne Bay may have contributed to the altered biological integrity of these estuarine ecosystems (Boesch et al., 1993; Bancroft, 1993; Fenemma et al., 1994).

Benefits and Impacts of the Hydropattern Restoration Components of the Everglades Construction Project

A significant factor in the decline of the Everglades ecosystem functions has been the disruption of the system's historic hydrologic characteristics, specifically, the quantity, timing, frequency, and distribution of inflows. Hence, reestablishment of these hydropattern characteristics has been explicitly addressed by constructing Stormwater Treatment Areas (STAs) such that they discharge not only water with reduced P content, but also, discharge water as sheet-flow into areas needing rehydration: WCA-2A, WCA-3A, and the Rotenberger Wildlife Management Area. In a number of scientific and public workshops, the benefits and impacts of the "Current Plan" (i.e., STAs constructed with sheetflow outlets into natural areas), the "No Action" alternative (STAs not built), and the "Bypass" plan (STAs built but effluent diverted in other ways without sheetflow) were evaluated. A full description of these analyses is contained in Appendix M of the 1996 Programmatic Environmental Impact Statement (SFWMD, 1996).

The extent of hydropattern restoration benefits were estimated by comparing simulated hydroperiods for the Current Plan using the South Florida Water Management Model (see SFWMM described below) and the alternative plans with hydroperiod targets suggested by the Natural System Model (see NSM described below). A net improvement of 80,370 acres to the Everglades Protection Area and the Rotenberger Wildlife Management Area was calculated for the Current Plan compared to the alternatives (**Table 2-5**).

Table 2-5. Hydroperiod Benefit Summary (results from South Florida Water Management Model).

AREA	Acres Improved (%)	Acres Worsened (%)	Net Acreage Change (%)
WCA-1 (145,920 acres)	30,720 (21.0%)	0	30,720 (21.0%)
WCA-2A (104,960 acres)	10,240 9.8%)	2,560 (2.4%)	7,680 (7.3%)
North WCA-3A (204,800 acres)	58,880 (28.7%)	46,080 (22.5%)	12,800 (6.2%)
Rotenberger WMA (33,280 acres)	29,170 (100%)	0	29,170 (100%)
Total (488,960 acres)	129,010 (26.6%)	48,640 (9.5%)	80,370 (17.1%)

In addition to evaluating hydropattern benefits, the potential effects of P loads associated with the Current, No Action, and Bypass plans were investigated. For the 8-yr time frame (1999-2006) evaluated, the Current Plan had the least cumulative P discharged to the Everglades Protection Area (731 metric tons), the Bypass options released 765 metric tons (34 metric tons more than the Current Plan), while the No Action alternative resulted in an estimated discharge of 1,515 metric tons of P (785 metric tons more than the Current Plan). The implication of these loads for expanding the area of undesirable cattail, using the Walker and Kadlec (1996) Everglades Phosphorus Gradient Model (EPGM; see **Chapter 3**) and best professional judgement (SFWMD, 1996), determined that by 1/1/2007 the Current Plan could lead to expansion of the local WCA cattail area between 0 and 659 hectares (SFWMD, 1996). Based upon the EPGM, the most likely estimate of cattail expansion was 305 hectares. The majority of this expansion is expected to occur in WCA-2A (236 hectares), and the remaining 69 hectares is expected to occur in WCA-3A and the Rotenberger tract. However, antecedent conditions do play a critical role in determining the extent of impacts, particularly when determining the rate of change in existing emergent macrophyte communities. For example, observations in WCA-2A downstream of the S-10 structures suggest that conversion of desirable vegetation communities to cattails is most likely to occur first in numerous open-water slough communities. Conversion of desirable vegetation communities downstream of STA-2 would probably be less likely due to dense stands of sawgrass and few open water areas.

Information and Techniques for Hydrologic Management

There are at least nine different modeling programs/projects to simulate/evaluate Everglades hydrology and ecology. In this section on technological approaches to the management of hydrologic resources, these nine programs are divided into two groups: static index models and dynamic landscape models. These models will be briefly summarized and discussed in terms of their major features and significant findings. Detailed descriptions can be found in the cited literature.

Static Index Models

Static index models are not models in the true sense of numerical dynamics and computer simulations. They are not differential or analytical equations. Rather, they are ranges, schedules, or targets for hydrologic management that are based upon observations and conceptualizations of reality (Sklar et. al., 1990). They are built from a consensus of experts. There are two significant static index models for Everglades hydrologic management. They are: The River of Grass Evaluation Methodology (ROGEM) and The Criteria for Minimum Flows and Levels.

The River of Grass Evaluation Methodology (ROGEM)

ROGEM was developed by the U.S. Army Corps of Engineers for the Comprehensive Review Study (**Chapter 10**). ROGEM assesses habitat quality for 11 historic landscapes. The 11 landscapes are Lake Okeechobee; St. Lucie Estuary; Caloosahatchee Estuary; Sawgrass Plains; Wet Prairie/Slough; Tree Island; Sawgrass Mosaic; Southern Marl Prairie; Sawgrass Dominated Mosaic; Cypress Swamp; and Florida Bay. ROGEM provides a formula to calculate the Community Suitability Index (CSI) for each type of landscape. The CSI is a qualitative measure of fish and wildlife habitat on a scale of 0 to 1. A value of one indicates the optimum; a hydrologic and environmental condition that supports native species at an abundance that resembles a sustainable, historic level. A value of 0 indicates the least desired habitat condition that will not support sustainable populations of native fish and wildlife. Four groups of variables were combined to produce a CSI: hydrological conditions, water quality, spatial extent of desired habitats, and suitability for exotic species.

