A.1 EVERGLADES RIDGE AND SLOUGH CONCEPTUAL ECOLOGICAL MODEL

A.1.1 Model Lead

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A.1.2 Introduction

In its pre-drainage condition, the ridge and slough portion of the Everglades was an expansive, long-hydroperiod, freshwater marsh, characterized by low-velocity "sheet flow", moderate-to-deep organic soils, and alternating sawgrass “ridges” and more open-water “slough” communities (Davis et al. 1994, Gunderson 1994, Gunderson and Loftus 1993, Olmsted and Armentano 1997, Browder and Ogden 1999). The ridge and slough systems were dominated by sawgrass (*Cladium*), water lily, and “wet prairie” species (*Eleocharis* and *Rhynchospora*) communities. A spatially variable mosaic of discreet hardwood hammock, bay head, and willow tree islands occurred throughout, ranging from widely spaced in the central Everglades to more densely distributed in the Loxahatchee basin and Shark River Slough. The ridge and slough system modeled here (Figure A-4) is that portion of the Everglades basin where there are Loxahatchee or Everglades Peat soils (the combined “wet prairie/slough, tree island, sawgrass mosaic” and “sawgrass dominated mosaic” in Davis et al. 1994). The ridge and slough system makes up the deeper central portion of the total Everglades basin. On a much smaller scale, ridge and slough systems occur on both the eastern and western flanks of the Shark Slough in the southern Everglades (e.g., Taylor, East, Middle, Lostman's Sloughs). These sloughs are within the boundaries of the Southern Marl Prairies Conceptual Ecological Model (Section A.2), but are ridge and slough systems, not marl prairie systems. The ridge and slough Everglades was the principal center for primary and secondary production and interannual survival of aquatic organisms in the pre-drainage, freshwater wetlands of southern Florida.

The major, known changes in the ridge and slough systems have been caused by modern land use practices, and by drainage and water management programs in South Florida (Davis and Ogden 1994, Science Subgroup 1993). The stressors resulting from these regional “drivers” include reduced spatial extent, compartmentalization and reduced sheet flow, loss of organic soils, altered water depth, distribution and flow patterns, altered water and soil chemistry, and the introduction of exotic species. It is the effects from these “stressors” that are modeled in the conceptual ecological model for the ridge and slough system.

Figure A-4: The Boundary of the Ridge and Slough Conceptual Ecological Model

A.1.3 External Drivers and Ecological Stressors

During the workshops to develop the Everglades Ridge and Slough Conceptual Ecological Model, four major sources of societal influences (drivers) on the Everglades ridge and slough systems were identified: urban and agricultural expansion, influences from industrial and agricultural practices, water management practices, and cultural influences on species composition. These drivers lead to five major ecosystem stressors: reduced spatial extent, degraded water quality, reduced water storage capacity, compartmentalization, and exotic species. The combined effects from these stressors explain much of the ecological changes that have occurred in the ridge and slough system (Figure A-6, Section A.1.9). The four societal drivers, their respective stressors (bold face in text), and the ecological significance of the prestressed condition in the natural system, are discussed below.

A.1.3.1 Urban and Agricultural Expansion

Drainage of wetlands and the subsequent conversion of ridge and slough habitat into agricultural and urban uses have **reduced the total spatial extent** of the ridge and slough system in the main Everglades from 490,000 hectare in the pre-drainage system to 365,000 hectare in the current system (Davis et al. 1994). Space was the one physical characteristic of the South Florida wetlands that was necessary for all other physical and ecological components of these systems to be in place. The broad spatial extent of the pre-drainage ridge and slough system was essential for collecting and storing the amount of regional rainfall that was required to maintain the ecological vigor of these systems (Davis and Ogden 1994, Ogden et al. 1999). Large spatial extent provided the foundation for the processes that created and maintained a mosaic of habitats in a low profile terrain (Craighead 1971, DeAngelis and White 1994). Disturbances, such as fire, freezes, tropical storms, and animal related impacts (e.g., an abundance of alligator created ponds and trails), served to increase the complexity of habitats, as well as the range of habitat choices for species of wildlife with either small or large home ranges (Craighead 1968, DeAngelis 1994, Duever et al. 1994, Gunderson and Snyder 1994, Davis and Ogden 1994). Extensive space was necessary for supporting robust numbers of animals requiring extensive feeding and hunting ranges during different seasons and a range of hydrological conditions. For example, the location of feeding and nesting sites for white ibis and other wading birds, snail kites, and other common aquatic birds shifted across large spatial scales, across seasons and years, in response to variability in hydrological patterns (Kushlan 1979, Bennetts et al. 1994, Hoffman et al. 1994, Ogden 1994). The large number of ponds and depressions occurring over an extensive region allowed for comparatively sedentary species such as the alligator to maintain very large regional numbers (Craighead 1968). Greater space enabled the system-wide aquatic production in a nutrient-poor ecosystem necessary to support large numbers of wading birds and alligators (Browder 1976, Mazzotti and Brandt 1994).

A.1.3.2 Influences from Industrial and Agricultural Practices

Another stressor on the Everglades ridge and slough system is **degraded water quality**. Increased loads of phosphorus and mercury, originating as by-products from an array of agricultural and urban industrial practices, were identified as the two alterations in water and soil quality that have been demonstrated or hypothesized, respectively, to have had the greatest ecological significance in the ridge and slough systems (Roelke et al. 1991, Spalding and Forrester 1991, Lange et al. 1994, Browder et al. 1994, Davis 1994, Frederick et al. 1997, Fink and Rawlik 2000).

The pre-drainage ridge and slough Everglades was a shallow, clear-water, low nutrient system (Davis et al. 1987, SFWMD 1992). Aside from fire and infrequent frosts, the unique vegetation of the Everglades evolved in response to both low-nutrient water quality conditions and the seasonal fluctuations of water levels. Gleason and Spackman (1974) described a periphyton community in the northeastern Everglades that may be a remnant of a more widespread community prior to the impacts of elevated phosphorus levels. This is a noncalcareous periphyton (less than 10 percent calcium carbonate) community that is rich in desmids, a type of green algae found most abundantly in low-mineral, oligotrophic waters. Although the dynamics of mercury in the pre-drainage Everglades are poorly known, the level of total mercury in Everglades peat soils was about one-sixth the level found during the 1990s (Fink and Rawlik 2000).

A.1.3.3 Water Management Practices

All five of the major ecological stressors acting on the ridge and slough systems, **reduced spatial extent**, the introduction and spread of **degraded water**, **reduced water storage capacity**, **compartmentalization**, and the introduction and spread of **exotic species**, have had part or all of their origins in water management practices. Major objectives of water management have included water supply and flood control, which have been achieved by means of a complex system of structural and operational modifications to the natural system. These modifications have 1) contributed to the substantial reduction in spatial extent, 2) provided a network of canals and levees that have accelerated the spread of degraded water and exotic species, 3) greatly reduced the water storage capacity within the remaining natural system, 4) created an unnatural mosaic of impounded and overdrained marshes in the Water Conservation Areas, and 5) substantially disrupted natural patterns of sheet flow direction, location and volume (SFWMD 1992, Science Subgroup 1993, Davis and Ogden 1994, Light and Dineen 1994, Fennema et al. 1994).

The pre-drainage ridge and slough Everglades was a single, hydrologically integrated system, with water depth and distribution (temporally and spatially) largely determined by seasonal and annual rainfall, evaporation, transpiration, natural topography, outflow through natural streams into the ocean, and the system's capacity for surface and ground water storage of water (SFWMD 1992, Fennema et al. 1994). A key feature of the pre-drainage system was its large water storage capacity for extended periods of time, resulting in a system that was much wetter (but not necessarily deeper) than the current system. Water storage was facilitated by the natural damming effects of the east coast ridge and downstream coastal embankments, the large spatial extent of the system, the sponge-like properties of the peat soils, and the slow flow rates through the extensive marshes. As a result, the pre-drainage Everglades sloughs maintained multiyear surface water hydroperiods throughout the deeper, central marshes and along the downstream, marsh-mangrove ecotone, and extensive, shallow water "edges" that varied both spatially and temporally among seasons and years. The depth, distribution, and duration of surface flooding in this environment largely determined the vegetation patterns, as well as the distribution, abundance and seasonal movements and reproductive dynamics of all of the aquatic and many of the terrestrial animals in the Everglades (Kushlan 1989, Davis and Ogden 1994, Holling et al. 1994, Walters and Gunderson 1994).

A.1.3.4 Cultural Influences on Species Composition

The introduction, both intended and unintended, of large numbers of **exotic species** of plants and animals that have been considered desirable from the perspective of a wide range of human values, has resulted in regions of enhanced recreational fishing, localized shifts in fish community structure, loss of tree island habitat, and changes in marsh plant community structure. These changes are due to the interaction of nonnative species with changes in habitat, water quality, and hydrology. Although large areas of the ridge and slough are still considered "pristine," if current trends continue or if vegetation management funds do not increase there may be substantial impacts locally and regionally to the ridge and slough landscape pattern, food web dynamics, and genetic biodiversity. Cultural impacts condidered most likely to require both monitoring and assessment include a) invasions by *Melaleuca*, *Schinus* and lygodium, and b) the distribution of nonnative fishes (Thayer et al. 2000, Loftus 1990, Loftus and Kushlan 1987, Goodyear 2000).

A.1.4 Ecological Attributes

The Everglades ridge and slough model workshops recommended seven biological attributes of the ridge and slough systems that collectively, will provide the best measure of system responses to restoration projects (Figure A-6, Section A.1.9). The model shows how each attribute is linked to one or more stressors. The recommended measures for each attribute should be treated as priority components for a system-wide ecological monitoring program designed to measure the success of the CERP.

A.1.4.1 Peat Soils

The prevailing soils of the ridge and slough systems are Loxahatchee and Everglades peats, which are hydric soils created by depositions of decayed aquatic plants (e.g., *Nymphaea*, *Pontederia*, *Utricularia*, *Sagittaria*, and *Cladium*). Peats are indicators of prolonged flooding, characterized by 10 to 12 month annual hydroperiods, and ground water that only uncommonly dropped more than one foot below ground surface (Tropical BioIndustries 1990). Soil accretion rates for peats in the pre-drainage system were estimated at 7.5 centimeters per 100 years.

Losses of peat soils of a few centimeters up to a meter have occurred widely in the ridge and slough Everglades, beginning with the earliest water management practices (Stober et al. 1996, Sklar et al. 2000). Shortened hydroperiods and lowered ground water levels in the ridge and slough system have caused extensive desiccation of soils. The overdrained soils have been lost through oxidation, and increased frequencies and intensities of fires (especially during dry seasons). Loss of soils has substantially altered hydrological gradients, microtopography and flow patterns, increased surface concentrations of phosphorus, and contributed to changes in the structure and distribution of plant communities.

A.1.4.2 Periphyton

The species composition of the microalgal mats in the ridge and slough Everglades is broadly controlled by water depth, duration of surface flooding, and water chemistry (Browder et al. 1994). These algal mats are highly important as a food web base, and for oxygenating the water column. Communities of green algae and diatoms may be especially important to periphyton grazers.

Water management practices and changes in water chemistry including increased levels of total phosphorus have changed the spatial distribution and species composition of the periphyton mats (Browder et al. 1994, Davis 1994). Water management practices have shortened hydroperiods in some areas and increased water depths in other areas. Shortened hydroperiods cause a reduction in the proportion of diatoms and green algae, and an increase in calcareous blue-green algae, thus reducing the food value of periphyton, and affecting the overall productivity of the Everglades. In nutrient enriched areas, species characteristic of low-nutrient waters are replaced by filamentous species.

A.1.4.3 Marsh Plant Communities

The pre-drainage Everglades ridge and slough system was a network of discreet sawgrass (*Cladium*) strands (ridges) and more open water sloughs dominated by water lilies (*Nymphaea*), spikerush (*Eleocharis*), and beakrush (*Rhynchospora*) (Gunderson 1994, Gunderson and Loftus 1993). It has been hypothesized that flow volumes in the pre-drainage ridge and slough system were largely responsible for maintaining the sharply discreet community and elevation differences between the ridges and sloughs

(Sklar et al. 2000). The sloughs, deeper than the ridges, were the primary refugia for aquatic animals during dry periods, and were the most important wading bird foraging habitats in the Everglades.

The reduced water storage capacity of the managed Everglades, and the compartmentalization of the northern and central ridge and slough system, have slowed flow rates, have created areas that are either overdrained or are more deeply flooded than was the case in the pre-drainage system, have substantially altered the affects of fire on the marsh communities, and have altered the rates and magnitude of flooding and drying events. As a result, sawgrass has invaded sloughs and wet prairies, beak rush communities have been lost, woody plants have invaded marsh communities, and the extent and species composition of marsh communities has become extensively altered (Kolopinski and Higer 1969, Davis et al. 1994, Sklar et al 2000). Substantial increases in levels of total phosphorus in water and soil have converted both ridge and slough communities into extensive beds of cattails (*Typha*).

A.1.4.4 Tree islands

Discreet hardwood tree and shrub islands are a conspicuous feature of the Everglades ridge and slough system. Depending on elevation, these islands are dominated by swamp hardwoods (e.g., *Acer*, *Salix*, *Persea*, and *Annona*) or upland temperate and tropical species (e.g., *Ficus*, *Celtis*, *Eugenia*, *Mastichodendron*). 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 ridge and slough systems to changes in hydrology (Van der Valk et al. 1998).

Water management practices have substantially impacted Everglades' tree islands (Van der Valk et al. 1998, Sklar et al. 2000). An increase in the frequency and duration of unnatural high water events during wet seasons and an increase in the frequency and intensity of fire during dry seasons has damaged or destroyed many tree islands. The number of tree islands in Water Conservation Area 3 declined from 1,041 to 577 between 1940 and 1995 (Patterson and Finck 1999, Sklar et al. 2000). For this same period, the total spatial extent of tree islands in Water Conservation Area 3 declined by 13,527 acres (61.5 percent).

A.1.4.5 Marsh Fishes, Invertebrates, and Herps

The Everglades ridge and slough systems were the most important centers of secondary production in the freshwater marshes of South Florida. In addition, the deeper, open sloughs were the principal refugia for fishes and aquatic invertebrates during low water periods, and were the places in the Greater Everglades where great numbers of wading birds concentrated to forage during dry seasons (Loftus and Eklund 1994, Hoffman et al. 1989, Kushlan 1986).

The total abundance (numbers and biomass) of fishes, crayfish, grass shrimp, frogs, and turtles in the ridge and slough system has been greatly reduced due to the combined affects of reduced spatial extent of total wetlands, increased frequencies and durations of dryouts in remaining wetlands, altered water recession rates, and possible reductions in secondary production associated with shifts in periphyton composition (Loftus and Eklund 1994, Trexler and Jordan 1999, Browder et al. 1994).

A.1.4.6 Alligators

The American alligator is a keystone species in the Everglades basin. Alligators create trails and ponds that become important wetland corridors and refugia during low water periods. They are top level predators that greatly influence the size classes, distribution, and abundance of marsh animals. Alligators were abundant in the pre-drainage Everglades. Highest numbers and densities in the pre-drainage system apparently were in the broad marl prairies that flanked the southern ridge and slough Everglades, and in the inner, "freshwater" mangrove forest zone downstream from the southern Everglades (Craighead 1968).

In the modern Everglades, alligators are most numerous in the remaining ridge and slough systems (Craighead 1968, Mazzotti and Brandt 1994). It is hypothesized that alligator numbers have been greatly reduced in the marl prairies because of overdrainage and substantially lowered ground water levels (especially during dry seasons). Numbers have been reduced in the lakes and streams of the mainland mangrove forest because of reduced freshwater flow from the Everglades and the resulting higher salinities in these waters. Conversely, alligators may have increased in some portions of the ridge and slough systems (particularly Shark River Slough) where management practices have lowered wet season depths, thereby increasing the extent of suitable, shallowly flooded nesting and foraging habitat. Improved conditions for nesting have not occurred in all portions of the remaining ridge and slough systems, particularly in Water Conservation Areas 2 and 3 where compartmentalization has caused unnaturally deep water in the southern "conservation" areas and overdrained conditions in the northern areas. Alligators have also suffered in the managed system because of increased frequencies of nest flooding caused by impoundments and regulatory flows, reduced survival of juveniles in canals during low water periods, and poor rates of growth and development due to reduced prey populations in overdrained marshes (Jacobsen and Kushlan 1984, Kushlan and Jacobsen 1990).

A.1.4.7 Wading Birds

The large numbers of wading birds that once nested in the Everglades basin was one of the most defining features of the region. The largest and most persistent wading bird nesting colonies in the pre-drainage Everglades were located at the southern edge of the ridge and slough system along the marsh/mangrove ecotone at the lower end of Shark River Slough, and in the downstream mangrove region (Ogden 1994). It is hypothesized that the unusually large "super colonies" (nesting numbers greater than one standard deviation in excess of the long-term annual mean; Frederick and Ogden in press) that periodically formed in the historical Everglades were a response by wading birds to extreme peaks in prey abundance created in the system by the affects of multiyear wet and dry cycles (Frederick and Ogden 2001).

Wading birds in the current managed system have shown a 75 to 90 percent reduction in the number of nesting birds compared to 1930s numbers (primarily by snowy egrets, tricolored herons, white ibis and wood storks), have relocated colonies away from the estuaries and into the impounded central and northern Everglades, and for white ibis and wood storks, have altered the timing of nesting compared to historical patterns (Ogden 1994). The percentage of wading birds nesting in and adjacent to the southern ridge and slough system in southern Everglades National Park has declined from greater than 90 percent during the 1930s to less than 5 percent for 1996-1999 (Gawlik 1999). The vast majority of wading birds now nest in the Water Conservation Areas.

It is hypothesized that the reduction in number of nesting birds is largely due to a substantial decline in the abundance and availability of the aquatic prey base, caused by water management practices that have overdrained substantial portions of the remaining sloughs, and have altered the location, seasonal timing and magnitude of high water and low water events, relative to traditional colony locations. These hydrological changes have served to alter the location and timing of the centers of prey concentrations in the system. For animals such as wading birds, which operate over large spatial scales, compartmentalization and peripheral drainage have combined to convert a single, expansive wetland system into several, much smaller and hydrologically independent systems. Levees and canals have replaced shallowly flooded marsh edges with more deeply flooded marsh along levee slopes.

A.1.5 Ecological Effects
Critical Linkages between Stressors and Attributes/Working Hypotheses

The ecological effects of the five principle stressors in the Everglades Ridge and Slough Conceptual Ecological Model are based on seven key hypotheses developed during the conceptual ecological model workshops. These hypotheses build on earlier Everglades' hypotheses presented in Davis and Ogden (1994) and Ogden et al. (1999). These seven hypotheses determine the content and organization of the Everglades Ridge and Slough Conceptual Ecological Model. The seven hypotheses are presented here, organized by stressor.

A.1.5.1 Reduced Water Storage Capacity

The ridge and slough Everglades has lost much of its original capacity to store natural volumes of water due to the reduction in the spatial extent of marshes. Two hypotheses have been developed for this effect.

Wet Season

Greater than historical (pre-drainage) water depths occur in the ridge and slough system when the spatial extent of natural wetlands (and of man-made water storage areas) is insufficient to hold and distribute the wet season and/or wet year volumes of water that enter the system either as rain or surface flow. As a result of this reduction in region-wide storage capacity, water becomes “stacked” to unnatural depths in the marshes during wet seasons and wet years. Increased wet season/wet year depths leads to flooding of tree islands, loss of shallow feeding habitat for wading birds, altered and stressed periphyton communities (reduced light penetration), flooding of alligator nests and reduced quality of alligator feeding conditions, and altered species composition and size classes of fishes.

Dry Season

Greater than historical (pre-drainage) frequencies and durations of marsh dryouts occur in the ridge and slough system when the spatial extent of natural wetlands (and of man-made water storage areas) is insufficient to hold the wet season and wet year accumulations of water into the following dry season and dry years, respectively. As a result, water is not available to maintain marsh and ground water levels during dry periods. Increased frequencies and durations of dryout leads to increased rates of loss of organic soils due to increased fire and oxidation, spread of woody vegetation into marshes, reduced survival of fishes, small herps, and aquatic invertebrates, altered periphyton communities (diatoms/greens to blue-greens), reduced alligator nesting effort (dry marshes during courtship period), and expansion of sawgrass into slough communities (i.e., a degradation of the discreet ridge/slough mosaics).

A.1.5.2 Compartmentalization

The ridge and slough Everglades have been converted from a single, hydrologically integrated ecosystem to a collection of hydrologically independent systems (SCT 2003). This change was brought about by the current network of internal levees and canals, and the water management operational criteria that were established for each discreet compartment. Two hypotheses have been developed for this effect.

Effects of Levees

Internal levees have disrupted the directions, timing and rates of sheet flow, and have created mosaics of shallowly and deeply flooded marshes that are unnatural in location, juxtaposition, and in the duration and depths of flooding. Reduced rates of sheet flow have contributed to the leveling of pre-drainage ridge and slough topography and the loss of large amounts of open slough habitats. Ponding, in place of the strong seasonal and multiyear differences in flow rates and volumes that once characterized the interior Everglades, has disrupted the dynamics of cycling and transport of natural nutrients, and has substantially reduced the levels of primary and secondary production in the system. The patchwork of overdrained and overflooded marshes has changed the locations and times when and where aquatic animals operate in the Everglades. Wading bird nesting colonies have moved away from the traditional estuarine locations, and have relocated around the less productive pools that have been created in each impoundment.

Effects of Canals

Internal and peripheral canals have altered the timing of water movement through the Everglades, and have created unnatural deep water corridors and habitats in many formally shallow water marshes. Increased rates of water movement in canals have substantially increased the rates of change in the depth of water in the marshes, and have altered the timing and duration of high water and low water events. These hydrological changes, in turn, have stressed many aspects of animal reproductive cycles (e.g., rapid increases in depth have flooded everything from alligator nests to apple snail egg clusters; rapid reductions in depth lead to longer periods of marsh dryout and reduced survival by aquatic animals). Deep-water corridors have degraded water quality by introducing nutrients and toxins into the interior marshes, and have reduced the amount of water that moves through the marshes as sheet flow. Deep-water corridors and habitats have altered the dynamics and sizes of alligators and fishes, and have opened up much of the Everglades to invasions by exotic fishes.

A.1.5.3 Exotic (Nonnative) Species

Exotic plants have invaded marsh and tree island communities in the ridge and slough Everglades, resulting in substantial shifts in species composition and community structure, and, where exotic plants have formed dense "stands," have reduced habitat diversity (e.g., where *Schinus, Melaleuca*, and *Lygodium* have invaded tree islands). The introduction and spread of nonnative fishes into localized habitats of the Everglades marshes may alter the dynamics of marsh fish communities, foraging behavior of wading birds, or genetic biodiversity. The CERP assumes a "precautionary conservation" approach in this regard. That is, nonnative animal introductions are not targets for restoration and are assumed to have negative impacts unless monitoring data can prove otherwise.

A.1.5.4 Reduced Habitat Extent

The spatial extent of the ridge and slough Everglades has been reduced from an estimated 490,000 hectare in the pre-drainage system to 365,000 hectare in the current system (a loss of 25 percent). The large extent and comparatively longer hydroperiods that characterized the original ridge and slough system made it the major center for total secondary production in the freshwater Everglades, and the most important refugia for the survival of aquatic animals during dry seasons and years. The reduced extent of this habitat type has 1) substantially reduced the number of options for where animals with large feeding ranges can find suitable foraging sites (e.g., wading birds and snail kites), 2) lowered the overall amount of aquatic production in a naturally, nutrient-poor environment, where space may have been essential for producing the total biomass of prey necessary to support large numbers of higher vertebrates, and 3) eliminated large areas of long-hydroperiod habitat that kept many fishes and aquatic invertebrates alive during dry periods.

A.1.5.5 Degraded Water and Soil Quality

The pre-drainage ridge and slough system was characterized by clear, clean water; low levels of nutrients; and a periphyton community dominated by species of green algae and diatoms. Slower flow rates, unnatural patterns of ponding and overdrainage, and the addition of excess nutrients and toxins, have greatly altered the water and soil chemistry of the Everglades sloughs. Soil oxidation has resulted in increases in surface concentrations of phosphorus. Excess nutrients have contributed to the conversion of extensive strands and patches of sawgrass into dense cattail “plains,” resulting in the loss of plant diversity and a reduction in the extent of useable wildlife habitat (e.g., for foraging wading birds). The increased nutrient loadings also have shifted the dominance of periphyton communities to species of blue-greens, resulting in considerable disruption in aquatic food chains. Toxins such as methylmercury have killed individual animals, and may be causing behavioral changes that interfere with the reproductive success and long-term rates of survival by many aquatic vertebrates.

A.1.5.6 Critical Ecological Linkages

The seven key hypotheses described above are converted into four critical ecological pathways in the Ridge and Slough Conceptual Ecological Model. These pathways show that the principal, broad-scale ecological responses from the combined affects of the five major ecosystem stressors acting on the ridge and slough systems have been 1) a substantial alteration and degradation in the natural patterns of plant community composition and structure and 2) substantial changes in the distribution, and reductions in abundance, among many of the native animals that are dependant on aquatic habitats and food chains. The relative contribution made by each of the stressors, along the different pathways to these two primary responses is not well known. For example, the presence of physical and biological thresholds, some of which may have been crossed as a result of the affects of the stressors, have yet to be demonstrated for most functions and relationships in the sloughs (an exception might be the 10 parts per billion value for phosphorus). Never-the-less, current understandings of the ridge and slough systems, as expressed by the conceptual ecological model workshop participants, suggest that these four ecological pathways have been most important for explaining how these two broad-scale, ecological responses have been linked to the stressors. These four pathways are as follows:

- The pathway that links the reduction in water storage capacity and the substantial increase in the extent and frequency of overdrained marshes (shortened hydroperiods), with an array of ecological effects characterized by a spread in woody vegetation, reduced numbers of nesting alligators, reduced marsh production, reduced dry season survival by aquatic organisms, and the loss of peat soils.

- The pathway that links compartmentalization, and the adverse affects that levees have on water depth/distribution patterns and sheet flow, with altered patterns of nutrient cycling and reduced marsh production, and relocated animal distribution, production and survival centers.

- The pathway that links the reduction in water storage capacity, compartmentalization and the adverse affects of regulatory releases, with flooded tree islands and flooded alligator nests.

- The duel pathways that link degraded water quality and the effects of canals with increased phosphorus loading, resulting in the spread of cattail monocultures, degraded periphyton communities, and reduced marsh production.

A.1.6 Research Questions

Key uncertainties regarding causal relationships in the Everglades Ridge and Slough Conceptual Ecological Model need to be researched. The recommended research to support this conceptual ecological model is discussed in this section.

Causal Factors Determining the Spatial Coverage, Directionality and Persistence of Sawgrass Ridges, Sloughs, and Tree Islands in the Landscape

How do hydrology and fire interact to sustain the spatial coverage, directionality and coexistence of sawgrass ridges, sloughs, and tree islands that characterized pre-drainage landscapes? What are the respective roles of hydrologic variables and fire as causal factors that sustain discreet, directional slough systems and prevent encroachment by sawgrass? What are the respective roles of hydrologic variables and fire as causal factors that sustain viable tree islands and prevent drowning under high-water conditions and burn-out under low-water conditions? What are the potential impacts and eradication technologies for *Lygodium* spread on tree islands?

Prevention and Reversal of Cattail Spread under Conditions of Elevated Soil Phosphorus in Nutrient-Enriched and Nonenriched Areas in the Landscape

In nutrient-enriched areas of the ridge and slough landscape, how can current trends of cattail expansion be reversed once phosphorus inputs are reduced? In overdrained, nonenriched areas of the ridge and slough landscape, how can elevated phosphorus concentrations in the subsided peat be sequestered in forms that are unavailable for cattail growth upon the recovery of more natural hydropatterns?

Functional Role of Periphyton Mats in Driving Food Webs

How are populations of marsh fishes and other aquatic fauna related to the spatial cover, primary productivity, and taxonomic composition of periphyton mats?

Functional Importance of Crayfish in Everglades Food Webs

What is the functional importance of the crayfish as an intermediate trophic level and prey base supporting higher consumers, in that the former abundance of white ibis and otter suggests that the Everglades was dominated by a crayfish-based food chain? How are crayfish population density and taxonomic composition related to annual and interannual patterns in hydroperiod and depth, including droughts?

Causal Factors Related to the Formation of Wading Bird Super Colonies

What triggers the formation of super colonies of white ibis and other wading birds after major droughts following multiyear hydroperiods? What are the functional contributions and interrelationships of pulsed nutrient releases, reduction in numbers of predatory fishes, and spikes in abundance of small aquatic prey (particularly crayfish) in supporting super colony formation?

A.1.7 Hydrologic Performance Measures

The four critical pathways (above) suggested by the Everglades Ridge and Slough Conceptual Ecological Model are largely driven by hydrological stressors (**reduced extent of wetlands**, **degraded water quality**, **reduced water storage capacity**, and **compartmentalization**). These pathways suggest that the need for four high priority hydrological restoration targets for meeting the ecological objectives of the CERP.

A.1.7.1 Hydropatterns

The performance measure for hydropatterns includes hydroperiod, water depth and depth-duration patterns, and sheet flow. The targets for each of these aspects of the performance measure are discussed below.

For hydroperiod, the target is the reestablishment of pre-drainage, as depicted by the Natural System Model (NSM), annual and multiyear patterns in the duration of uninterrupted surface flooding in Everglades National Park and the Water Conservation Areas. The frequency, duration, extent and magnitude of marsh dry outs must be reduced. Included in this target is an increase in duration of flooding in the overdrained, northern ends of the Water Conservation Areas without an increase in unnatural flooding in the southern Water Conservation Areas, and a recovery of the pre-drainage patterns of multiyear hydroperiods in Shark River Slough.

The target for water depth and depth-duration patterns is the recovery of more natural water depth and depth/distribution patterns throughout the ridge and slough systems. This includes the elimination of both overdrainage of the northern portions of the Water Conservation Areas and overflooding of the southern portions of the Water Conservation Areas.

For sheet flow, the target is the recovery of natural patterns in the volume and direction of sheet flow throughout the ridge and slough systems. This includes eliminating or reducing unnatural ponding, and altering patterns of volume and direction of marsh flow.

A.1.8 Ecological Performance Measures

A.1.8.1 Peat Soils

The performance measure for peat soils is accretion rate. The recovery of a peat-accreting system throughout the Everglades ridge and slough should be the short-term restoration target. Included in this target are the recovery of peat accretion in portions of the sloughs where overdrainage has converted soil production from peats to marls (e.g., northeastern Shark River Slough), and the minimization of anthropogenic enrichment of soils. The long-term target is the recovery of pre-drainage soil depth and microtopography contour patterns.

A.1.8.2 Periphyton

The performance measure for periphyton is community composition, distribution and productivity. The restoration target for periphyton is to increase mat cover, biovolume, organic content, and percent noncalcareous algae and diatom composition. Measures of species composition can be used to reflect improvements in water and soil chemistry, and in hydroperiod and depth parameters.

A.1.8.3 Marsh Plant Communities

The performance measures for marsh plant communities are community distribution, proportions, and composition. The long-term restoration targets for marsh plant communities are 1) recover, at a system-wide scale, the expected mosaics and spatial and temporal dynamics of the marsh communities, as should occur with natural patterns of hydrology, fire and soils; 2) decrease the proportion and extent of sawgrass, where sawgrass has invaded slough and wet prairie habitats; and 3) reestablish spatial patterns of ridge and slough communities by restoring pre-drainage flow directionality and volumes. The short-term goal for cattails and exotic plants is to minimize the invasions of these species into ridge and slough communities. The long-term goal for cattails is to eliminate large, monotypic stands.

A.1.8.4 Tree Islands

The performance measures for tree islands are distribution, size and composition. The restoration targets for the ridge and slough tree islands are as follows:

- Prevent any further net loss in the extent and quality of tree islands, using the following criteria: 1) landscape distribution and spatial extent, 2) vegetation community composition, 3) habitat value and ecological function, and 4) geomorphology, including accretion, shape, elevation profile and orientation

- Recover lost tree island habitat where natural elevation rises are preserved, and where natural patterns of succession would be expected, using the above four criteria as measures of recovery

- Recover a more natural mosaic of tree island types across the landscape

A.1.8.5 Marsh Fishes and Invertebrates and Herps

The performance measures for marsh fishes and invertebrates and herps are community composition, size distribution and abundance. The following targets have been established:

- Recover multiyear patterns of fish dynamics, including multiyear increases in marsh fish numbers and biomass, to levels comparable to those measured in Shark River Slough following multiyear, uninterrupted hydroperiods
- Increase densities of the pig frog (Rana grylio) in portions of the ridge and slough system where hydroperiods have been unnaturally reduced to densities comparable to those found in remaining long-hydroperiod marshes
- Increase density of apple snails (Pomacea)
- Increase the size range in biomass and length distributions of marsh fishes
- Increase the relative of abundance of centrarchids and chubsuckers
- Increase the frequency of the species of crayfish typical of long hydroperiod marshes (Procambarus fallax) in relation to the species more characteristic of shorter hydroperiod marshes (P. alleni)
- Maintain the current low frequencies of exotic fishes in the interior ridge and slough system
- Reduce levels of mercury and other toxins in marsh fishes

A.1.8.6 Alligator

The performance measures for alligators are abundance, distribution, nest success, and occupied holes. The targets for alligators in the Everglades ridge and slough system are as follows:

- Shift the highest densities of nests in Everglades National Park from the center to the edges and downstream portions of Shark River Slough
- Establish more uniform density and distribution of alligators, occupied holes, and nests in the Water Conservation Areas
- Improve the overall “health” of alligators in Shark River Slough and the central/southern Water Conservation Areas and establish baselines for contaminant loadings for alligators
- Increase alligator reproduction rates in Shark River Slough and the central and southern Water Conservation Areas, as measured by 1) the frequency of alligator nesting, 2) the frequency of hatching, and 3) the survival of hatchlings
- Decrease the incidence of nest flooding caused by wet season regulatory releases and other water management practices in the Shark River Slough and Water Conservation Areas
- Increase the proportion of juveniles size classes in the total alligator population

A.1.8.7 Wading Birds

The performance measures for wading birds are the abundance, location, and timing of colonies, and the return frequency of super colonies. The targets are 1) increase in total number of wading birds nesting in and adjacent to the ridge and slough Everglades to those proposed by Ogden et al. (1997); 2) substantially increase the proportion of the total birds that nest in the area of the southern Everglades marsh-mangrove ecotone; 3) reestablish historical (1920s-1960s) timing patterns for nesting wading birds, especially for the wood stork and white ibis; and 4) return super colonies to the system at a return frequency of 1 to 2 events per decade. To recover their historical size, super colonies should occur in the headwaters' ecotone at the lower end of Shark River Slough. Super colonies may be the best indicators of the effects of natural hydrologic variability in the system.