The Criteria for Minimum Flows and Levels

The Florida Legislature requires that all water management districts establish minimum flows and levels for surface waters and aquifers within their jurisdiction. Florida Statute 373.042(1) defines the minimum flow as "...the limit at which further withdrawals would be significantly harmful to the water resources or ecology of the area...." Likewise, 373.042 (1) F.S. defines the minimum level as the "...level of ground water in an aquifer and the level of surface water at which further withdrawals would be significantly harmful to the water resources of the area...". The statute directs the water management districts to establish minimum flows and levels based on the best information available.

A draft technical report titled "Proposed Minimum Water Level Criteria for Lake Okeechobee, the Everglades and the Biscayne Aquifer within the South Florida Water Management District" was produced in 1998 by the District. The minimum criteria developed for the Everglades in this report are intended to protect these wetland habitats by preventing the loss of hydric soils (organic peat and marl). The development of these criteria was based on review of the literature and historical water levels, fire histories, and comparison to the Natural System Model (see below). Criteria were developed for both organic peat and marl soils, which together underlie more than 90 percent of the Everglades. The minimum water level criteria developed for hydric soils consisted of three components:

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

- **Frequency of Occurrence:** The average periodicity that ground water levels recede to minimum levels over a prescribed period of time (e.g., once in seven years). If minimum water level conditions recur more often than the stated criteria, the risk of significant harm to wetland wildlife habitat or predator/ prey relationships is greatly increased.

Significant harm was defined as a loss of specific water resource functions that take multiple years to recover and result from a change in surface water or ground water hydrology. For the Everglades, adverse impacts include peat oxidation; increased frequency of severe fires; soil subsidence and loss of hydric soils; loss of dry season aquatic refugia; loss of tree island communities; long-term loss or change in Everglades plant communities; and long-term loss or change in the distribution and abundance of Everglades wildlife communities. Once such changes have occurred, many years, decades or perhaps centuries may be required to restore these resources to their former condition. The criteria for minimum flows and levels, for peat-forming areas of the Everglades is: "*Water levels within wetlands overlying organic peat soils within the WCAs, Rotenberger/ Holeyland WMAs and Shark River Slough (the Park) should not fall 1.0 ft or more below-ground-level for more than 30 days at return frequencies ranging from one in five years to one in seven years depending on location.*" The criteria for minimum flows and levels, for marl-forming areas of the Everglades is: "*Water levels within marl-forming wetlands that are located east and west of Shark River Slough, the Rocky Glades, Taylor Slough and the C-111 basin within the Park should not fall below 1.5 ft. below- ground level for more than 90 days, at a return frequency not more than once in five years.*"

These MFL criteria were based on the rationale that groundwater draw-downs and durations greater than those recommended have the potential to cause harm to hydric soils and associated wetland vegetation and wildlife. According to this model, the following impacts can be expected to occur if the MFL criteria are exceeded:

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

Dynamic Landscape Models

These are numeric temporal simulations (hence the word dynamic) of spatial change (hence the word landscape). At least seven of these types of models deserve to be mentioned (**Table 2-6**) because they will influence USACE plans for Everglades restoration or they can influence District hydrologic management schedules. These seven models differ in terms of their goals, structure, and complexity (**Table 2-6**). The term complexity is used only to create a relative ranking of the modeling approaches based on

Table 2-6. Dynamic landscape models of the Everglades being developed by state and federal agencies, in increasing order of ecological complexity from left to right.

Feature	NSM	SFWMM	EWQM	ELVM	WWQM	ELM	ATLSS
Key variables simulated	Water levels & flows	Water levels & flows	Phosphorus fate & transport	Vegetation type, plant biomass, fire, hurricanes, succession	Water levels & flows, nutrients, plants & algal biomass	Water levels & flows, nutrients, soil, vegetation, type, plant biomass, succession	Trophic dynamics, animal abundance, reproductive potential, plant biomass, succession
Physical system simulated	Pre-drainage Everglades from Lake Istokpoga to Florida Bay	EPA including Lake Okeechobee, Big Cypress, EAA and Lower East Coast urban areas	Everglades Protection Area	Everglades Protection Area	WCA-2A and the Everglades Nutrient Removal Project	Everglades Protection Area and Big Cypress Preserve	Historical Everglades and Big Cypress Preserve
Spatial resolution	4 sq. miles	4 sq. miles	4 sq. miles	1 ha	1.5 ha	1 sq. km	1 ha
Temporal resolution	1 day	1 day or less	1 day	1 day	< 1 hr	0.1-1 day	1 day
Data requirements	Topography, rain, ET vegetation type, seepage	Topography, rain, water management rules, urban & agri. needs, seepage, ET, vegetation type	Hydrologic output from the SFWMM, nutrient inflow conc.	Hydrologic output from the SFWMM, climate, time-series (soil & vegetation)	Topography, rain, hydrologic & nutrient inflows	Topography, climate, boundary conditions from the SFWMM, hydrologic & nutrient inflows	High resolution vegetation maps, output from the SFWMM, physiological parameters, behavioral rules
Purpose	Estimate the hydrologic response of the pre-drainage Everglades to current climate.	Simulate current or proposed hydrologic conditions	Predict P transport & fate; identify P loads that will meet downstream [P] criteria	Simulate vegetation type as a function of hydrologic restoration plans	Identify hydrologic management options for optimizing nutrient retention in STAs	Predict vegetation growth, succession, and water quality impacts associated with plans for hydrologic restoration	Predict animal growth, trophic interactions and reproductive potentials associated with plans for hydrologic restoration
Is the model complete and operational?	Yes	Yes	Yes	WCA-2A: yes EPA: no	Hydrology: yes Nutrients: no	WCA-2A: yes EPA: no	Some species are complete, most are not

Geographic acronyms: WCA = Water Conservation Area; EPA = Everglades Protection Area (all WCAs and ENP); ENP = Everglades National Park; STA = Stormwater Treatment Area
Modeling acronyms: NSM = Natural Systems Model; SFWMM = South Florida Water Management Model; EWQM = Everglades Water Quality Model; Everglades Landscape Vegetation Model; WWQM = Wetland Water Quality Model; ELM = Everglades Landscape Model; ATLSS = Across Trophic Level System Simulation

the complexity of the ecological processes in the model. The Natural Systems Model (NSM), a model of pre-drainage hydrology, is relatively the most simple because it does not include operational rules for water control structures (as in the South Florida Water Management Model) and biogeochemical processes (as in the Everglades Landscape Model). Note that this does not imply that NSM is truly “simple”. All these models take many years to develop, calibrate, and verify. The Across Trophic Level System Simulation (ATLSS), a model of animal distributions and population dynamics, is probably the most complex because it simulates the behaviors of a broad group of animals, requires output from the South Florida Water Management Model, and operates across a very large area at very fine spatial resolutions.