The size, timing, and location of wading bird nesting colonies, as well as the occurrence and frequency of "super colonies", should reflect improvements in foraging habitat options under a range of climatological conditions. The quality of foraging habitat depends upon marsh production rates, survival rates of marsh organisms during dry periods, and the location of the major production and survival centers in the slough systems. Protective criteria need to be established for contaminant levels in sediment and water that result in no negative impact to wading birds.

A.1.9 Model

The diagram for the Everglades Ridge and Slough Conceptual Ecological Model is presented in Figure A-5. The key to the symbols used in the diagram is presented in Figure A-6.

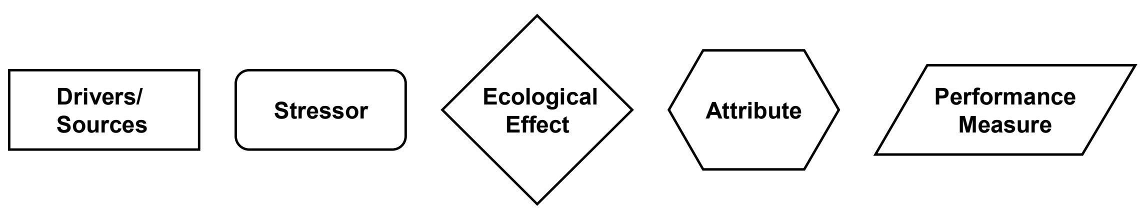

Figure A-5: Key to the Symbols Used in the Following Diagram

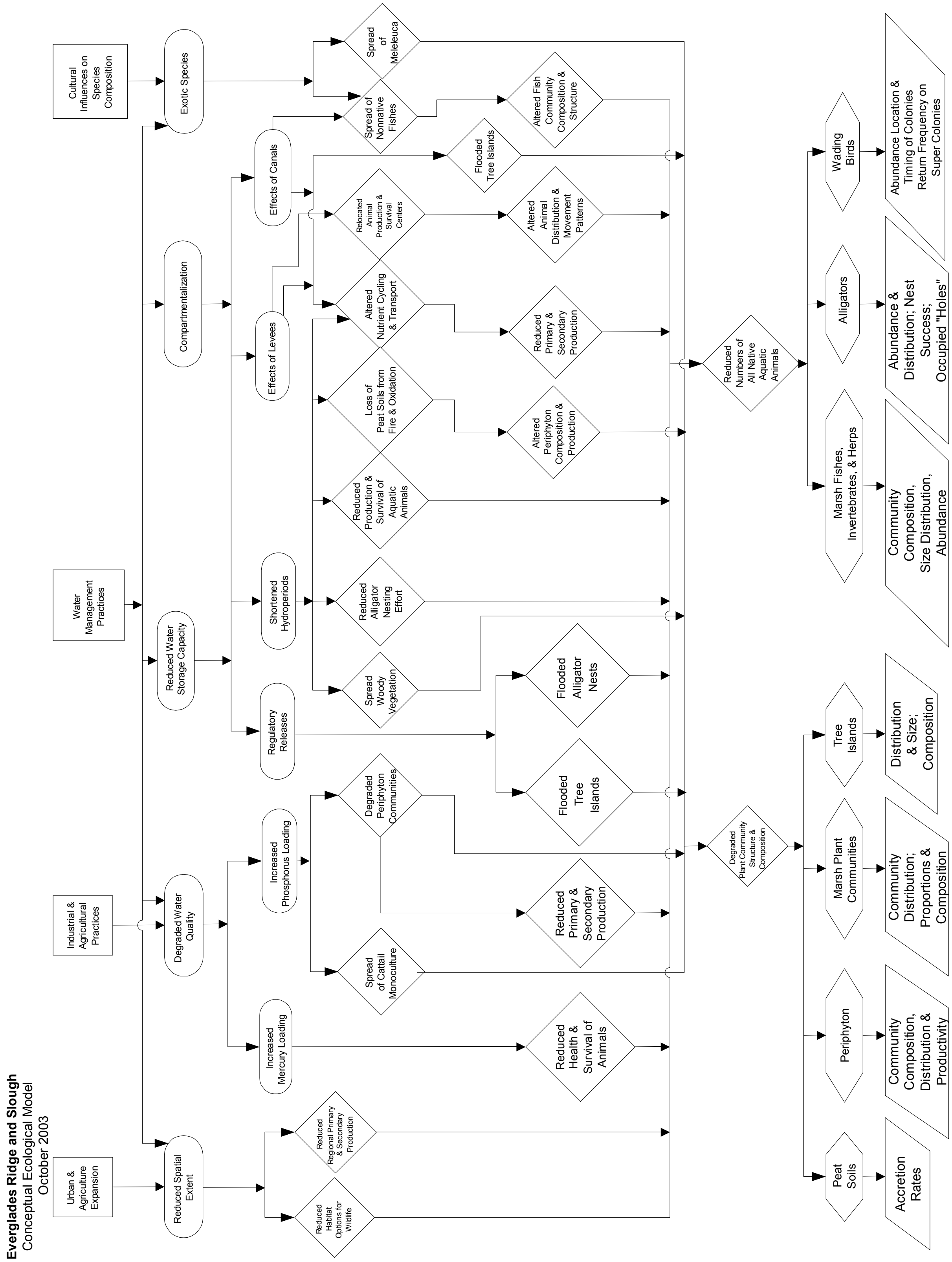

Figure A-6: Everglades Ridge and Slough Conceptual Ecological Model Diagram

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A.2 SOUTHERN MARL PRAIRIES CONCEPTUAL ECOLOGICAL MODEL

A.2.1 Model Lead

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A.2.2 Introduction

About 190,000 hectares of higher-elevation, freshwater marshes are found on either side of Shark River Slough (Figure A-7). In these systems, water levels typically drop below the ground surface each year (Davis et al. 1994). Consequently peat accretion is inhibited, and substrates consist either of marl produced by periphyton mats, or exposed limestone bedrock (Gleason 1972).

Marl prairies are mosaics of wet prairie, sawgrass, tree island, and tropical hammock communities that support a high diversity of plant species (Olmstead and Loope 1984). A separate landscape, called the rocky glades, occurs at slightly higher elevations than the marl prairies. The rocky glades are characterized by shorter hydroperiods and exposed karst formations of limestone and solution holes. Deposits of marl and organic sediments are limited to the solution holes in the rocky glades. The southern marl prairies to the east of Shark River Slough comprise the watershed for Taylor Slough, a lower-elevation waterway that meanders through the higher-elevation marl prairie south of Long Pine Key, becoming the Taylor River that flows into Little Madeira Bay. Peat deposits and more aquatic plant communities in Taylor Slough indicate prolonged periods of inundation compared to its surrounding marl prairie-rocky glade watershed. The narrow ribbon of slough flowing through more extensive higher-elevation marshes is not amenable to modeling at the 2-by-2 mile grid scale of the regional models used to simulate Comprehensive Everglades Restoration Plan (CERP) scenarios, thus hydrologic performance measures for Taylor Slough require finer-scale models currently under development.

The ephemeral hydrologic characteristics of the southern marl prairies pose stresses to the wetland animal communities regarding survival through the dry season when standing water is usually absent (Loftus and Eklund 1994, Loftus et al. 1990). In that respect, the American alligator represents a keystone species in the southern marl prairies as alligator holes provide important refugia for aquatic fauna during dry periods (Craighead 1968).

Figure A-7: The Boundary of the Southern Marl Prairies Conceptual Ecological Model

A.2.3 External Drivers and Ecological Stressors

The two major sources of societal influences (drivers) on the southern marl prairies are water management practices and agricultural and urban development (Figure A-9, Section A.2.9). The introduction of exotic plants and burning practices exacerbated by compartmentalization also, to a lesser extent, drive the southern marl prairies system. These drivers lead to eight major ecosystem stressors: 1) loss of spatial extent, 2) shortened hydroperiod, 3) increased drought severity, 4) wet season water level reversals, 5) drying pattern reversals, 6) compartmentalization, 7) expansion of exotic plants, and 8) high intensity dry season fires. In Figure A-9, the first four of these stressors are combined under an altered hydropattern stressor. These altered hydropattern stressors and their cooresponding effects and attributes are shown in detail in Figure A-10 (Section A.2.9). The two main societal drivers and their respective stressors are summarized in the next few paragraphs. The stressors are then discussed in more detail in the following subsections (A.2.3.1 through A.2.3.8).

Agricultural and urban development represents a direct loss of spatial extent of the southern marl prairie wetlands through conversion of marshes to farmland and housing (Davis et al. 1994). Development of eastern portions of the southern marl prairies has reduced the spatial extent of these landscapes and has cut off portions of the Taylor Slough watershed. The connectivity of the southern marl prairies to upland habitats has been broken by the development of the eastern portions of these wetlands and of most of the Miami rock ridge. The lost spatial extent and connectivity to uplands on the eastern side of the southern marl prairies cannot be restored on a large scale and must influence expectations for ecosystem restoration.

The water management system that controls flooding in the eastern, developed parts of the southern marl prairies has altered hydropatterns of the remaining wetlands primarily through the lowering of water tables and through the unseasonable regulatory release of water from upstream (Van Lent et al. 1993). A network of canals, levees and roads, particularly the C-111 system, United States Highway 1 (US 1), and Card Sound Road, have compartmentalized the remaining southern marl prairie wetlands. The compartmentalization has geographically altered hydrologic patterns, particularly in the Model Lands area between US 1 and Card Sound Road. The canals and pump stations, in addition to draining wetland areas, are conduits for potential inputs of nutrients, mercury, other toxins, and for the introduction of exotic fishes into the remaining wetland system.

The southern marl prairies to the west of Shark River Slough are geographically isolated from the human population centers of Florida's lower east coast. Consequently, these wetlands have escaped the development, compartmentalization and lowered water table stressors of their eastern counterparts. To the contrary, the western marl prairies are negatively impacted by extended flooding. Water that once flowed eastward into Northeast Shark River Slough is presently diverted to the west through the S-12 A and B discharge gates of Water Conservation Area 3A, resulting in lengthened hydroperiods in the western marl prairies. The extended flooding is exacerbated by drying pattern reversals caused by regulatory water releases through the S-12 A and B structures.

Development provides potential sources of excess nutrients, mercury and other toxins to the natural system via runoff water. Agricultural and urban runoff water from the lower east coast that may be needed for hydropattern restoration of the southern marl prairies may provide elevated inputs of these contaminants. A probable effect of nutrient additions to the southern marl prairies is the loss in the periphyton mat and the dominance of blue-green algae, resulting in a diminished role of periphyton in aquatic food webs and in marl substrate accretion (Browder et al. 1994). Nutrient and contaminant inputs do not appear to currently represent major stressors to the southern marl prairies. However, caution must be taken in utilizing lower east coast runoff for hydropattern restoration because of the potential of nutrients and contaminants as future stressors on these systems.

A.2.3.1 Shortened Hydroperiod

Hydroperiod is the duration of uninterrupted flooding. Shortened hydroperiod is one of the stressors on the southern marl prairies. Under present conditions, most of the southern marl prairies to the east of Shark River Slough remain dry most of an average year, compared to the duration of uninterrupted flooding averaging up to nine months pre-drainage as indicated by the Natural System Model (NSM) (Van Lent et al. 1993, Fennema et al. 1994, VanZee 1999). Shortened hydroperiod directly affects ecosystem food webs through the 1) decrease in the percent composition of diatoms and green algae associated with the periphyton mat, shifting near dominance by the blue greens *Schizothrix* and *Cytonemia* (Browder et al. 1994), 2) reduced secondary production and altered species composition of marsh fishes and other aquatic fauna (Loftus and Eklund 1994, Loftus et al. 1990, Trexler and Loftus 2000, Turner 1999), 3) reduced population density and altered species composition of small herpetofauna, based on abundance in short-hydroperiod habitats in relation to rainfall and water levels on Long Pine Key (Diffendorfer et al. in preparation; Dalrymple 1987; G. Dalrymple personal communication, Everglades Research Group, Inc.), 4) loss of the potential for wading bird and wood stork foraging during the early dry season (Fleming personal communication in Ogden 1994), and 5) decline in the American alligator population in the landscape where it was once abundant (Craighead 1968, Mazzotti and Brandt 1994). In addition to the already noted alteration of the periphyton mat and filling in of alligator holes, shortened hydroperiod directly affects plant community and habitat structure, by enabling the invasion of nuisance native woody plants (e.g., willow) and exotics (e.g., Brazilian pepper and melaleuca) in a naturally herbaceous landscape (Armentano et al. 1995, Jones and Doren 1997), and by altering the plant species composition of macrophyte vegetation toward more terrestrial plant species (Hofstetter and Hilsenbeck 1980, Hilsenbeck et al. 1979). Shortened hydroperiod indirectly affects plant community and habitat structure by altering the fire regime; hotter and more severe fires exacerbated by the prolonged dry season (Gunderson and Snyder 1994) further alter herbaceous plant species composition and reduce plant community heterogeneity by burning out hardwood hammock tree islands (Loope and Urban 1980). Shortened hydroperiod, in combination with increased drought severity, threatens Cape Sable seaside sparrow reproductive success and survival in the marl prairies to the east of Shark River Slough by increasing the frequency and severity of nest-destroying fires, and by enabling the invasion of woody plants in the absence of fire (Pimm 1995)

A.2.3.2 Increased Drought Severity

Another stressor is increased drought severity. In a system where water levels typically fall below the ground surface each year, remnant pools of standing water in solution holes and alligator holes during the dry season are critical to the survival of aquatic and amphibious fauna such as fish, crayfish, herpetofauna and alligators (Loftus et al. 1992, Mazzotti and Brandt 1994, Diffendorfer et al. in preparation, Dalrymple 1987, Dalrymple personal communication). The function of these dry season refugia is diminished or eliminated when dry conditions are prolonged and minimum water levels during a dry season fall below the bottoms of the solution holes and alligator holes.

A.2.3.3 Wet Season Water Level Reversals

Wet season water reversals is also a stressor. Field observations indicate that when water depth drops to less than 0.2 feet during a period of flooding, aquatic fauna population densities decline, survivors retreat to refugia in solution holes or alligator holes, and population recovery is slowed (Loftus and Eklund 1994; W. Loftus, United States Geological Survey, personal communication).

A.2.3.4 Drying Pattern Reversals and Extended Hydroperiods

Unnaturally high flow volumes from Water Conservation Area 3A through the S-12 A and B outflow gates into the marl prairies to the west of Shark River Slough have created delays and reversals in seasonal drying patterns. The drying pattern reversals and extended hydroperiods detrimentally affect nesting of the endangered Cape Sable seaside sparrow (Pimm 1995). The Cape Sable seaside sparrow depends on predictably dry conditions during its spring nesting period, which corresponds to the late dry season (Pimm 1995).

A.2.3.5 Compartmentalization

The levees that bound and dissect the southern marl prairies on the east side of the Everglades, including the L-31 levee, C-111 system, US 1 and the Card Sound Road, geographically alter hydrologic patterns and break connectivity of wetlands to adjacent uplands resulting in compartmentalization. Canals adjacent to the levees provide corridors of permanently flooded, deep-water habitat that would not otherwise occur in the southern marl prairies. These corridors allow the expansion of exotic and higher trophic level fishes into areas where they could not survive naturally (Howard et al. 1995). The prevalence of higher trophic fishes in the canals may diminish the value that this habitat might otherwise serve as a dry season refugium for aquatic and amphibious fauna.

A.2.3.6 Loss of Spatial Extent

The conversion of eastern portions of the southern marl prairies to agriculture and residential development has reduced the spatial extent of aquatic habitat and production that negatively impacts fish, crayfish, herpetofauna, alligators, and wood storks and wading birds. The extent of loss in aquatic habitat and production is directly proportional to the spatial extent of the area that has literally been taken out of production as wetland (Davis et al. 1994). Loss of spatial extent may have reduced the range of habitat options that are available at any given time for faunal populations (DeAngelis and White 1994), including nesting by the Cape Sable seaside sparrow (Pimm 1995) and potential foraging by wood storks and wading birds (Fleming, personal communication in Ogden 1994).

A.2.3.7 Expansion of Exotic Plants

Melaleuca, Brazilian pepper and Australian pine are the three most widespread invasive exotic plant species that have spread into native plant communities of the southern marl prairies. The shortened hydroperiod of these systems allows their rapid population expansion after introduction (Olmstead and Loope 1984, Armentano et al. 1995, Jones and Doren 1997).

A.2.3.8 High Intensity Dry Season Fires

Burning practices, particularly from illegally set fires, have shifted the seasonal timing of lightning sparked fires from the May-June early wet season, to the winter-spring dry season (Gunderson and Snyder 1994). Fire severity is exacerbated by shortened hydroperiod and increased drought severity. The road access provided by levees contributes to fire ignition by humans by allowing arsonists access to the marshes and by creating a source of ignition from vehicle sparks (G. Burzycki, Dade County Department of Environmental Resource Management, personal communication). Intense, dry season fires have burned out hardwood hammock tree islands in the southern marl prairies to the east of Shark River Slough. Fire hazard due to overdrainage also poses a threat to Cape Sable seaside sparrow nesting success and survival in the marl prairies to the east of Shark River Slough.

A.2.4 Ecological Attributes

A.2.4.1 Periphyton Mat

The periphyton mat of calcitic algae contributes to aquatic food webs (Browder et al. 1994), habitat structure (Loftus personal communication), and marl sediment accretion (Gleason 1972) in the southern marl prairies. Periphyton species composition is a sensitive indicator of both hydrologic conditions and water quality (Browder et al. 1994). Severely reduced hydroperiod in the southern marl prairies results in a decrease in the diatom and green algal species in the periphyton mat, leaving mostly mat-forming blue-green algae *Schizothrix* and *Cytonemia* (Browder et al. 1994).

A.2.4.2 Marl Substrate

Mat-forming calcitic algae deposit the marl substrate characteristic of the marl prairies (Gleason 1972, Browder et al. 1994), where hydroperiod is too short for the accretion of peat soils. Most of the plant communities described by Olmstead and Loope (1984) and Gunderson (1994) for this region are supported by the marl soils. The dependence of marl deposition on the productivity of the calcitic periphyton mat implies that the negative impacts of shortened hydroperiod noted above for the periphyton mat would also slow the rate of marl accretion.

A.2.4.3 Vegetation Mosaic and Diversity

A unique feature of the southern marl prairies is the extremely high species richness of the flora. Within the mosaic of low-stature graminoid communities, sawgrass and muhly grass dominate, although more than 100 species of mostly herbaceous plants have been reported (Olmstead and Loope 1984). The higher-elevation tropical hammock and pine forests islands within the prairie landscape support flora of West Indian origin unique to South Florida and the Florida Keys, and contain the highest number of rare and threatened plant species in southern Florida (Gunderson 1994). The plant communities of the southern marl prairies have been impacted by man through development, drainage, exotic invasion and burning practices. Tree island burn-out (Loope and Urban 1980), shifts to more terrestrial plant associations in the graminoid communities (Hofstetter and Hilsenbeck 1980, Hilsenbeck et al. 1979), loss of vegetation heterogeneity associated with the micro-topography of alligator holes (Craighead 1968), and woody plant invasion of the graminoid communities (Armentano et al. 1995) have accompanied shortened hydroperiods and lowered water tables. These effects are exacerbated by the spread of exotic trees (Olmstead and Loope 1984, Armentano et al. 1995, Jones and Doren 1997) and by dry season burning practices (Gunderson and Snyder 1994), particularly from illegally-set fires.

A.2.4.4 Cape Sable Seaside Sparrow

The Cape Sable seaside sparrow is an endangered species endemic to the marl marshes of the southern Everglades. The three major breeding colonies of the sparrow include the western subpopulation in marl marshes to the west of Shark River Slough, the eastern subpopulation to the east of mid-Shark River Slough, and the central subpopulation to the east of southwestern Shark River Slough (Pimm 1995). The sparrow nests during the dry season months, usually April–June, in sites free of standing shrubs or trees. The construction of nests approximately 10 centimeters above the ground at the bases of tussocks of muhly grass and other marsh graminoids makes the sparrow vulnerable both to spring wildfires and unseasonable water depth increases (dry season water level reversals). Successful nesting requires approximately 60 days of nearly dry conditions without fire. Dry season water level reversals have been a particular problem to the nesting success of the western subpopulation, where regulatory water releases through the S-12 A and B outflow gates of Water Conservation Area 3A contribute to the reversals and subsequent nest drowning (Pimm 1995). The eastern subpopulation occupies an overdrained region of marl prairie subject to spring wildfires or to invasion of woody vegetation. The central population is the most stable because of its remote location, although it is vulnerable to naturally-occurring dry season fires.

A.2.4.5 Marshes Fishes, Herpetofauna and Other Aquatic Fauna

The aquatic fauna of freshwater Everglades' marshes include the myriad of small fishes, amphibians, reptiles, crayfish, grass shrimp, snails, amphipods and other invertebrates that play enormously important roles in food webs, nutrient cycles and energy transfers from primary consumers to the highest trophic levels in the ecosystem. Considering their prevalence, little is known about the life histories, population dynamics and ecosystem roles of the aquatic fauna, particularly regarding their ecology in the southern marl prairies.

Population density of small marsh fishes in the Everglades is directly related to the duration of uninterrupted flooding (Trexler and Loftus 2000), and maximum densities are reached only after eight or more years of continual surface water (Loftus and Eklund 1994, Loftus et al. 1990, Turner 1999). The herpetofauna of the short-hydroperiod wetlands reach higher abundance in habitats with longer hydroperiods and higher water tables (Diffendorfer et al. in preparation, Dalrymple 1987, Dalrymple personal communication). The southern marl prairies, with annual drydowns during most years, represent stressful environments for aquatic fauna. Under pre-drainage conditions, these marshes dried annually for an average of three months; however, under present conditions extensive areas of this landscape are dry for an average of nine months each year (Van Lent et al. 1993, Fennema et al. 1994, VanZee 1999). Survival of aquatic fauna during dry periods in the southern marl prairies depends upon the availability of refugia in solution holes, alligator holes, and under periphyton mats which may retain aquatic or moist environments during absence of surface water (Loftus et al. 1990, Loftus et al. 1992, Dalrymple 1987, Diffendorfer et al. in preparation, Loftus personnal communication, Dalrymple personal communication).

The small marsh fishes provide the major prey base for the wading birds, wood storks and roseate spoonbills that forage and nest in the Everglades (Ogden 1994, Bjork and Powell 1994). Crayfish are particularly important in the diets of white ibis. The marl marshes may provide foraging opportunities for wading birds early in the dry season, when deeper water depths in the lower-elevation sloughs are unsuitable for efficient feeding (Fleming personal communication in Ogden 1994).

Reduced production and altered species composition of fishes and herpetofauna in the southern marl prairies result from 1) the direct impact of shortened hydroperiod (Loftus and Eklund 1994, Trexler and Loftus 2000, Turner 1999, Diffendorfer et al. in preparation, Dalrymple 1987, Dalrymple personnal communication), 2) indirect impacts of shortened hydroperiod via the loss of the periphyton mat and a reduced primary production food base (Browder et al. 1994), 3) reduction in dry season minimum water levels via the diminished dry season refugium function of solution holes, alligator holes and periphyton mats (Loftus et al. 1992, Diffendorfer et al in preparation, Dalrymple 1987, Loftus personal communication, Dalrymple personal communication), 4) reduction in spatial extent of wetland habitat (Davis et al. 1994), and 5) compartmentalization via levees as movement barriers and via canals as corridors for the spread of exotic and higher trophic level fishes (Howard et al. 1995).

A.2.4.6 American Alligator

Prior to drainage, the American alligator was more abundant in the southern marl marshes than in the deeper central marshes of the Everglades (Craighead 1968, Mazzotti and Brandt 1994). By excavating sediments from large solution holes in the limestone bedrock, the alligator created aquatic habitats in which it, and many other groups of aquatic fauna, survived the few months of dry conditions that occurred most years (Craighead 1968). In the excavation of holes and the creation of nest mounds, the alligator created a micro-topography that supported aquatic as well as terrestrial flora and fauna (Craighead 1971, Kushlan 1974). The mounds provided nesting sites not only for the alligator, but also for other marsh reptiles (Deitz and Jackson 1979, Kushlan and Kushlan 1980). In these ways, the alligator was a keystone species in the southern marl prairies because of the aquatic habitats and dry season refugia it created. The high abundance of alligators in the southern marl marshes, in comparison to lower densities in Shark River Slough, was attributed to high water depths in the slough that would have been less suitable for alligators prior to drainage (Ogden 1976, Mazzotti and Brandt 1994). Given the shortened hydroperiods and lowered water tables in the Everglades caused by drainage (Van Lent et al. 1993, Fennema et al. 1994, VanZee 1999) the alligator has mostly abandoned the southern marl prairies, and today the distribution of the alligator in the southern Everglades has shifted to Shark River Slough (Craighead 1968, Mazzotti and Brandt 1994). With the loss of alligators from the southern marl prairies, the habitats and dry season refugia that were provided by its holes and nest mounds have also been lost.

Abandonment by the alligator of the southern marl prairies has resulted from shortened hydroperiod, lowered water table and increased drought severity, as the alligators do not occupy predominantly dry habitat. Cumulative effects leading to the reduced production of aquatic fauna at all trophic levels have probably contributed to the demise of the alligator in the marl prairies, since the alligator depends upon these organisms for food during various stages of its life history. The reduced population of alligators has in turn allowed depressions that were previously alligator holes to fill in, further diminishing the populations of aquatic fauna upon those approaching which upon which the alligator fed. The restoration of hydroperiods and water tables to near pre-drainage conditions in the southern marl prairies is anticipated to allow the alligator to recolonize this region.

A.2.4.7 Wading Bird and Wood Stork Early Dry Season Foraging

Prior to drainage, the southern marl prairies may have provided shallow-water foraging opportunities for wading birds and wood storks early in the dry season, at a time when water was too deep to allow successful foraging in Shark River Slough (Fleming personal communication in Ogden 1994). The early dry season foraging opportunities may have contributed to the early formation of nesting colonies, and consequent nesting success of the birds. Low fish densities in these seasonally flooded landscapes (Trexler and Loftus 2000) would require considerable concentration to provide an adequate prey base to attract the birds. However, crayfish densities and their linkages to wading bird nesting have yet to be determined in the southern marl prairies. The relationship of the southern marl prairies to wading bird and wood stork nesting remains poorly understood. Because of these uncertainties, wading bird foraging activity is considered to be an indicator of restoration in the southern marl prairies, but not necessarily an indicator of regional wading bird restoration success. Under present conditions, both shortened hydroperiod (Van Lent et al. 1993, Fennema et al. 1994, VanZee 1999) and loss of spatial extent (Davis et al. 1994) have directly reduced the area of feeding habitat and the range of feeding options available to the wading birds and wood storks in the southern marl prairies (Ogden 1994). The value of these landscapes for wading bird and wood stork foraging appears to be very limited today in comparison to pre-drainage conditions (Fleming personal communication in Ogden 1994).

A.2.5 Ecological Effects
Critical Linkages between Stressors and Attributes/Working Hypotheses

As a result of water management-induced stressors, five major causal pathways appear to account for the decline in the ecological attributes of the southern marl prairies. Each pathway, other than that of the Cape Sable seaside sparrow, has been most severely impacted in the southern marl prairies to the east of Shark River Slough. The causal pathways are as follows:

- The periphyton mat has been altered in ways that reduce its contribution to aquatic food chains and marl formation. Diatom and green algal components of the periphyton mat have decreased as a result of severely shortened hydroperiod.

- The American alligator has been mostly eliminated, due to severely shortened hydroperiod and lowered water table, from the landscape where it was once most abundant. Alligator holes in depressions in the limestone bedrock have silted in with organic debris and no longer function as dry season refugia for aquatic fauna. Their loss has decreased the heterogeneity of vegetation habitat and micro-topography.

- The marsh fishes, herpetofauna and probably other aquatic fauna of the southern marl prairies can maintain only a diminished population density and secondary production given the shortened hydroperiod and lowered water table, the altered periphyton mat, the loss of dry season refugia in alligator and solution holes, and the physiological stress due to wet season water level reversals.

- The vegetation community mosaic has lost heterogeneity and changed in species composition due to shortened hydroperiod, lowered water table, and altered fire regime, subsequently there is loss of alligator holes microtopography, tropical hammock tree island burn-out, woody plant invasion, and the spread of exotic invasive plants.

- The Cape Sable seaside sparrow is limited in reproductive success and population size due to extended flooding and drying pattern reversals from upstream water releases to the west of Shark River Slough. To the east of the Slough, the sparrow is threatened by shortened hydroperiod and lowered water table, resulting either in increased fire frequency and severity, or in woody plant invasion in the absence of fire.

These casual pathways are based on key hypotheses developed during the conceptual ecological model workshops. These hypotheses determine the content and organization of the Southern Marl Prairies Conceptual Ecological Model. The hypotheses are presented here, organized by attribute.

A.2.5.1 Periphyton Mats

Relationship to Hydroperiod

A defining characteristic of marl wetlands is the presence of extensive mats of calcitic algae (Gleason 1972). These mats form during the wet season and require at least four months to fully develop and reach equilibrium between production and respiration. In marl wetlands with shortened hydroperiod due to drainage activities, periphyton mats decrease in spatial cover and primary production. Areas of severely drained marl wetlands to the east of Shark River Slough are devoid of periphyton mats. Reduced hydroperiod also results in a decrease in the diatom and green algal species in the periphyton mat, leaving mostly the mat-forming blue-greens *Schizothrix* and *Cytonemia* (Browder et al. 1994).

Level of certainty – high

Functional Contribution to Food Webs

Periphyton mats are functionally important as a primary production base for aquatic food webs supporting fishes and other aquatic fauna in marl wetlands (Browder et al. 1994). Reduced primary production and decreased representation of diatoms and green algae in periphyton mats contribute to reduced populations of fishes and other aquatic fauna in marl wetlands where hydroperiod has been shortened (Browder et al. 1994). Renewed primary production and food web functions of periphyton mats that will result from the resumption of natural hydroperiods will contribute to increase population densities of fishes and other aquatic fauna.

Level of certainty – low

Functional Contribution to Marl Accretion

Periphyton mats are functionally important in the precipitation of calcite and the accretion of the calcitic sediments that form the marl soils. Rates of marl accretion are directly related to the spatial extent and production of the mats (Gleason 1972). Marl accretion rates will increase as hydroperiods and periphyton mats are restored in presently overdrained marl wetlands.

Regulatory water releases from Water Conservation 3A have lengthened hydroperiod in marl wetlands to the west of Shark River Slough, reducing calcite precipitation and marl production by the periphyton, and shifting the wetlands to peat-forming systems. Reduction of hydroperiods to natural durations will restore calcite-precipitating mats and marl accretion in those wetlands.

Level of certainty – moderate

A.2.5.2 Vegetation Community Mosaic

Relationship to Hydroperiod and Water Table

Natural hydrologic patterns in marl wetlands support gradients of vegetation subtypes are aligned sequentially along hydrologic gradients ranging from 1-2 month hydroperiods (*Schizachrium rhizomatum*-dominated) to 3-5 months (*Muhlenbergia filipes*-dominated) to 6-8 months (*Cladium jamaicense*-dominated). These communities are notable for the high floral species richness, which includes more than 100 herbaceous plant species (Olmstead and Loope 1984). Hydrologic patterns that maintain these community gradients also support higher-elevation tropical hammocks and pine forests that occur as islands within the marl wetlands. These forested communities contain a flora of West Indian origin that is unique in the Florida mainland and that includes the highest number of rare and threatened plant species in southern Florida (Gunderson 1994).

Shortened hydroperiod and lowered water table in overdrained marl wetlands east of Shark River Slough expand the distribution of vegetation subtypes that grow at the upper end of the hydrologic gradient and decrease the distribution of vegetation subtypes that grow at the lower end of the hydrologic gradient (Hofstetter and Hilsenbeck 1980). Lengthened hydroperiod in marl wetlands west of Shark River Slough that receive regulatory water releases from Water Conservation Area 3A have the opposite effect on vegetation distribution. Resumption of natural hydroperiods will restore gradients and distributions of the full range of vegetation subtypes that are representative of marl wetlands (Hofstetter and Hilsenbeck 1980).

Level of certainty – high

Interactions of Hydroperiod and Water Table with Fire

Shortened hydroperiod and lowered water table contribute to the burn-out of islands of tropical hammocks and pine forests in overdrained marl wetlands due to increased intensity of wildfires (Loope and Urban 1980). Wildfire intensity and tree island damage may be augmented by a shift in fire seasonality from naturally-occurring, lightning-ignited fires during the early wet season to burning practices by humans during the dry season. The restoration of natural hydroperiods and water tables, combined with prevention of dry season wildfires, will reduce the incidence of tree island burn-out in marl wetlands (Gunderson and Snyder 1994).

Shortened hydroperiod and lowered water table allow the invasion of woody shrubs and trees into graminoid wetlands of overdrained marl systems (Armentano et al. 1995). Reduction in the frequency of naturally-occurring fires also supports woody plant establishment. Restoration of natural hydroperiods and water tables, in combination with natural fire regimes, will control woody vegetation and deter its expansion in graminoid wetlands.

Level of certainty – high

Relationship to Exotic Plants

The spread of exotic plants into the graminoid wetlands and forested islands of marl systems changes community composition, displaces native species, and contributes to woody invasion. The restoration and maintenance of vegetation mosaics of marl wetlands is contingent to the control and eradication of invasive exotics (Olmstead and Loope 1984, Armentano et al. 1995, Jones and Doren 1997).

Level of certainty – high

A.2.5.3 Cape Sable Seaside Sparrow

Requirements for Sustainability

The sustainability of the Cape Sable seaside sparrow, which is endemic to marl wetlands of the Everglades, requires the maintenance of three stable subpopulations and breeding colonies in the areas where they presently occur: a western subpopulation to the west of Shark River Slough, an eastern subpopulation to the east of mid-Shark River Slough, and a central subpopulation to the east of southwestern Shark River Slough (Pimm 1995).