The Natural Systems Model (NSM)

The Natural Systems Model (NSM) is a mathematical model that simulates the hydrologic response of a pre-drainage Everglades system to 1965-1995 climatic data (SFWMD, 1998). The use of recent input data (e.g., rainfall, potential evapotranspiration, tidal and inflow boundaries), allow for meaningful comparisons between the current managed system and the natural system under identical climatic conditions. The complex network of canals, structures and levees in the current system are replaced in the NSM with the rivers, creeks and transverse glades which were present prior to the construction of drainage canals. Infiltration and evapotranspiration (ET) processes simulate vertical movement of water within model cells. The infiltration process simulates the downward movement of water from a ponded water surface to the water table. The overland flow process simulates surface water movement between adjacent cells. Surface elevations in the NSM approximate the pre-drainage topography in south Florida. In general, land surface elevations and aquifer parameters (depth, permeability and soil storage coefficient) are consistent with current land surface elevations, except in areas impacted by soil subsidence. The NSM uses an explicit, finite difference methods to solve the overland and groundwater flow equations. Physical features such as topography, vegetation type and river locations are adjusted to represent the pre-drainage condition. The land-cover used by the NSM is static, i.e. the model does not attempt to simulate water quality or vegetation succession.

The results of the NSM indicate that water moved as sheet-flow from north to south (**Figure 2-16**). The large storage capacity of Lake Okeechobee, coupled with its long overflow perimeter, provided the buffering capacity required to transform large lake inflows from the north into a slow moving (small arrows in **Figure 2-16**), low gradient release to the south. Within the Everglades, the magnitude of the overland flows (length of arrows in **Figure 2-16**) are uniform with a south to southeast direction in the upper/central Everglades. The magnitude of the overland flows begins to increase in what is now WCA-2B. This increased magnitude of overland flows continues from the northern transverse glades south to Shark Slough and southwest toward the Gulf of Mexico.

The results of NSM also indicate that water levels generally fluctuated between 2.0 to 2.5 ft annually, with a somewhat smaller range (1.75 ft) in Lake Okeechobee and Shark Slough (**Figure 2-17**). It indicates that at any given time, water levels were historically uniform throughout the upper and central Everglades and variable in the lower Everglades. Water levels in virtually all of the Everglades dropped below land surface at some point during the simulation. Although much of the Everglades is subject to annual low water levels that drop below land surface, the NSM also indicates that duration of the dry down was on average, very short (**Figure 2-18**).The median number of days of inundation per year (hydroperiod) for the Everglades was generally greater than 330 days/year. Even under very dry conditions, hydroperiods in the upper/central Everglades were generally greater than 150 days/yr and hydroperiods in the Shark Slough still exceeded 335 days/yr.

The South Florida Water Management Model (SFWMM)

The use of the NSM is closely linked to the South Florida Water Management Model (SFWMM). The design of the SFWMM takes into consideration south Florida's unique hydrologic processes and geologic features, including the integrated surface and ground water hydrology and the operation of water control structures. The model simulates the major components of the hydrologic cycle in south Florida

Figure 2-16. Water in the NSM generally moves as surface water slowly from north to south in response to the low land surface water gradient. Flow direction and strength are depicted as arrows (vector). (From SFWMD, 1998)

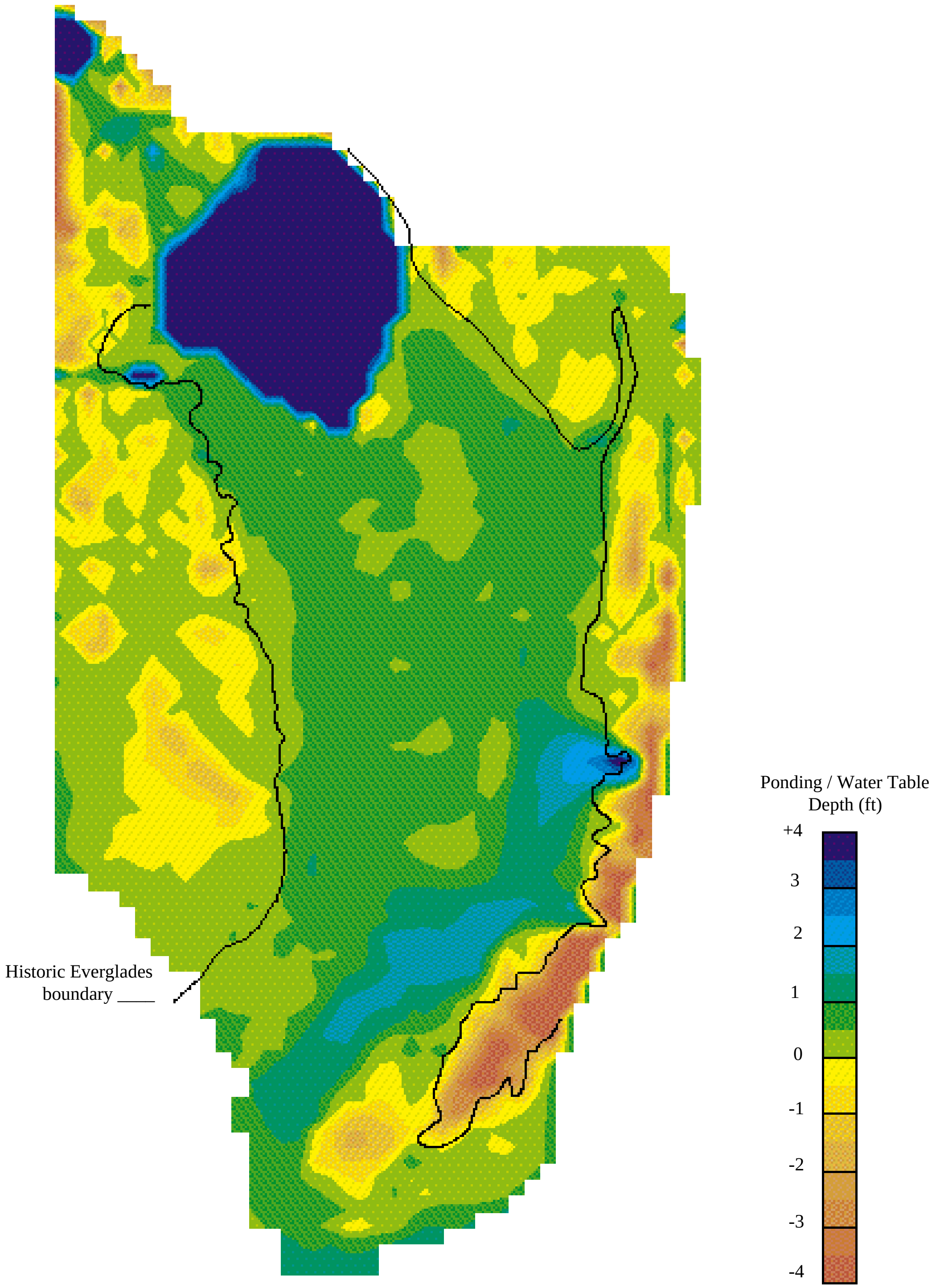

Figure 2-17. According to the NSM, water levels should be uniform throughout the upper and central Everglades with median ponding depths of 0.5 to 1.0 ft. Water levels should be more variable in the lower Everglades with depths up to 4 ft in the northern transverse glades region, 2.0 ft in Shark River Slough, and 0.5 ft above to 0.5 ft below land surface in the marl wetlands in the Park. (From SFWMD, 1998)