Cape Sable seaside sparrows usually raise one or two broods in a season, although they may raise a third brood if weather conditions allow (K. Palmer, United States Fish and Wildlife Service, personal communication). Although 45 days of nearly dry conditions without fire would be sufficient for a single nesting event, however, an 80 day period is preferred in order to allow time for subsequent clutches which are considered key to population recovery. The current legal requirement for subpopulation A is a minimum of 50-60 (60 being most desirable) consecutive nesting days, preferably 80 consecutive nesting days, in all years until subpopulation A numbers have increased to at least 1,000 individuals.

The target for subpopulations B-F are as follows (Palmer personal communication):

- 40 consecutive days of water levels below ground for 8 out of 10 years (80 percent of the time) is considered favorable
- 40 consecutive days of water levels below ground for 7 out of 10 years (70 percent of the time) is considered borderline for persistence
- 80 consecutive days of water levels below ground for 8 out of 10 years (80 percent of the time) is considered very favorable
- 80 consecutive days of water levels below ground for 7 out of 10 years (70 percent of the time) is considered favorable

The sustainability of each subpopulation requires successful nesting at least 7 out of 10 years. Sustainability also requires a total population size, based on a five-year running average, ranging from a minimum of 2,000-3,000 birds, to as many as 6,600 birds during particularly good years, with trends in increasing population shared among the three subpopulations.

A habitat maintenance performance measure with a target of 0- to 2-months (0- to 60-days) average discontinuous hydroperiod is not expected to support vegetation favorable to sparrow nesting, a 2- to 4-month (60- to 120-day) average discontinuous hydroperiod is considered favorable and supportive of *Muhlenbergia*-dominated habitat, a 4- to 6-month (120- to 180-day) average discontinuous hydroperiod is considered good for other vegetation favorable to sparrow nesting, and an average discontinuous hydroperiod greater than 6 months (greater than 180 days) is not expected to support vegetation favorable to sparrow nesting.

Level of certainty – moderate

Relationships to Drying Patterns, Fire, and Invasion of Woody Vegetation

The Cape Sable seaside sparrow nests during the dry season months, mostly during April-June, in sites free of standing shrubs or trees. The construction of nests approximately 10 centimeters above the ground at the bases of tussocks of muhly grass and other marsh graminoids makes the sparrow vulnerable to both spring wildfires and unseasonable water depth increases (dry season water level reversals). Successful nesting requires at least 60 days of nearly dry conditions without fire. Dry season water level reversals have been a particular problem to the nesting success of the western subpopulation, where regulatory water releases through the S-12 A and B outflow gates of Water Conservation Area 3A contribute to reversals and subsequent nest drowning. The eastern subpopulation occupies an overdrained region of marl prairie subject to spring wildfires or the invasion by woody vegetation. The central subpopulation is the most stable because of its remote location, although it is vulnerable to naturally-occurring fires.

The restoration of natural hydroperiods throughout the marl wetlands of the southern Everglades will provide an average of at least 3-4 months of dry conditions during the spring nesting season of the sparrow, fulfilling its water level requirements for successful nesting and multiple clutches most years in all three subpopulations. Hydroperiod restoration in the overdrained marshes of the eastern subpopulation will assist in containing wild fires during the nesting season by increasing soil moisture, and by extending the duration of standing water low-lying areas functioning as fire breaks. Hydroperiod restoration, in combination with natural fire regimes, will prevent the spread of woody vegetation into the nesting grounds of the eastern subpopulation.

Level of certainty – high

A.2.5.4 Aquatic Fauna

Relationship to Spatial Extent

The conversion of portions of the marl wetlands east of Shark River Slough to agricultural and urban land use represents a proportional loss in the populations of fishes and other aquatic fauna that once inhabited that region (Davis et al. 1994). That loss is considered to be irreversible, short of reflooding developed areas and reconnecting them to the remaining natural system.

Level of certainty – high

Relationship to Hydroperiod

The population density, size structure and relative abundance of fishes in marl wetlands are limited by the annual duration of uninterrupted flooding (Trexler and Loftus 2000), which averages approximately 8-9 months per year under natural hydrologic conditions. The annual drying pattern that is typical of marl wetlands limits small fish density to less than 10 fish per square meter, compared to densities approaching 60 fish per square meter in areas of Shark River Slough with multi-year hydroperiods. This difference in densities occurs because fish density is directly related to the period of population recovery between marsh drydowns. The relative abundance of fish species also responds to hydroperiod. Blue-fin killifish, golden topminnow, lake chubsucker, and dollar sunfish are less represented under shorter hydroperiods (Trexler and Loftus 2000). Relative abundance affects size structure, in that the lake chubsucker and dollar sunfish represent larger species in the native fish assemblage of the marl marshes. The reduction of hydroperiod in overdrained marl wetlands limits fish density, size structure and representation of long-hydroperiod species to levels below those expected under natural hydrologic conditions (Trexler and Loftus 2000). Hydroperiod restoration is expected to result in the recovery of fish density, size structure and relative abundance.

Level of certainty- high

Relationship to Dry Season Refugia

Solution holes in exposed bedrock hold standing water during the dry season and supplement alligator holes as drought refugia for fishes and other aquatic fauna in marl wetlands (Loftus et al. 1990, Loftus et al. 1994, Dalrymple 1987, Diffendorfer et al. in prep). The refugia enable these animals to survive the annual dry season and to disperse upon reflooding to repopulate the landscape during the wet season. Lowered water table and shortened hydroperiod in overdrained marl wetlands have increased the frequency and duration of the drying of solution holes and alligator holes, diminishing their drought refugium function and reducing the populations of aquatic fauna that depend on them. Restoration of hydroperiods and water tables toward pre-drainage conditions are expected to renew this refugia function.

Renewal of the dry season refugia functions of alligator holes and solution holes is central to any restoration strategy for overdrained marl wetlands (Loftus et al. 1992, Dalrymple 1987). Their restoration will sustain substantially higher populations of fish and other aquatic fauna by supporting increased survival during dry conditions and increased dispersal and reproduction during the wet season. Success will be realized as increased population density and size structure, and as decreased inter-annual variation in these parameters.

Level of certainty – low

Relationship to Exotic Fishes

The construction of the C-111 and L-31 canal systems through and adjacent to the marl wetlands to the east of Shark River Slough has provided corridors for the spread of exotic fishes into those wetlands (Howard et al. 1995). The most important impact on native fish populations currently appears to result from the occupancy of solution holes by the black acara during the dry season. This South America cichlid appears to prey upon native species in the solution holes, thereby reducing their survival through the dry season, as evidenced by observations of only black acara remaining alive in receding pools of water in the solution holes as the dry season progresses. There is no known deterrent to the persistence and spread of higher trophic level exotic fishes such as the black acara in the marl wetlands where they have become established. The potential for diminished dry season refugium functions of solution holes and possibly alligator holes for native species, as a result of displacement by exotic species, must be considered in restoration strategies and expectations for aquatic fauna in affected marl wetlands.

Level of certainty – low

Relationship to Primary Production

Populations of fishes and other aquatic fauna in marl wetlands are supported by food webs based on the primary production of periphyton mats (Browder et al. 1994). Reduced spatial coverage, reduced primary production, and altered taxonomic composition of periphyton mats support lower population densities of these animals in marl wetlands where hydroperiod has been shortened. Renewed primary production and food web functions of periphyton mats resulting from the resumption of natural hydroperiods will contribute to increase population densities of fishes and other aquatic fauna.

Level of certainty – low

Functional Importance of Macroinvertebrates and Herpetofauna

The constraint that annual drying patterns place on fish populations suggests that macroinvertebrates and herpetofauna may dominate the aquatic fauna as important intermediate trophic levels and prey bases for higher consumers in marl systems (Fleming personal communication in Ogden 1994). However, little is known about the life histories, population dynamics and ecosystem roles of species such as grass shrimp, crayfish, ranid and hylid frogs, and water snakes. Although they would also be expected to decline in abundance with the overdrainage of marl wetlands, in response to the same factors affecting the fishes, quantitative relationships are mostly lacking. Crayfish and water snakes were noted to be conspicuously abundant in marl wetlands in the early 1900s, apparently at densities much higher than those observed today. Crayfish constitute an important prey item in the diets of many vertebrates that have declined in abundance with the drainage of the Everglades, including pig frogs, otters, alligators, and white and glossy ibis (Momot et al. 1978, Kushlan and Kushlan 1979, Hogger 1988, Hobbs et al. 1989). The lack of information regarding the population dynamics functional roles of macroinvertebrates and herpetofauna in the Everglades, despite the potential importance of these groups, represents an important gap in our information regarding the degradation and restoration of marl systems.

Level of certainty – low

A.2.5.5 American Alligator Populations

Distribution and Abundance

The American alligator was historically abundant and nested in marl wetlands, where it excavated sediments from large solution holes in the limestone bedrock to produce alligator holes. Prior to drainage, alligator populations in the southern Everglades were concentrated in these higher elevation marshes (Craighhead 1968, Mazotti and Brandt 1994). Densities of alligators in the rockland marl marshes north of Long Pine Key exceeded densities in Shark River Slough, where the water was often too deep for nesting. Alligator abundance and reproduction have declined in the marl wetlands where they were previously most abundant. Alligator populations in the southern Everglades are now concentrated in Shark River Slough. As a result, abandoned alligator holes in the marl wetlands have filled in with debris (Craighead 1971, Kushlan 1974).

Alligator population distribution and abundance may be vary geographically due to underlying geology as a limiting factor for nesting habitat in the marl system, in that nesting may be limited to areas where irregularities in the bedrock surface allow for the excavation of alligator holes. For example, establishment of alligator populations and holes due to hydrologic restoration is expected in the rockland marl marshes to the north of Long Pine Key, but it may be less likely in the marl prairies further south.

Level of certainty – high

Relationship to Hydroperiod and Water Table

The decline in alligator abundance and reproduction in marl wetlands is attributed to shortened hydroperiods and lowered water tables (Van Lent et al. 1993, Fennema et al. 1994, Van Zee 1999). Alligators are expected to repopulate presently overdrained areas of marl wetlands, to occupy and excavate most presently filled-in holes, and to resume nesting and successful reproduction over a 5-15 year time frame after restoration of natural hydroperiods and water tables.

Level of certainty – high

Alligator Holes as Dry Season Refugia

The alligator is a keystone species in marl wetlands as alligator holes provide important refugia, allowing aquatic fauna to survive the annual dry season and to radiate out, repopulating the marshes upon reflooding. The loss of alligators, and the filling-in of alligator holes, has diminished the survival, resilience and population density of populations of aquatic fauna in overdrained marl wetlands (Deitz and Jackson 1979, Kushlan and Kushlan 1980). The restoration of alligator holes is expected to restore their keystone function as drought refugia. As a result, the resilience and density of aquatic fauna populations dependent on the refugium function of the alligator holes should increase.

Level of certainty- low

Alligator Holes as Micro-Topographic Gradients

In the excavation of holes and nest mounds, the alligator also plays a keystone role in creating micro-topographic gradients that support aquatic as well as terrestrial fauna and provide nest sites for other species of marsh reptiles in marl wetlands (Craighead 1971, Kushlan 1974). With the loss of the micro-topographic gradients associated with the holes, aquatic and terrestrial habitats, and dependent flora and fauna have also declined in abundance. The restoration of alligator holes is expected to restore micro-topographic gradients. As a result, the communities and populations of the flora and fauna that depend upon the micro-topography should return to former levels of abundance.

Level of certainty – high

Feedback Loop

A positive feedback loop probably exists from beneficial hydroperiods and water tables to alligator populations, to alligator holes, to aquatic fauna density and distribution, and back to alligator populations. That feedback loop is assumed to have been functional under pre-drainage conditions in marl wetlands where alligators were formerly abundant, although it is clearly not functional in overdrained marshes today. Increasing hydroperiods and water tables toward pre-drainage conditions is expected to renew the positive feedback loop, although the necessary level of hydrologic restoration to accomplish this is uncertain.

Level of certainty – low

A.2.5.6 Wading Birds, Wood Stork and Roseate Spoonbill

Relationship to Hydroperiod and Drying Pattern

It has been proposed that the marl wetlands provide foraging opportunities for wading birds, wood storks and roseate spoonbills during unusually wet years and early in the dry season, when water is too deep to allow successful foraging elsewhere in the southern Everglades (Fleming personal communication in Ogden 1994). The depauperate fish populations resulting from annual drying patterns in the marl wetlands might be considered unlikely to provide enough food resources to influence regional nesting success. However, during specific years when a prolonged wet season is followed by a beneficial drying pattern, the normally low fish density in a relatively unproductive marl system can be concentrated to levels comparable to more productive regions such as Shark River Slough and the Gulf of Mexico estuaries (Trexler and Loftus 2000). Those years have been shown to correspond to the years when roseate spoonbill nested successfully in nearby Florida Bay colonies. Thus, marl wetlands may contribute to regional nesting success under specific hydrological conditions during specific years. Hydroperiod restoration in presently overdrained marl wetlands is expected to increase the frequency of years when prolonged wet seasons and natural drying patterns produce and concentrate fishes to attract larger seasonal aggregations of foraging birds.

Level of certainty – moderate

A.2.6 Research Questions

Key uncertainties regarding ecological response to hydrologic restoration in the marl wetlands pertain to the population dynamics of the marsh fishes and other aquatic fauna in relation to food webs and drought refugia. The overarching question is how hydroperiod restoration of the marl wetlands will influence populations of aquatic fauna representing the food base for higher predators, including wading birds.

Periphyton Productivity Limitation on Aquatic Fauna Populations

Are populations of marsh fishes and other aquatic fauna regulated by food webs generated from primary production of periphyton mats? Will the restoration of periphyton mat spatial cover, primary productivity and taxonomic composition due to hydroperiod restoration yield densities of aquatic fauna above those predicted in response to hydroperiod restoration alone? Develop quantitative relationships and models of periphyton productivity as a factor limiting populations of marsh fishes and other key taxa of aquatic fauna.

Dry Season Refugia Limitation on Aquatic Fauna Populations

Are populations of marsh fishes and other aquatic fauna regulated by the availability of dry season refugia of standing water in alligator holes and solution holes? Although fishes and other aquatic fauna condense in alligator holes and solution holes as marl wetlands dry, do survival rates during the dry season and subsequent wet season dispersal and reproduction sustain population densities above those predicted in relation to hydroperiod alone? Determine survival rates of marsh fishes and other aquatic fauna in alligator and solution holes during dry seasons in relation to the depth and persistence of standing water and the presence of exotic fishes. In relation to duration of flooding, determine rates of dispersal and reproduction of dry season survivors during the wet season. Compare populations of marsh fishes and other aquatic fauna with and without functional dry season refugia in marl wetlands of similar hydroperiod. Develop quantitative relationships and models of dry season refugia as a factor limiting populations of marsh fish and other aquatic fauna in marl wetlands.

Functional Importance of Macroinvertebrates and Herpetofauna

What is the functional importance of crayfish, grass shrimp, ranid and hylid frogs as intermediate trophic levels and prey bases for higher consumers in restored marl wetlands, considering the constraint that annual drying patterns place on marsh fish populations? Are their populations regulated by the same factors regulating marsh fish populations, including hydroperiod, dry season refugia and primary productivity? Are white ibis reproduction and super colony formation related to marl wetland crayfish populations, as influenced by inter-annual hydrologic patterns? Develop quantitative relationships and models of crayfish, grass shrimp and frog populations in relation to hydroperiod, dry season refugia, and primary production in marl wetlands. Develop quantitative relationships and models of the energetic requirements of wading bird nesting colonies, including super colonies, in relation to the density, seasonal concentration and inter-annual variation of populations.

A.2.7 Hydrologic Performance Measures

Recovery of the ecological values of the southern marl prairies is dependent upon the reversal of the cumulative effects of decades of drainage, detrimental fire regimes and exotic plant invasion. Therefore, hydrologic performance measures have been developed for hydroperiod, drought severity and water level reversal.

A.2.7.1 Hydroperiod

The performance measure for hydroperiods is the mean water depth and duration of flooding. The target for flood events is a mean water depth equal to or exceeding 0.2 feet because depths less than 0.2 feet have been observed to impair the establishment of populations of aquatic organisms. The target for duration is the recovery of mean duration of flooding indicated by NSM.

A.2.7.2 Drought Severity

Drought severity exacerbates the effects of shortened duration of flooding and is identified as a hydrologic variable that affects most of the ecological attributes in the conceptual ecological model. Dry events occur when the water level drops either to or below the ground surface. The performance measure for drought severity is the depth water levels drop below the ground surface during a dry event. The target is not to exceed depths below ground indicated by NSM for each dry event.

A.2.7.3 Water Level Reversal

Wet season water level reversal may also be an important hydrologic variable for ecological restoration in the marl prairie/rocky glades. A reversal is distinguished from a dry period in that during a reversal, water depth does not drop to or below the ground surface. The performance measure is the number of reversals. The target is not to exceed the number of reversals indicated by NSM.

A.2.8 Ecological Performance Measures

A.2.8.1 Periphyton Mat

The performance measure for periphyton mats is spatial extent, species composition and primary productivity. The target for periphyton is to increase mat cover, biovolume, organic content, percent noncalcareous algae and diatom composition.