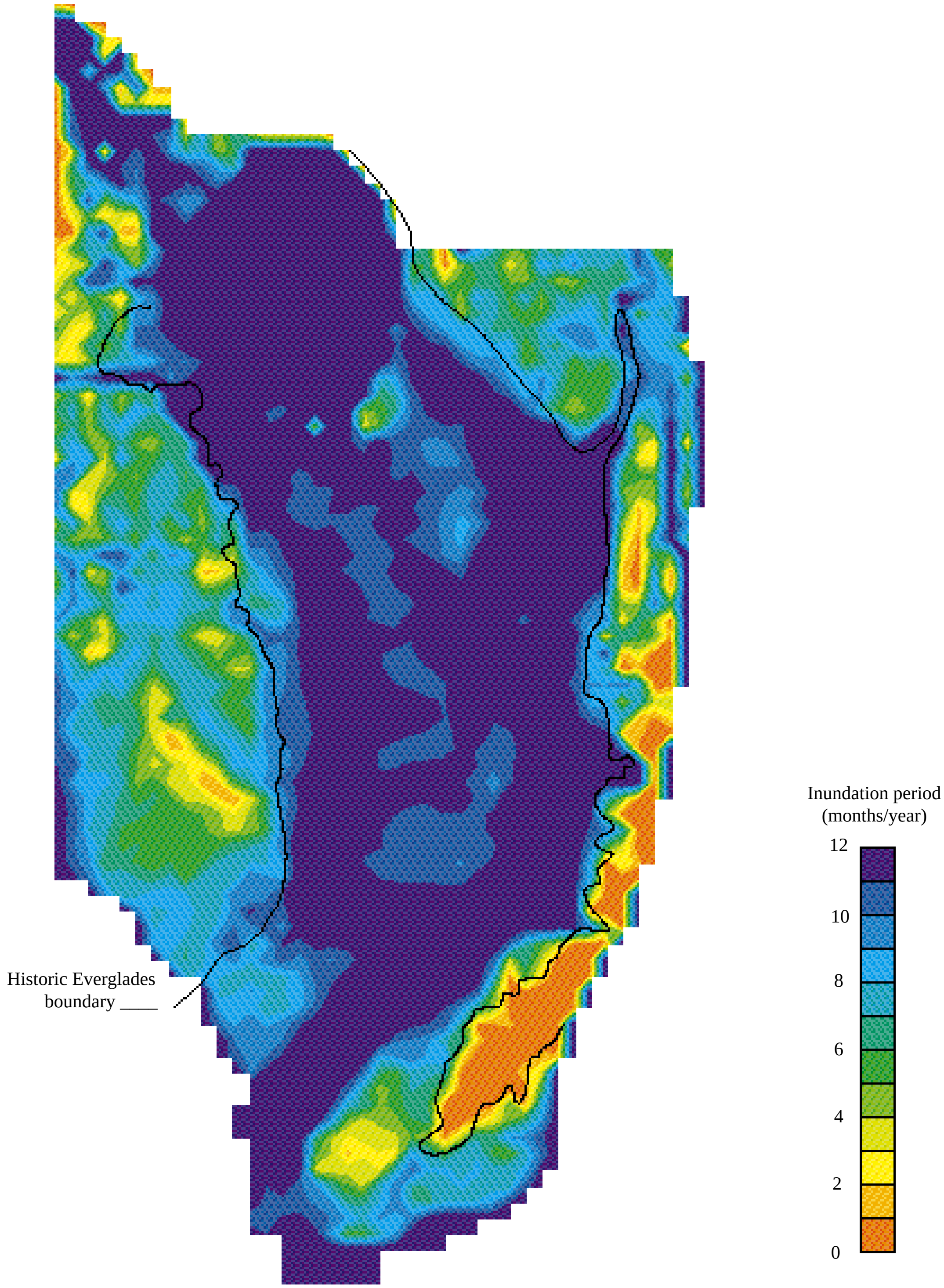

Figure 2-18. Although much of the Everglades is subject to annual low water levels which drop below land surface, according to the NSM the duration of the dry down was very short. The NSM median number of days of inundation per year hydroperiod for the Everglades was generally greater than 330 days/year. (From SFWMD, 1998)

including rainfall, evapotranspiration, infiltration, overland and groundwater flow, canal flow, canal-groundwater seepage, levee seepage and groundwater pumping (MacVicar et al., 1984; SFWMD, 1997). The SFWMM utilizes daily estimated rainfall for each cell interpolated from 671 stations in 10 counties. Daily potential ET was computed for 11 stations using the modified Penman-Monteith Method (Giddings and Restrepo, 1994). Technical staffs of many federal/state/local agencies and public/private interest groups have accepted the SFWMM as the best available tool for analyzing regional-scale structural and/or operational changes to the complex water management system in south Florida. The SFWMM has been used for several studies including:

- USACE Modified Water Deliveries General Design;
- Regional-scale Hydrologic Effects of the Everglades Construction Project;
- Lower East Coast Regional Water Supply Planning effort;
- Lake Okeechobee Regulation Schedule Study;
- C & S Comprehensive Review Study (C&SF Restudy).

The Everglades Water Quality Model (EWQM)

The EWQM adds historical P loading rates to the SFWMM hydrologic flows and levels to simulate downstream P water-column concentrations and P accretion rates. This makes the EWQM only slightly more complex than the SFWMM because the equation used to calculate downstream concentrations is a simple, first-order settling term (see **Chapter 3**).

The Everglades Landscape Vegetation Model (ELVM).

The Everglades Landscape Vegetation Model (ELVM) is a District model for predicting vegetation succession as a function of hydroperiod and water depth. With water and soil nutrient quality as an input, either from the EWQM or from statistical analysis, the ELVM will simulate life cycles of plant communities on a daily basis within a one hectare grid cell. Maps of cattail distribution and tree island distribution in WCA-2A, based on aerial photography, are being used for model calibration and verification. The ELVM does not simulate hydrology. Preliminary runs, using hydroperiod and water stages from the NSM and SFWMM, were made to evaluate ELVMs ability to simulate tree islands. The model simulated tree growth and recruitment starting in 1950, when there was some 50 individual tree islands in WCA-2A (i.e., 1,400 ha). When the model

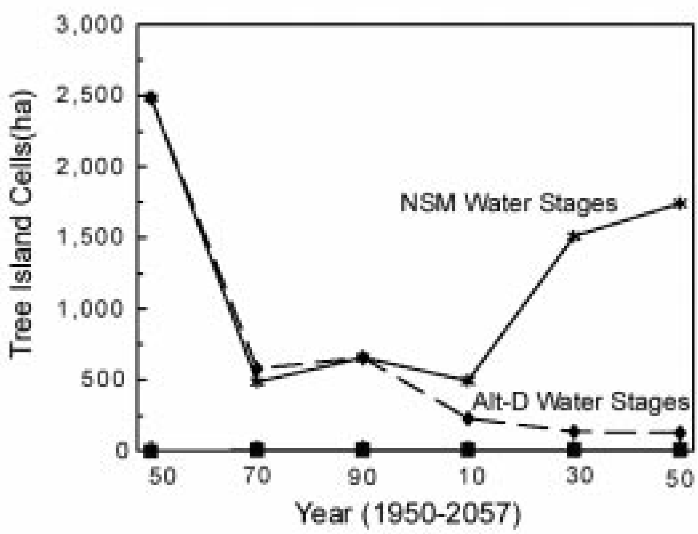

Figure 2-19. A 62-year ELVM simulation predicts WCA-2A tree island survival in the year 2057 as a function of the historic hydrology as predicted by the Natural Systems Model and by Alternative-D, of the USACE Restudy plan for hydrologic restoration.

stopped in 1970, ELVM accurately reproduced the spatial distribution of tree island conversion to marsh habitat (**Figure 2-12**).

The ELVM has been used to conduct preliminary evaluations of different restoration alternatives, although the model is still under final development and has not yet received the benefit of peer review by a scientific journal. According to the present version of the ELVM, Restudy alternatives A through D (alternative D-13R has not been simulated yet) cannot maintain the present tree island configuration in WCA-2A (dash line, **Figure 2-19**) due to hydroperiod conditions that do not favor rejuvenation (seed germination and seedling growth). However, if NSM water stages are provided, more that 60 percent of the tree islands are predicted to rejuvenate within 60 years. Implications for restoration and hydrologic management are: Water stages associated with Restudy plans A through D (alternative D-13R has not been simulated yet) will not help rejuvenate tree islands in WCA-2A to their original 1950s distribution. Using NSM hydrology, it may take about 100 years to rejuvenate 100% of the 1950s tree island distribution in WCA-2A.

The Wetlands Water Quality Model (WWQM

The wetland water quality model-package simulates the interactions between hydrodynamics and biogeochemistry in a wetland environment. The WWQM consists of three submodels; a hydrodynamic model (Hamrick and Moustafa, 1998a&b; Moustafa and Hamrick, 1998), a eutrophication submodel (Fitzpatrick et al., 1998, 1997), and a sediment and nutrient flux submodel (HydroQual, 1989; DiToro et al., 1990). The hydrodynamic submodel predicts velocity, water surface elevation, and temperature on a 5 minutes time scale. The hydrodynamic submodel is capable of simulating three-dimensional unsteady flow through wetlands with dense emergent vegetation and allows for drying and wetting in shallow areas. Transport predicted by the hydrodynamic submodel are used as an input to derive the eutrophication submodel.

The eutrophication submodel incorporates 31 state variables including three periphyton groups (i.e., floating mates, epiphytic, benthic), two vegetation type (i.e., cattail and seagrasses), calcium carbonate, oxygen, and multiple species of carbon, N and P. The eutrophication submodel simulates significant physical, chemical, and biological processes governing nutrient transport and biogeochemistry including: (1) mass transfer of constituents across the water-soil/sediment interface; (2) physical-chemical processes that affect the transport and interaction of nutrients; and (3) physical, chemical, and biological processes governing storage and transformation of organic and inorganic compounds. The eutrophication submodel simulates periphyton as floating and benthic mats. It simulates vegetation as above and below ground sawgrass and cattail biomass. The periphyton and vegetation are coupled to the sediment and nutrient submodel. The sediment and nutrient submodel incorporates detailed equations for sediment depositional fluxes of particulate organic matter from the overlying water, mineralization of particulate organic matter, and the return of nutrients to the overlying water column. The wetland water quality model package was tested and applied to WCA-2A and the ENR Project (see **Chapter 6**). Currently, the wetland water quality model-package is being used to determine the impacts of changing inflow water and P loading rates on P-removal performance at the ENR Project.

The Everglades Landscape Model (ELM)

The ELM simulates interactions among hydrology, chemistry, and biology of the marshes across the landscape and predicts ecosystem behavior in response to changing environmental inputs. This complex model, under development at the District, is the only one of its kind that completely integrates hydrology, ecology, and biogeochemical processes. Details can be found in Fitz et al., (1993) and Fitz and Sklar (in press). To evaluate hydrologic needs and various management alternatives for the Everglades, two spatially explicit versions of ELM are under development -- one for WCA-2A (the Conservation Area Landscape Model or CALM) and the other for the entire Everglades/Big Cypress region (the Everglades Landscape Model or ELM). Both use the same computer code, but the models are applied at different scales.

Periphyton and macrophyte community types in the ELM change in response to long-term water and nutrient supply. The growth and mortality of macrophyte and periphyton communities in the ELM responds to available nutrients, water, sunlight, and temperature. Hydrology, in turn, is linked directly to processes associated with the vegetation, such as resistance to flow and evapotranspiration. Plant uptake, remineralization, sorption, diffusion, and organic soil loss/gain affect P and N in the soil and surface water. Water levels and soil moisture affect these nutrient cycling processes. To date, calibration has focused on WCA-2A, where the most synoptic and experimental data are found, and observed and simulated parameters are well correlated (Fitz and Sklar, in press).

The ELM predicts state changes of these variables, but also incorporates many of the processes associated with these processes. Of the numerous questions that arise when evaluating Everglades ecosystem dynamics, several relate to the interactions among hydrologic and biogeochemical dynamics in the soils. For example, when the water table drops below the soil surface, the unsaturated soil zone becomes more aerobic and thus more favorable for peat oxidation. Subsequent rehydration of the area can potentially increase levels of biologically available P. To determine the effects of reduced hydroperiod on P dynamics, the evapotranspiration (i.e., water loss due to biological and physical processes) was increased. Higher evapotranspiration was used as a surrogate for lower managed water levels, effectively altering the water depths in the region without changing the water control structure, atmospheric inflows, or P loadings. Compared to the reference condition, the lower water table produced a feedback that increased decomposition and soil PO_4 remineralization by as much as 300% (**Figure 2-20**).

Not all of this increased porewater P in the analysis of the above model scenario was due to increased peat decomposition; surface water, and its dissolved nutrients, are advected downward to replace transpired water. Davis (1982) found that more than half the radio-labeled P moved from the surface water to soils in 10 days. A rate too high to be accounted for by diffusion. Thus, high transpiration from macrophytes has the potential to move surface water and its dissolved nutrients into the soil. How significant is this process in making PO_4 available to the root zone? In terms of hydrologic exchange due to downward advection associated with transpiration losses, the ELM found that the time required for the upper 30 cm of the soil water to be completely replaced was as little as three months in cattail sites and several years in sawgrass sites. Thus, depending on the concentration of PO_4 in the surface water relative to that in the soil, this transport mechanism can potentially be a significant source of P to the plant root zone.

The ELM is being used to explore these links of water flows to natural system dynamics. Water losses through evapotranspiration and the friction effects of vegetation on sheet flow are two very sensitive and important processes in determining regional and/or local water budgets. While macrophyte biomass dynamics over short-time scales and limited areas may not significantly influence the total water budget for a region, there is evidence that altered evapotranspiration associated with altered plant communities has the potential to alter water storage (see Root Zone turnover, **Table 2-7**). The simulated difference in