A.2.8.2 Marl Substrate

The performance measure for marl substrate is marl accretion. A target has not been developed.

A.2.8.3 Vegetation Mosaic and Diversity

The performance measure for vegetation mosaic and diversity is emergent macrophyte and tree island community cover and compostion. The target is to increase spatial cover and species composition of gaminoid and tree island communities.

A.2.8.4 Cape Sable Seaside Sparrow

The performance measure for the Cape Sable seaside sparrow is nesting distribution and success and population density. The target for the Cape Sable seaside sparrow is to increase the number of stable subpopulations and the number of individual birds.

A.2.8.5 Marsh Fishes, Herpetofauna and other Aquatic Fauna

The performance measure for marsh fishes, herpetofauna, and other aquatic fauna is density and distribution. A target for marsh fishes and associated fauna in marl prairies is to increase the seasonal production to pre-drainage (NSM) levels as indicated by late wet season population densities in areas where natural hydroperiods are restored. Another target is to provide high prey-availability patches where wading birds can feed effectively as water levels recede during the dry season.

A.2.8.6 American Alligator

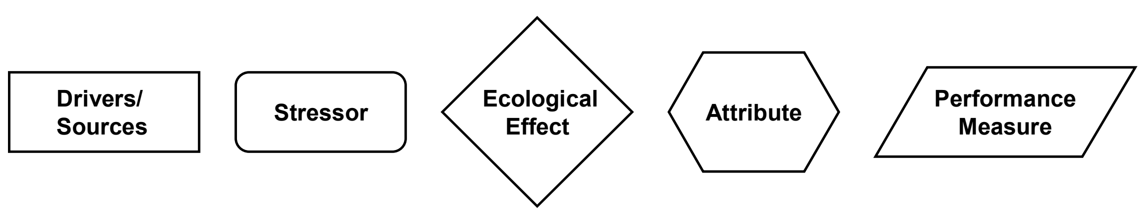
The restoration of pre-drainage (NSM) hydropatterns in the southern marl prairies is anticipated to allow the alligator to recolonize this region. The performance measure for American alligators is spatial distribution and abundance, rate of hole occupancy, frequency of nesting and hatching, and size distribution. The targets are to increase spatial distribution and relative abundance, hole occupancy, nesting success and juvenile size classes.

A.2.8.7 Wading Bird and Wood Stork Foraging Opportunity

The performance measure for wading bird and wood stork foraging opportunity is seasonal abundance, foraging activity, and distribution. The target for wading bird and wood stork foraging opportunity is an increase in flock size and numbers of birds foraging in previously overdrained southern marl prairies.

A.2.9 Model

The diagram for the Southern Marl Prairies Conceptual Ecological Model is presented in Figure A-8. The effects of the altered hydropattern stressors are provided in more detail in Figure A-9. The key to the



symbols used in the diagrams is presented in Figure A-10.

Figure A-8: Key to the Symbols Used in the Following Diagram

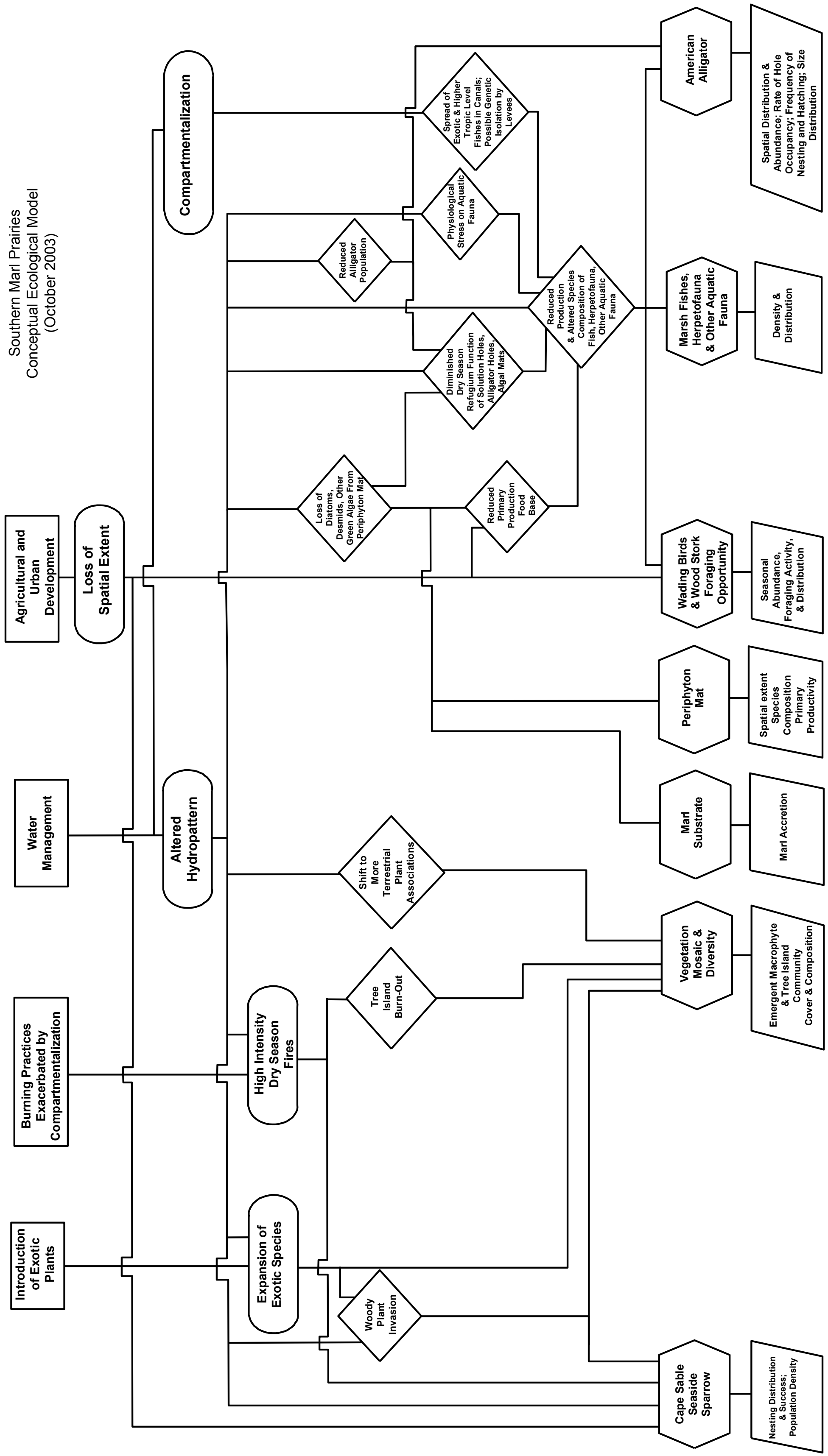


Figure A-9: Diagram of the Southern Marl Prairies Conceptual Ecological Model

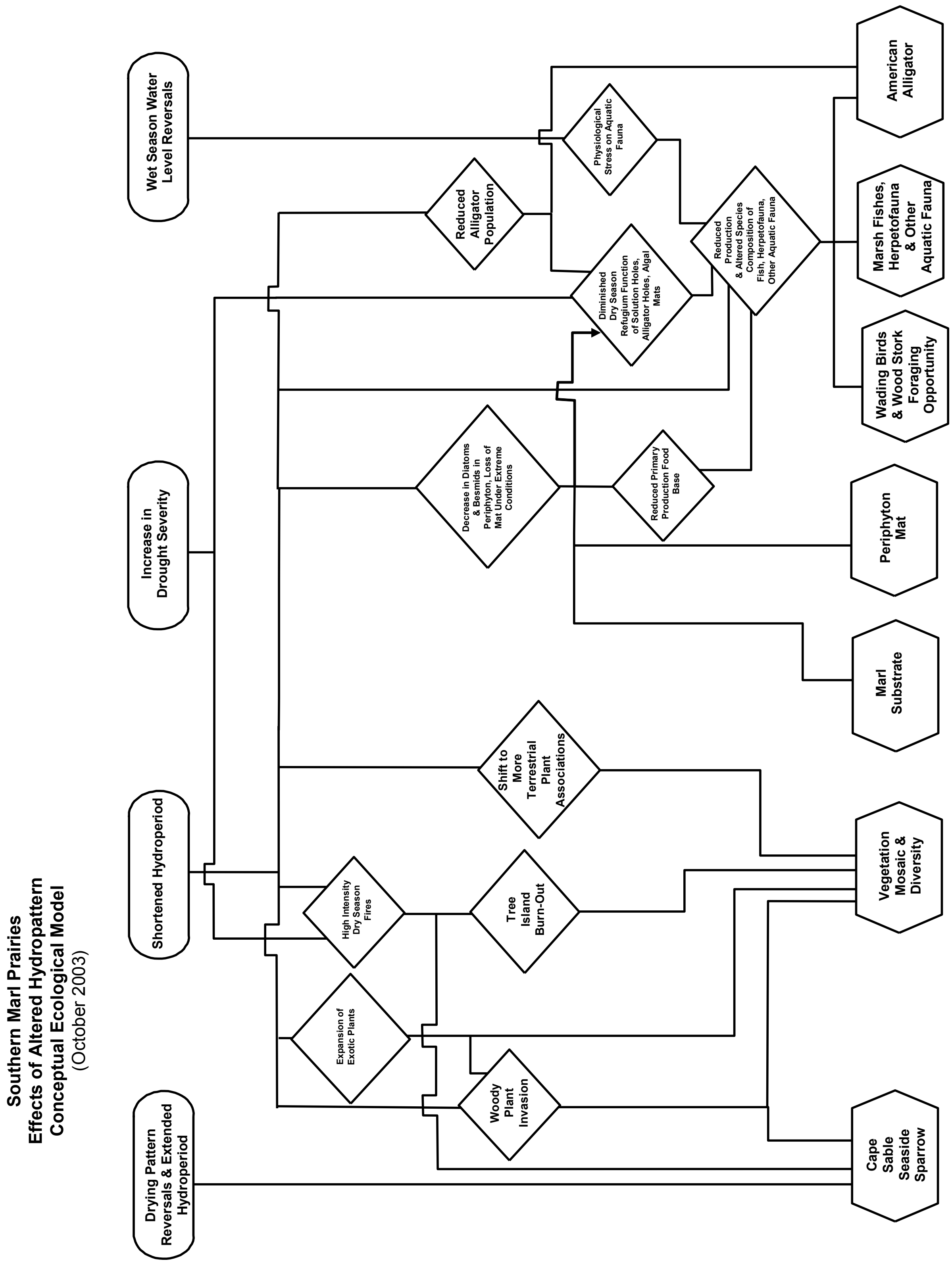


Figure A-10: Diagram of the Effects of Altered Hydropattern in the Southern Marl Prairies

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A.3 EVERGLADES MANGROVE ESTUARIES CONCEPTUAL ECOLOGICAL MODEL

A.3.1 Model Lead

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A.3.2 Introduction

A brackish water ecotone of coastal bays and lakes, mangrove and buttonwood forests, salt marshes, tidal creeks, and upland hammocks separates Florida Bay from the freshwater Everglades. The 24-kilometer-wide ecotone adjoins the north shoreline of Florida Bay and the Gulf of Mexico. The model boundary from Turkey Point west to Lostman's River delineates the interface of Biscayne and Florida Bays and the Gulf of Mexico that is affected by freshwater flows from the Everglades (Figure A-11). The Everglades mangrove estuaries are characterized by a salinity gradient and mosaic that vary spatially with topography and that vary seasonally and inter-annually with rainfall and freshwater flow from the Everglades. Because of its location at the lower end of the Everglades drainage basin, the Everglades mangrove estuaries are potentially affected by upstream water management practices that alter the freshwater heads and flows that drive salinity gradients.

Figure A-11: The Boundary of the Everglades Mangrove Estuaries Conceptual Ecological Model

A.3.3 External Drivers and Ecological Stressors

The Everglades mangrove estuaries are the product of an interplay of marine and freshwater influences that dominate every aspect of the system as external drivers and ecological stressors (Figure A-13, Section A.3.9). The controlling marine influence is sea level. There is strong evidence that present rates of **sea level rise** in South Florida, which are attributed to global climate change, will massively reconfigure the geomorphology, circulation patterns, salinity patterns, and ecological processes of the during the Twenty-First Century (Wanless et al. 1994). The controlling freshwater influence is flow from the Everglades. The construction and operation of South Florida's water management system during the Twentieth Century has depleted freshwater flow to the estuary and has altered its timing and distribution (VanZee 1999, McIvor et al. 1994). Ecological patterns and processes in the mangrove estuary are closely linked to patterns of hydrology and salinity that have been altered by **reduced freshwater flow**. Declines in many ecological attributes of the estuary correspond to the development of the water management system.

The introduction of **exotic fishes and plants** into South Florida through the aquarium and nursery trades has resulted in the spread of three nuisance species that represent ecosystem stressors in the Everglades mangrove estuaries. The Mayan cichlid presently dominates the fish community in the mangrove wetlands east of Taylor Slough (Trexler et al. 2001), and the exotic plants *Schinus* and *Colubrina* have invaded mangrove forests. Although less pervasive than sea level and freshwater flow, potential impacts from the spread of exotics merit a better understanding of their ecological roles and potentials for control in the Everglades mangrove estuaries.

A.3.4 Ecological Attributes

This section provides a general overview of the ecological attributes that have been selected as indicators of ecological health in the Everglades mangrove estuaries, and the rationale for their selection. Detailed descriptions of the attributes, and of our current understanding of the relationships of attributes to stressors, are provided in the following section on linkage hypotheses.

A.3.4.1 Estuarine Geomorphology

The shoreline and landscape mosaic of the Everglades mangrove estuaries is likely to be massively reconfigured during the Twenty-First Century due to the interaction of sea level rise and hurricanes (Wanless et al. 1994). The dynamics of the coastal storm berm that separates the estuarine zone from Florida Bay, and the accretion of peat in Gulf of Mexico mangrove forests, are key factors determining the rate and extent of that reconfiguration. As a result of shoreline transgression, the Everglades mangrove estuaries are expected to move inland into the lower Everglades. Thus a functional estuary and its ecological attributes, as influenced by the resumption of natural freshwater flow volume and duration, must be viewed as spatially dynamic with a long-term trend toward inland movement. Regardless of rising sea level, a salinity gradient supportive of ecologically functional Everglades mangrove estuaries will be required to maintain the integrity of the South Florida ecosystem. The spatially dynamic aspects of the Everglades mangrove estuaries, resulting from sea level rise and geomorphic processes, influence all the ecological attributes and restoration expectations for the estuary.

A.3.4.2 Mangrove Forests and Associated Plant Communities: Structure and Function

Mangrove forests (*Rhizophora*, *Avicennia*, *Laguncularia*, and *Conocarpus*) dominate the primary productivity and soil accretion within the Everglades mangrove estuaries (Childers et al. 1999). That productivity appears to reflect the nutrient status of the estuarine interface, which is related to the mixing of water from the Everglades with that from the Gulf of Mexico and Florida Bay. Childers et al. (1999) observed a clear productivity peak in the oligohaline zone of Shark River Slough. The peak is found in soil and water nutrient concentrations, in biomass and productivity of marsh plants, mangroves and phytoplankton, and in secondary consumer biomass. The peak appears to result from low-phosphorus, high-nitrogen fresh water meeting higher-phosphorus, lower-nitrogen marine water (Rudnick et al. 1999). The productivity peak that was found in the interface of the Shark River Slough basin with the Gulf of Mexico was not found in the interface of the Taylor Slough/Panhandle basin with Florida Bay (Childers et al. 1999). This appears to occur in part because northeast Florida Bay scavenges available phosphorus from coastal waters before it reaches the oligohaline zone of the Taylor Slough/Panhandle basin (Fourqurean et al. 1993). The mangrove estuary provides a sink for nitrogen from Everglades water before it enters Florida Bay (Chen and Twilley 1999; D. Rudnick, South Florida Water Management District unpublished data), which may represent an important support function regarding the nutrient status of the bay.

The mosaic of mangrove forests and associated plant communities, documented by Welsh et al. (1995), defines the habitats of the Everglades mangrove estuaries. The spatial distribution of those habitats, in combination with the salinity gradient that overlays them, determines the suitability of this region to sustain its faunal attributes (Browder and Moore 1981).

Embedded within the mangrove forests are tidal creeks and adjacent salt marshes, upland tropical hardwood hammocks, halophytic prairies, and coastal lakes. The coastal lakes such as Seven Palm Lake, Cuthbert Lake, Long Lake, West Lake, Lake Monroe and the Taylor River ponds support seasonal beds of submerged aquatic vegetation (SAV) under oligohaline to mesohaline conditions. At the seaward interface of the mangrove estuaries, coastal basins adjoin Florida Bay and the Gulf of Mexico. These basins, including Joe Bay, Little Madeira Bay, Terrapin Bay, Garfield Bight, and Whitewater Bay, also support SAV characteristic of their salinity regimes. At the landward interface of the mangrove estuaries with marl wetlands, a "white zone" band of sparse, relatively unproductive, mixed mangrove and graminoid vegetation is considered an indicator of the balance between freshwater flow and sea level rise (Ross et al. 2002). Working hypotheses relate the distribution and persistence of each of these plant communities to one or more of the stressors that have been identified for the Everglades mangrove estuaries.