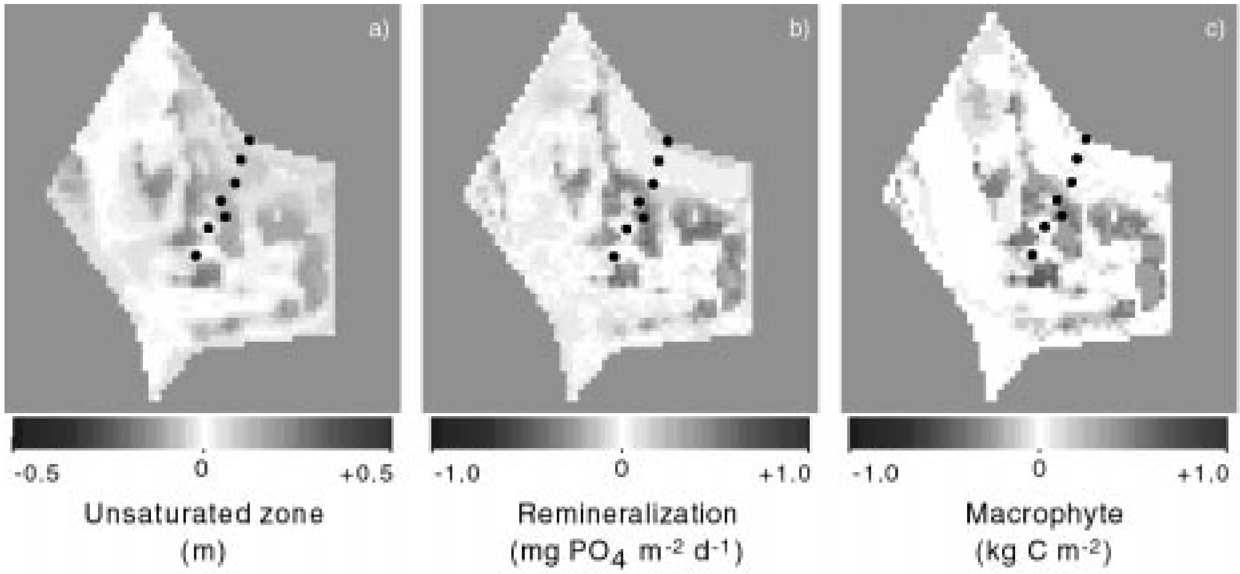

Figure 2-20. Annual mean difference between two 17-year simulation runs of the ELM. A test run with increased evapotranspiration was compared to a nominal run by subtracting the nominal from the test run values, and plotting the differences for one dry year (1989). a) Depth of the zone of unsaturated soil, b) Remineralization rate of PO4 in the soil, and c) Macrophyte total biomass. Dots are data collection sites for calibration.

remineralization rates (**Figure 2-20b**) was as much as 2.5 to 3 times greater in drier regions. Once completed, the ELM will provide a better understanding of these complex interactions and an ecological basis for evaluating the indirect effects of altered water and nutrient flows as they propagate across the landscape.

The Across Trophic Level System Simulation (ATLSS) Program

The National Biological Service, of the U. S. Geological Service, has developed the federal ATLSS program to create models of different animal populations in the Everglades and at some time, in the future, put them all together (DeAngelis et al., 1998). Due to the varying scales at which trophic interactions occur, and the importance of population structure and individual behavior for population prediction in higher trophic level organisms, the use of a single modeling approach was deemed inappropriate. The ATLSS program divides all animal communities into three types of models: 1) process models - for lower trophic levels (including benthic insects, periphyton and zooplankton); 2) structured-population models - for five functional groups of fish and macroinvertebrates; and 3) individual-based models - for large consumers (Wood Storks, Great Blue Herons, White Ibis, American Alligators, White-tailed Deer and Florida Panther). The wood stork and panther models are almost complete (DeAngelis et al., 1998). The wood stork model (Fleming et al., 1994) indicates that the loss or hydrologic alteration of short hydroperiod wetlands can cause a much greater reduction in Wood Stork reproduction than any other habitat. The Panther model (Comiskey et al., 1994; DeAngelis et al., 1998) indicates that ponding depths has a negative impact upon deer fawning (Panther prey). Thus, current hydrologic management in WCA-3A can have a negative impact on long-term panther survival. Spatial scales of resolution for these models will range from 100 m to 1000 m, with the capability of varying the scale as a function of available input data. Recently, some ATLSS models were used to analyze the results of the NSM and the SFWMM, in an assessment of the effects of alternative restoration scenarios on trophic structure (see **Chapter 10**). In the future, ATLSS models will be coupled to the ELM. This new modeling effort, when complete, will likely have a major impact on hydrologic management for endangered, critical, and ubiquitous species of the Everglades.

Table 2-7. Simulated response of year-1 (1980) mean total ET, surface water evaporation and porewater transpiration to varying macrophyte canopy conditions, at a high nutrient site (F1) and a low nutrient site (U3).

Variable	F1-Nominal[a]	F1-Low Canopy[b]	U3-Nominal	U3-Low Canopy
Total ET (mm/d^1)	4.1	3.6	3.6	3.5
Evaporation (mm/d^1)	1.4	2.5	3.0	3.4
Transpiration (mm/d^1)	2.7	1.1	0.6	0.2
Porewater tracer conc.[c] (µg/l^1)	420	190	90	30
Root zone turnover[d] (d)	89	218	400	1200

a. The Nominal condition used the nominal, best estimates of the leaf area index associated with the macrophytes at a high nutrient site (F1) and a low nutrient site (U3) in WCA-2A.
b. The run under the Low Canopy condition used leaf area indices that were 0.5 x Nominal values.
c. The final concentration of a conservative tracer determined the extent to which dissolved constituents were advected from the surface to the pore waters.
d. Root zone turnover is the time required for transpiration and downward advection to completely replace the water volume in the upper 30 cm of soil of a continuously flooded area. (Actual root zone is 35 cm and 30 cm for sawgrass and cattail, respectively).

Information Gaps and Future Research Needs

Florida has now entered an important third phase in the evolution of the Everglades. Although the media will call this the “restoration” phase, it is really more of a “sustainability” phase with restoration of particular components where it is feasible. This Everglades Interim Report summarizes the results of various scientific programs designed to support decision-making, improve sustainability of the current system, and stop the further degradation of the Everglades. Better predictive understanding and increased knowledge of hydrologic assessments to support Everglades sustainability will be obtained if the following topics are pursued.