The SAV of coastal lakes and basins provide an important food resource for seasonal waterfowl aggregations. Reduction in these beds of SAV, due to shifts toward more marine conditions, appear to have contributed to the decline in numbers of coot, scaup, widgeon and pintail that once were seasonally abundant in the coastal lakes and basins.

A.3.4.3 Estuarine Fish Communities and Fisheries

The oligohaline wetlands of the mangrove estuary support a resident community of small fishes that is functionally important as an intermediate trophic level supporting wading birds and other higher consumers (Lorenz 2000). The production and seasonal concentration of the wetland fishes appear to vary with salinity, hydrology and nutrient status in the estuary (Trexler and Loftus 2000, Lorenz 2000), all of which are controlled by freshwater flow and sea level.

Shoreline habitats and coastal basins of the mangrove estuary provide nursery grounds for sport and commercial fisheries including spotted seatrout, common snook and pink shrimp. Spotted seatrout complete their complete life cycle within Florida Bay and coastal Gulf waters, and thereby represent a good sport fish indicator of changing estuarine conditions. Post larval spotted seatrout utilize the coastal basins of the mangrove estuary as nursery grounds from Terrapin Bay west.

Mangrove estuaries in Everglades National Park, along with Florida Bay, are nursery grounds for pink shrimp, an ecologically and economically important species in South Florida. Pink shrimp are harvested commercially on the Tortugas grounds, and the pink shrimp fishery is one of South Florida's most valuable fisheries in terms of ex-vessel value. Pink shrimp are also a food source for many recreationally and commercially important estuarine and marine species such as mangrove snapper and spotted seatrout (Higher Trophic Levels Working Group 1998). Pink shrimp spawning occurs in the Dry Tortugas area, and eggs and larvae are carried inshore by currents and tides (Jones et al. 1970, Hughes 1969). Browder (1985) and Sheridan (1996) have found positive relationships between indices of freshwater inflow to the coast and Tortugas pink shrimp landings. The suitability of coastal and shoreline habitats as nursery grounds for spotted seatrout and pink shrimp appears to be largely dependant upon salinity patterns (Browder and Moore 1981) that are driven by freshwater flow and sea level.

A.3.4.4 Wood Stork and Roseate Spoonbill

The large nesting colonies of wood storks and great egrets in the Everglades during the early 1900s were concentrated in the Everglades mangrove estuaries (Ogden 1994). The East River, Lane River, Rookery Branch, Broad River, and Rodgers River Bay colonies, in the headwaters of the tidal rivers entering the Gulf of Mexico, supported approximately 90 percent of the total nesting population of these and other wading bird species during the period of 1931-1946. Additional colonies along the southern mainland of Florida Bay included Alligator Lake, Mud Lake, Mud Hole, Cuthbert Lake and Madeira Rookery. The collapse of all of these coastal nesting colonies during the second half of the century is attributed largely to a decline in the production and density the food base for the nesting birds (Ogden 1994), which consists of the resident mangrove fishes and particularly the topminnows and sunfish that grow to a size that wood storks can capture (Ogden et al. 1978).

A decline in roseate spoonbill nesting in northeast Florida Bay and a shift of nesting distribution from eastern to western Florida Bay (Powell et al. 1989) are also attributed to the reduction in populations of resident mangrove fishes upon which they feed (Bjork and Powell 1994). Small fishes have been reported to be the primary part of the diet of roseate spoonbills in Florida Bay (Allen 1942, Powell and Bjork 1990).

The collapse of coastal colonies of wood stork and great egret, and of northeast Florida Bay colonies of roseate spoonbill, corresponded to the construction of the Central and South Florida (C&SF) Project and the resulting reduction of freshwater flow to the estuarine interface compared to Natural Systems Model (NSM) simulations (VanZee 1999).

A.3.4.5 Estuarine Crocodilian Populations

The American alligator was historically abundant (and nested) in freshwater mangrove areas of the Everglades according to Craighead (1968). Today, reduced freshwater flow into estuaries apparently has resulted in succession of former freshwater mangrove areas to saltwater systems, changing the pattern of occupancy by alligators. Salinity is a major factor limiting the distribution and abundance of alligators in estuarine habitats (Dunson and Mazzotti 1989, Mazzotti and Dunson 1989). Alligators appear to be good indicators of restoring freshwater flows to estuarine systems and the subsequent reestablishment of an extensive freshwater/brackish water zone.

The American crocodile dwells in the ponds and creeks of the mangrove estuaries of Florida Bay (Ogden 1976, Mazzotti 1983). American crocodiles are tolerant of a wide salinity range as adults because of their ability to osmoregulate (Mazzotti 1989). Juvenile crocodiles lack this ability, however, (Mazzotti 1989) and their growth and survival decline at salinities exceeding 20 parts per thousand (ppt) (Mazzotti et al. 1988, Mazzotti and Dunson 1984, Moler 1991). Juvenile crocodiles tend to seek freshwater pockets such as black mangrove stands when those choices are available.

A.3.5 Ecological Effects
Critical Linkages between Stressors and Attributes/Working Hypotheses

Ecological changes resulting from the restoration of freshwater flow to the mangrove estuaries will be strongly influenced by three interrelated causal relationships. All involve estuarine productivity and subsequent effects on sediment accretion and food webs. Key hypotheses were developed based on these causal pathways during the conceptual ecological model workshops. These hypotheses determine the content and organization of the Everglades Mangrove Estuaries Conceptual Ecological Model. The hypotheses are presented here, organized by attribute.

A.3.5.1 Estuarine Geomorphology

Relationship to Sea Level and Sediment Accretion

Shoreline transgression of the Everglades mangrove estuaries will occur due to the present rate of sea level rise, which is conservatively estimated to be two feet over the next century (Wanless et al. 1994). The coastal storm berm of inorganic sediments that separates the estuarine zone from Florida Bay will accrete at a rate insufficient to keep up with sea level rise. The embankment will be breached by hurricanes during the next century, increasing the exchange of water, sediment, organic matter and nutrients between the bay and estuary, and allowing the influx of marine conditions into presently oligohaline-mesohaline areas of the estuary. The mangrove forests of the Shark River and other Gulf of Mexico estuaries to the west of Florida Bay will similarly be overtaken by rates of sea level rise that will exceed rates of organic soil accretion. Hurricanes will erode and blow-out portions the mangrove forests during the next century, creating new water courses, open-water lakes and basins, halophytic prairies and exchanges of water, sediment, organic matter and nutrients with the gulf. As a result of shoreline transgression, the Everglades mangrove estuaries are expected to move inland into the lower Everglades over the next century. Thus a functional estuary and its attributes, as influenced by the resumption of natural freshwater flow volume and duration, must be viewed as spatially dynamic with a long-term trend toward inland movement.

Shoreline transgression in the gulf mangroves may be partially offset by the productivity, peat accretion, and resulting increase in soil surface elevation of the mangrove forests, as affected by the mixing of water and nutrients from the Gulf of Mexico and the Everglades. Coastal wetlands accumulate sediment by accretion, with the result that they increase in elevation over time relative to stable features of the coast. Negative feedback between the process of accretion and the wetland's elevation, measured relative to local sea level, regulates wetland elevation so that it tracks long-term changes in sea level (Nyman et al. 1993). Measured accretion rates for wetlands along the Gulf of Mexico and Atlantic coasts of the United States generally equal or exceed the local long-term rise in relative sea level. Based on the assumption that accretion is controlled by the in situ production of organic matter, Bricker-Urso et al. (1989) estimate the maximum sustainable rate of accretion to be about 16 millimeters per year.

An alternative hypothesis (T. Armentano, Everglades National Park, personal communication) is that there is no demonstrable reason to conclude that sea level rise will simply trigger a landward shift of the present mangrove forest inland. Much of the present mangrove forest (other than peripheral populations) has occupied its present sites for centuries or millennia during a period of relatively stable sea levels. These sites are characterized by deep peat deposits and a specific range of nutrient conditions determined to a great extent by the locations of the forest relative to the Gulf of Mexico, Florida Bay and the freshwater sloughs. The environment of future mangrove forests may differ from present conditions. Clearly at least, soil conditions in sites that may experience future mangrove colonization differ markedly from present mangrove forest sites. In addition, with an accelerated sea level rise, there may not be sufficient time for mangrove forests to develop a deep peat substrate in new sites. Instead, the new forests may be structurally less developed, and less productive, resembling the stunted forests of some Florida Bay islands or the interior dwarf mangrove forest. It is also possible, however, that the "expansion forests" will be more diverse, supporting species excluded from the closed canopies of well-developed forests.

Sea level rise and shoreline transgression in South Florida are well documented, as summarized by H.R. Wanless (University of Miami, personal communication). Over the past 75 years, the mangrove margin of South Florida has undergone dramatic changes in response to a combination of a 0.7 foot rise in relative sea level in South Florida; four category 4-5 hurricane events; and reduction in water level and sheet flow from the interior freshwater marshes (the Everglades). The current condition is one of dramatic evolution of the coastal mangrove fringe. There has been a significant advance of the mangrove community into the freshwater wetlands in response to both sea level rise and reduced freshwater flow. Mangrove estuaries have retreated as much as 159 meters in response to hurricane events.

D.L. Childers (Florida International University personal communication) notes that although the mangrove ecotone is likely to be spatially dynamic over the time frame of Everglades' restoration, the future evolution of the coastal wetland margin involves many uncertainties. Predictions of the rate of sea level rise over the next 50 years are quite variable. It is difficult to predict how the balance of increased freshwater flow and variable predictions of sea level rise will control transgression. Long-term changes in regional climate will affect both storm frequency/intensity and inter-annual precipitation patterns. The dynamics of soil elevation change in these wetlands are not well documented. Models do not exist to reliably simulate the various combinations of sea level rise, freshwater flow, regional climate change, and soil elevation dynamics.

A sediment accretion model (Callaway et al. 1996) integrates information on sedimentation and substrate diagenetic processes and predicts substrate accretion under conditions of altered hydrology, water quality, and supply of mineral sediments. Despite trends and estimates of wetland soil accretion relative to sea level, the fact remains that shoreline transgression in relation to sea level rise is ongoing in South Florida. The lack of predictive capability regarding trends in the productivity and peat accretion of gulf mangrove forests, and the clearly suppressed productivity and peat accretion of the Florida Bay and Biscayne Bay mangrove fringes, yield a relatively high level of uncertainty that the mangrove forests of South Florida will accrete peat at a rate equal to the present rate of sea level rise.

Level of certainty - low

A.3.5.2 Mangrove Forests and Associated Plant Communities

Relationship of Mangrove Productivity to Nutrient Mixing and Freshwater Flow

Production and organic soil accretion in the oligohaline zone of mangrove forests of the Shark River and other gulf estuaries reflect enhanced levels of general estuarine productivity (Childers et al. 1999), as influenced by nutrient mixing between inflowing fresh water from the Everglades and tidally fluctuating salt water from the Gulf of Mexico (Rudnick et al. 1999). Production of the dwarf mangrove forests adjacent to Florida Bay reflects suppressed levels of general estuarine productivity, as influenced by limited nutrient mixing between relatively small Everglades inflows and dampened tidal fluctuations of low-phosphorus bay water. The lower production of Florida Bay mangrove forests appears to occur in part because northeast Florida Bay scavenges available phosphorus from coastal waters before it reaches the oligohaline zone of the Taylor Slough/Panhandle basin (Fourqurean et al. 1993). Productivity and organic sediment accretion in the mangrove estuary create a sink for dissolved organic nitrogen inputs from Everglades' flows (Chen and Twilley 1999, Rudnick unpublished data). This may provide a support function for Florida Bay by maintaining nitrogen limitation of productivity in the bay.

Productivity in the mangrove forests and associated plant communities is depressed by diminished nutrient mixing resulting from reduced freshwater flow volume and duration. Productivity in the mangrove forests and associated plant communities also is depressed by more frequent and extended periods of hypersalinity resulting from reduced freshwater flow volume and duration. Resumption of natural volumes and durations of freshwater flow are expected to increase productivity due to increased nutrient mixing and decreased incidence of hypersalinity.

A productivity peak in gulf estuaries is supported by evidence from many attributes (Childers et al. 1999). The relationship of the productivity peak to the balance between freshwater flow and nutrient content of gulf waters is likely but has yet to be demonstrated. It is not possible to predict how the balance between freshwater flow and nutrient content of Gulf of Mexico waters will change over the next 50 years, particularly when this requires parallel predictions of coastal eutrophication phenomena in this region of the gulf. Furthermore, no reliable models exist to aid in these difficult predictions. Nonetheless, we can hypothesize reliably well that increased freshwater flow alone should increase both the magnitude and spatial extent of the oligohaline productivity peak in the gulf mangrove ecotone.

The strong retention of phosphorus in the mangrove zone is already known, but the fate of nitrogen, which may strongly affect Florida Bay, is not known (D. Rudnick, South Florida Water Management District, personal communication). Evidence points toward potentially high denitrification rates which will help Florida Bay. Modeling by the Long-Term Ecological Research (LTER) Project based at Florida International University should provide a more accurate prediction of mangrove zone nutrient dynamics as a function of water levels and flows. The LTER project is funded by the National Science Foundation. It is investigating how variability in regional climate, freshwater inputs, disturbance, and perturbations affect the coastal Everglades ecosystem. The long-term research program will focus on testing the following central idea and hypotheses:

Regional processes mediated by water flow control population and ecosystem level dynamics at any location within the coastal Everglades landscape. This phenomenon is best exemplified in the dynamics of an estuarine oligohaline zone where fresh water draining phosphorus-limited Everglades' marshes mixes with water from the more nitrogen-limited coastal ocean.

Three hypotheses have been developed for this relationship:

- **Hypothesis 1:** In nutrient-poor coastal systems, long-term changes in the quantity or quality of organic matter inputs will exert strong and direct controls on estuarine productivity, because inorganic nutrients are at such low levels.
- **Hypothesis 2:** Interannual and long-term changes in freshwater flow control the magnitude of nutrients and organic matter inputs to the estuarine zone, while ecological processes in the freshwater marsh and coastal ocean control the quality and characteristics of those inputs.
- **Hypothesis 3:** Long-term changes in freshwater flow (primarily manifest through management and Everglades restoration) will interact with long-term changes in the climatic and disturbance (sea level rise, hurricanes, fires) regimes to modify ecological pattern and process across coastal landscapes.

Level of certainty - low

Relationship of Halophytic Prairie Expansion to Hurricane Impacts and Sea Level Rise

The area of halophytic prairie within the mangrove zone will expand in coming decades in association with hurricane impacts exacerbated by sea level rise (Armentano personal communication). Since the Labor Day hurricane of 1935, and more clearly, since Hurricane Donna in 1960, halophytic prairies have been a conspicuous feature of the mangrove zone. Evidence suggests that this community represents a long-term (on the order of decades, perhaps a century or more) landscape element that becomes established where tropical storms alter coastal sediments in such a way that mangrove and buttonwood forests are killed. Furthermore, in many areas, once the halophytic prairie (dominants include *Batis* *maritima*, *Salicornia* spp., and *Blutaperon vermicularis*) becomes established it appears capable of retarding recruitment of tree species, thus creating a long-term, low productivity nonpeat forming shrub-herb community within the forested mangrove zone.

The replacement of mangrove and buttonwood forests by halophytic prairie following severe hurricanes has been documented by Craighead (1971), Craighead and Gilbert, (1962), and Armentano et al. (1995). Uncertainty remains regarding the specific soil and seedling layer conditions in halophytic prairies, the factors limiting mangrove and buttonwood recruitment in these sites, and the specific forces that convert mangrove forest to halophytic prairie within the differing mangrove forest types of South Florida.

Level of certainty - moderate

Relationship of Tropical Forest Communities to Sea Level Rise

Sea level rise and consequent shifts in saline environments, mangrove environments and storm berms will differentially reduce or eliminate tropical forest communities and species that are intolerant of saline conditions, lowering overall (beta) diversity of the mangrove zone (Armentano personal communication). Embedded within the saline-adapted mangrove forest zone are unique tropical forest communities with limited tolerance of salt water and saline soils. Included are midden forests, thatch palm hammocks, mixed coastal hammocks and buttonwood hammocks. These communities, which contribute to the local and landscape species diversity within the mangrove zone (including providing substrate for epiphytes) are able to persist because of the presence of elevated substrates like storm berms and human-originated deposits. As coastal areas become increasingly marine, they will be exposed to salt stress and increasing competition from salt-adapted species. The extent to which the nonsalt adapted communities will be able to move inland in a dominantly freshwater wetland environment is unknown but may be limited by site availability and competition from freshwater wetland and bay swamp species. Thus these communities may become increasingly rare in the coming decades.

The distribution of nonsalt tolerant tropical forest communities on elevation rises within the mangrove zone has been described by Craighead (1971), Craighead and Gilbert (1962), Armentano et al. (2000), and Jones and Armentano (1999). Key uncertainties include the extent to which changing coastal conditions will reduce growth and aerial extent of these nonmangrove forest communities, and whether these species are capable of shifting to more interior sites.