Understanding sheet flow

Historic connectiveness can never be restored completely since only half of the original Everglades remain and society has spent hundreds of millions of dollars building and maintaining canals and flow control structures. However, the hydrologic flows in the past created an environment that moved at a certain pace. There were no point-sources of water and the ecosystem slowly accumulated peat and marl soils everywhere. The resulting landscape was partitioned into a mosaic of regions that functioned in ways not yet fully understood. The pond apple (*Annona glabra*) forest that once fringed Lake Okeechobee may have functioned as an upstream sediment and nutrient trap for sheet-flow south of the Lake. A more comprehensive landscape approach to managing water requires further study and although the exact mechanisms are not well understood, it is likely that the sheet-flow once present throughout most of the Everglades was a significant ecological driving force.

Understanding the impacts of groundwater

The vertical connectiveness of the Everglades is potentially as important as sheet flow (i.e., horizontal connectiveness). Diffusion, soil porosity, seepage, sink holes and aquifer dynamics are but a few of the complex ground water factors that influence water supply and subsidence for the entire south Florida region. Urbanization and compartmentalization of the Everglades has changed surface and ground water exchanges in ways never before possible. Deep canals, ones that cut through carbonate rock, may serve to bring mineral water up to the surface and distribute it to habitats adapted to soft, low pH, organic water. Little is being done to document these changes and their impacts on deep subsidence, water chemistry, and community structure in the Everglades. This will require a new system for monitoring water quantity and water quality. Wells that measure ground water flows need to be located at water quality stations. Tracer studies should to be implemented to identify areas of hydrologic sinks and sources.

Quantifying flows to Florida Bay

The hydrological restoration of Florida Bay requires information on the amount of freshwater that is now flowing to the Bay and the relationship between salinity levels in the Bay and freshwater flow. For the past three years, the USGS has measured the amount of freshwater flowing into the Bay through the main creeks along the north coast of the Bay. However, there are other sources of freshwater that enter the Bay from the Everglades, including small creeks, overland sheet flow and sub-surface seepage. Estimating this total freshwater input requires hydrological modeling of the southern Everglades and mangrove forest. Furthermore, estimating how any given rate of freshwater input affects the Bay's salinity also requires hydrodynamic modeling. Both wetland hydrological and bay hydrodynamic modeling projects are under way as part of the cooperation interagency science program.

Finally, the hydrological restoration of Florida Bay requires information on the ecological response of the Bay to changing salinity. This not only entails continuing to monitor water quality and biological (e.g. seagrass) changes, but also completing research on the cause and effect relationship between salinity change and the ecological response.

Controlling the spread of invasive species

Scientists know more about the biology of some of the invasive plant species of the Everglades than they do about most of the endemic ones. Nevertheless, more must be done to understand how hydrology may enhance or reduce the many plant species that are encroaching the Everglades.

Restoring natural fire regimes

It is unlikely that the natural ecosystems of the Everglades can be restored without also restoring some semblance of the natural fire regimes. The Everglades is composed of a heterogeneous mosaic of tree islands, shrubs, sawgrass, sloughs and open water. The mixed patches of vegetation, sloughs and open water in the Everglades function as natural fire breaks. Preserving this natural patchiness is critical to maintaining the landscape biodiversity as well as the natural fire regimes. Fire behavior and its role in shaping the structure of each habitat needs to be investigated. Little is known about the importance of crown fires, muck fires and wet season fires. Water managers need to know the long-term impacts of prescribed burns on the vegetation patterns, soil dynamics, and nutrient cycling in the Everglades. It is particularly important that soil dynamics be restored to compensate for soils lost or altered by managing the hydrology. Experiments on interactions among fire, hydrologic soil, and vegetation need to be designed.

Hydrologic impacts on flora and fauna

Recovery of plant and animal communities will require a better understanding of macrophyte and periphyton biology, fish population dynamics, plant-animal interactions, and spatial processes in relation to hydrology. Because of their prominence in setting hydrologic restoration targets, it is critical to identify clearly the effects of hydrology on wading bird feeding and nesting patterns. Large-scale monitoring will provide general trends related to hydrology, but short-term experiments are needed to provide more precise parameter estimates and to support complex simulation models.

Sustaining biodiversity

Tree islands and tropical hammocks are hotspots of biodiversity in the Everglades. They are part of a very heterogeneous landscape. This heterogeneous landscape is an environment where fish, birds, plant seeds and nutrients move from one habitat to another (not all on the same time scale). This movement and the movement of water create natural gradients. However, little is know about these natural gradients and their use by different species. It is known that hydrology can alter the biodiversity of the Everglades. Almost all the tree islands in WCA-2A have disappeared. As a result, local and landscape-scale biodiversity has declined. What are the implications to the greater Everglades and natural gradients? Sustaining biodiversity will require small scale experiments to evaluate how different species are dependent upon certain habitats and large scale computer simulations to evaluate how landscape heterogeneity is dependent upon hydrology.

Findings on Hydrological Needs

- The hydrology of the Everglades Protection Area has been altered fundamentally in quantity, timing, depth and duration.
- Altered hydrology has caused major losses of wetland soils and is fostering the spread of invasive species, such as Brazilian pepper, cattail, and the Old World climbing fern.
- The effects of altered hydrology have been widely documented for Everglades wildlife. A sustainable diversity of biological resources requires a patchwork of hydrological environments across the landscape. However, new information is needed to reduce the uncertainty of ecological predictions for restoration based on hydrology.

- Florida Statutes require minimum flows and levels for water bodies and the District has proposed a depth, duration and return frequency for the Everglades based on the loss of wetland soils.
- The Everglades Construction Project will help restore more natural quantity, timing, depth and duration for water in the EPA. Available information supports the direction being taken by the ECP, the Restudy and the Everglades Stormwater Program. Monitoring with adaptive management and research on hydrological effects are needed to reduce the uncertainty of decisions.

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