Level of certainty - moderate

Relationship of Coastal Lake Submerged Aquatic Vegetation to Salinity and Freshwater Flow

Submerged aquatic vegetation (SAV) in the coastal lakes and basins of the mangrove estuary reflects seasonal salinity variations from oligohaline to mesohaline conditions. Prolonged periods of elevated salinity in the coastal lakes and basins, resulting from diminished freshwater flow volume and duration, have reduced the seasonal duration and cover of these species along shorelines and in tributaries. Beds of SAV are expected to persist in larger beds, longer into the dry season, and lower in the estuarine system when oligohaline to mesohaline conditions are restored upon the resumption of natural freshwater flow volume and duration.

Reduction in beds of SAV has contributed to the decline in numbers coot, scaup, widgeon and pintail that were once seasonally abundant in the coastal lakes and basins (Kushlan et al. 1982). Extended persistence and cover of SAV resulting from prolonged periods of oligohaline to mesohaline conditions will encourage the return of winter populations of waterfowl to the coastal lakes and basins.

The species richness and total and species-specific percent cover of the SAV found in the individual lakes, ponds and bays that make up this aquatic network vary both seasonally and inter-annually in fairly predictable patterns that are related to salinity (Morrison and Bean 1997, Montaque et al. 1998, Richards and Fourqurean 1999). Salinity ranges for the suite of 10-12 species are well documented, including *Utricularia* and *Najas* under oligohaline salinities with an upper limit of approximately 5-8 ppt, *Chara* under mesohaline salinities of approximately 15-20 ppt, and *Ruppia* under mesohaline salinities of 10-25 ppt.

The waterfowl species that once aggregated in large numbers in the coastal lakes and basins of the mangrove zone are dependent on SAV as their primary food resource. Their local decline corresponds to the decline in that food resource, despite the overall resurgence of populations in other parts of North America. Recent high-rainfall years have witnessed an increase in coot numbers on the West Lake to approximately 2,000 during winter 1996-1997 (O.L. Bass, Jr., Everglades National Park, personal communication), but not to the population size of approximately 50,000 that overwintered there until the 1960s (Kushlan et al. 1982).

Level of certainty - high

Relationship of Tidal Creek Loss to Freshwater Flow and Sea Level Rise

The dendritic pattern of tidal creeks and adjacent salt marshes within the mangrove forests is being lost, due to mangrove encroachment and siltation resulting from reduced freshwater flow volume and duration in combination with sea level rise. The siltation and mangrove encroachment of tidal creeks (Craighead 1971, Meeder et al. 1996) has progressed to the extent that open water courses that were described earlier this century are no longer recognizable (G. Simmons, gladesman, personal communication). The causal factors, including the relative contributions of reduced freshwater flow and sea level rise, remain unclear.

Level of certainty - low

Relationship of Plant Community Structure to Invasion by Exotics

The spread of the exotic plants *Schinus* and *Colubrina* is changing community structure of mangrove forests and associated plant communities. *Schinus* and *Colubrina* have become established in some mangrove forests and tropical forest communities of the Everglades mangrove estuaries (Armentano et al. 1995). Prevention of their continued spread requires an intensive program of manual removal and herbicide application.

Level of certainty - high

Changes in the "White Zone" in Relation to Sea Level Rise and Freshwater Flow

The position of the "white zone", a band of relatively unproductive coastal wetland that appears white on color infrared or black-and-white aerial photos, is considered an indicator of the balance between fresh water supplied from upstream sources and rising sea level. If sea level continues to rise at its current rate or faster, the leading edge of the white zone will continue to move toward the interior, except along tidal creeks or major drainages. These changes will be least evident in areas in which freshwater input is augmented and greatest in areas cut off from freshwater flow. In settings where further interiorward movement is prevented by canals, roads or other barriers, the white zone will be entirely supplanted by closed-canopy mangrove scrub communities similar to those currently bounding it on the coastal side.

Although production and composition in the white zone are certainly affected by some of the same environmental factors, it is primarily its low cover and reflective substrate that defines it. Plant species composition within the white zone has changed over time, and currently varies considerably throughout South Florida. In the future, the long-term trend from a mangrove-graminoid mixture to a monodominant mangrove community is expected to continue, more rapidly in water-deprived basins than those experiencing surface water sheet flow. In general, the nature of the future white zone will be subject to many local factors, in ways our current understanding does not permit us to predict. For instance, inasmuch as the South Florida white zone is associated with phosphorus-deficient marl or limestone substrates, the soil materials encountered in its movement away from the coast are likely to affect it at population, community and ecosystem levels.

Egler (1952) described the white zone as a band of low, open vegetation separating the mangrove swamps adjacent to the southeast Saline Everglades coast (Taylor Slough to Turkey Point) from the sawgrass marshes of the interior. Its composition included a mixture of sawgrass, spikerush and red mangrove. He considered the inner edge to mark the farthest extent of storm tides. Ross et al. (2000) documented changes in the extent and plant species composition of the white zone since Egler's work. They found interiorward movement throughout the region over circa 50-year time period, ranging from less than 1 to about 4 kilometer. Movement was maximum in areas entirely cut off from upstream freshwater sources (wetlands east of US 1), minimum in wetlands whose water supply was supplemented by canal sources (wetlands west of US 1 and directly south of the C-111 Canal), and intermediate in more remote portions of Everglades National Park (wetlands north of Joe Bay and southwest of the C-111 Canal). These patterns strongly suggest that freshwater input may partially mitigate for a phenomenon driven primarily by sea level rise. Working along a hydrologically isolated coastal transect south of Turkey Point, Meeder et al. (1996) documented an inland movement of the interior boundary of the white zone of 1,900 meters during the period 1940-1994. This distance equated to a vertical shift of 13 centimeters, during a period in which sea level rose by about 11 centimeters.

The white zone is not necessarily fixed or invariant in species composition over time. Egler (1952) described its composition as a mixture of sawgrass, spikerush and red mangrove. Ross et al. (2000) integrated their own vegetation data with field results presented by Egler (1952), and concluded that the compositional gradient in southeast saline Everglades marshes had shifted considerably further inland between the two surveys than had the position of the white zone. In a subsequent study at Turkey Point, Ross et al. (2002) found several diatom taxa, but no plants or mollusks that were restricted to the white zone.

The South Florida white zone is a local manifestation of a more widespread coastal phenomenon, in which a zone of relatively unproductive or low-stature vegetation occupies a position near the interface of marine with fresh water or terrestrial ecosystems (e.g., Carter 1988, Montague and Wiegert 1990). To our knowledge, there has been little or no research on the origin of this biogeographic pattern. Ross et al. (2002) hypothesized that the following four factors were involved locally: 1) wide seasonal fluctuations in salinity and moisture content, 2) absence of freshwater input from upstream sources, 3) heavy marl soils that may contribute to phosphorus limitation, and 4) sporadic occurrence of natural disturbances. However, a better functional understanding of white zone dynamics will require more extensive transect surveys, as well as manipulative experiments in which one or more of the above factors are controlled.

Level of certainty - moderate

A.3.5.3 Estuarine Fish Communities and Fisheries

Relationship of Resident Mangrove Fish Populations to Estuarine Salinity, Nutrient Status and Hydrology

Populations of small marsh fishes in the mangrove zone (sheepshead minnows, sailfin mollies, topminnows, rainwater killifish and sunfish) reflect 1) estuarine salinity, 2) estuarine nutrient status and productivity, and 3) estuarine hydroperiod and drying patterns. These stressors and their effects on populations of small wetlands fish are discussed in the following paragraphs.

The resident fish assemblage decreases in density and size distribution when salinity exceeds 5-8 ppt (Lorenz 1997, 1999, 2000). This relationship has been demonstrated for the Florida Bay mangrove wetlands, but not for the Gulf of Mexico estuaries. Furthermore, salinity is inversely auto-correlated with hydroperiod in the Florida Bay mangrove wetlands, and the relative contribution of each of these variables is not known.

Densities of small fishes in Shark River Slough are approximately 50 percent higher at Rookery Branch, near the interface with the Gulf of Mexico, in comparison to more upstream sites (Trexler and Loftus 2000). Higher fish densities at Rookery Branch correspond to the enhanced nutrient status and productivity peak in that area (Childers et al. 1999). In contrast, lower fish densities at the estuarine interface of Taylor Slough relative to sites upstream (Lorenz 1999, 2000, Trexler and Loftus 2000) correspond to low nutrient status and productivity there. The hypothetical relationship of fish density to enhanced productivity in gulf estuaries is based on a limited number of fish samples collected from one site (Rookery Branch).

Seasonal drying patterns following extended periods of flooding can condense the oligohaline marsh fishes in the Florida Bay estuarine interface to densities comparable to those in the gulf estuaries. Populations of small marsh fishes in the mangrove zone are expected to increase in density, size distribution and seasonal concentration upon the resumption of natural freshwater flow volume and duration to the estuary, due to the combined effects of extended periods of oligohaline salinity, enhanced estuarine nutrient status and productivity, enhanced hydroperiod and drying patterns, and tidal creek restoration. Receding water levels following an extended annual hydroperiod can concentrate small fishes in Craighead Basin, at the estuarine interface of Taylor Slough, to densities comparable to the estuarine interface of Shark River Slough (Lorenz 2000).

Relationships of fish populations to hydrology in gulf estuaries are unknown. Populations of small marsh fishes in gulf estuaries may respond to hydroperiod and water recession patterns very differently than Everglades marsh fish communities because of more complex topography created by a dendritic pattern of tidal creeks. The tidal creeks may further influence the resident mangrove fish community as corridors for the immigration of juveniles of more marine species.

Level of certainty - low

Relationship of Resident Mangrove Fish Community to Exotic Fishes

The resident mangrove community of small marsh fishes is presently dominated by the exotic Mayan cichlid between Highway Creek and the Taylor River, and expansion of the cichlid into other parts of the estuary is likely. Trexler et al. (in review) has reported that the Mayan cichlid is the dominant species in the mangrove estuary of Florida Bay from Taylor River east to Highway Creek.

Level of certainty - high

Relationship of Spotted Seatrout and Common Snook Populations to Salinity

Juvenile density and sport catch of spotted seatrout in the coastal basins of the mangrove estuary reflect the suitability of estuarine habitat and nursery grounds as influenced by salinity and water levels. Juvenile density is expected to increase in the coastal basins from Terrapin Bay west due to the resumption of natural volumes and timing of freshwater flow to the estuary, in response to the reduction of the frequency and duration of hypersalinity events in the basins, in combination with the prolongation of oligohaline conditions in the tidal tributaries. Sport catch per unit effort is anticipated to follow a similar trend, indicating beneficial estuarine conditions for the survival of juveniles to adults.

Post larval spotted sea trout utilize the coastal basins of the Florida Bay mangrove estuary as nursery grounds from Terrapin Bay west to Whitewater Bay. Densities of post-larvae in those basins are highest at an intermediate salinity range of 20-30 ppt, and densities drop when salinity exceeds that of seawater (35 ppt) (Thayer et al. 1998, Schmidt 1993). It is unknown if growth and survival of spotted seatrout will predict the adult abundance and distribution based on sport catch per unit effort in relation to environmental conditions.

Level of certainty - moderate

Relationship of Pink Shrimp Juvenile Density and Adult Catch Per Unit Effort to Salinity and Freshwater Flow

Juvenile density of pink shrimp in Whitewater Bay reflects the suitability of estuarine nursery grounds as influenced by salinity. Optimal salinity conditions for survival appear to be somewhat below that of seawater (35 ppt). Pink shrimp juvenile density is expected to increase in Whitewater Bay in response to the restoration of estuarine salinity ranges and the reduction of the frequency and duration of hyper-salinity events. Beneficial conditions in Whitewater Bay will augment the annual pink shrimp recruitment from the Florida Bay and gulf estuaries to contribute to increased annual catch per unit effort in the Tortugas fishing grounds.

Pink Shrimp spawning occurs in the Dry Tortugas area, and eggs and larvae are carried inshore by currents and tides (Jones et al. 1970, Hughes 1969). Browder (1985), Sheridan (1996) and Browder et al. (1999) have found positive relationships between indices of freshwater inflow to the coast and Tortugas pink shrimp landings. Sheridan's annually updated statistical model based on various freshwater inflow indices has successfully predicted annual pink shrimp landings in most of the past decade (P. Sheridan, National Marine Fisheries, unpublished data; Sheridan 1996). The salinity gradient associated with coastal runoff may provide navigational directions to immigrating young pink shrimp (Hughes 1969). Survival rates of juvenile pink shrimp are sensitive to salinity and decrease markedly under extreme hypersaline conditions (Browder et al. 1999). Optimal salinities for survival are not fully determined, but probably are somewhat below that of seawater (35 ppt). Tabb et al. (1962), Rice (1997), and others have documented that the mangrove estuaries in the Whitewater Bay system of Everglades National Park are pink shrimp nursery grounds. However, two areas of uncertainty remain. It is not possible to trace the origins of Tortugas landings to specific nursery grounds and environmental conditions, including the mangrove estuary coastal basins, Florida Bay and Gulf of Mexico estuaries. There is a lack of sufficient information to quantitatively link juvenile pink shrimp abundance and salinity in the estuary to upland water management practices.

Level of certainty - moderate

A.3.5.4 Wood Stork and Roseate Spoonbill Nesting Colonies

Relationship of Nesting Colony Locations to Resident Mangrove Fish Populations

Nesting colonies of wood stork and great egret in South Florida were concentrated in the tributary headwaters and southern mainland of the Everglades mangrove estuaries during much of the Twentieth Century. Those colonies have completely collapsed beginning in the 1960s. Nesting colonies of roseate spoonbill have shifted in distribution westward from northeast Florida Bay to the Gulf of Mexico during the same time period.

The collapse of the wood stork and great egret colonies, and the abandonment of northeast Florida Bay nesting islands by spoonbills, are attributed to a decline in the production and availability their food base, which is the resident community of small marsh fishes in the Everglades mangrove estuaries. The topminnows and sunfish that grow to a size that wood storks can capture are considered to be particularly important (Ogden et al. 1978). Because of their close linkage to the resident mangrove fish community, the nesting colonies reflect conditions of estuarine salinity, hydrology, nutrient status and productivity that affect the density, size distribution, and seasonal concentration of the fishes.

The resumption of natural freshwater flow volume and duration to the estuary is expected reestablish nesting colonies of wood stork and great egret in the tributary headwaters and southern mainland, and to renew spoonbill nesting in northeast Florida Bay, in response to increased production and availability of the resident mangrove fishes. Contributing factors include increased frequency and duration of oligohaline salinity conditions, restored hydroperiods and related drying patterns, and enhanced estuarine nutrient status and productivity.

There is a high degree of certainty that the large nesting colonies of wood storks and great egrets in the Everglades during the early 1900s were concentrated in the Everglades mangrove estuaries (Ogden 1994). The East River, Lane River, Rookery Branch, Broad River, and Rodgers River Bay colonies, in the headwaters of the tidal rivers entering the Gulf of Mexico, supported approximately 90 percent of the total nesting population of these and other wading bird species during the period of 1931-1946. Additional colonies along the southern mainland of Florida Bay included Alligator Lake, Mud Lake, Mud Hole, Cuthbert Lake and Madeira Rookery. There is also a high degree of certainty that roseate spoonbill nesting in northeast Florida Bay has decreased and has shifted in distribution from eastern to western Florida Bay (Powell et al. 1989).

There is a low degree of certainty regarding the causes of the collapse of all of the coastal nesting colonies of wood storks and great egrets and the likelihood of their reestablishment upon the resumption of natural freshwater flows. The hypothesis that colony abandonment is related to population decline in the resident mangrove fishes due to altered hydrology (Ogden 1994) depends on the validity of the hypotheses relating estuarine geomorphology to sea level, estuarine productivity to nutrient mixing and freshwater flow, and resident mangrove fish populations to estuarine salinity, nutrient status and hydrology. Levels of certainty in all three of these hypotheses have been characterized as low.

Bjork and Powell (1994) provide evidence that the decline of spoonbill nesting in northeast Florida Bay is related to the reduction in populations of resident mangrove fishes upon which they feed, due to increased salinity resulting from reduced freshwater flow. Small fishes have been reported to be the primary part of the diet of roseate spoonbills in Florida Bay (Allen 1942, Powell and Bjork 1990). The relatively sparse populations of marsh fishes along the estuarine interface of northeast Florida Bay today require very specific drying patterns to make them available in densities adequate to support spoonbill nesting. Lorenz (2000) reported a water depth threshold of 12 centimeters, averaged over the 21-day post-hatching period of roseate spoonbills that is necessary to concentrate the fish prey base in Taylor Slough coastal sites. Water level recession to 12-centimeters depth during that period can concentrate the normally low fish density in that region to 85 fish per square mile in the remaining pockets of water. The 12-centimeter depth threshold fits well with success or failure of spoonbill nesting in northeast Florida Bay colonies.

Level of certainty - low

A.3.5.5 Estuarine Crocodilian Populations

The loss of alligators from the mangrove estuary is attributed to increased salinity in the tidal tributaries resulting from diminished freshwater flow volume and duration. According to Craighead (1968) alligators were historically abundant (and nested) in freshwater mangrove areas of the Everglades. Today nesting is limited, and few juveniles are observed. Reduced freshwater flow into estuaries apparently has resulted in succession of former freshwater mangrove areas to saltwater systems, changing the pattern of occupancy by alligators. Salinity is a major factor limiting the distribution and abundance of alligators in estuarine habitats (Dunson and Mazzotti 1989, Mazzotti and Dunson 1989). Alligators lose the capacity to utilize estuarine habitats for feeding, growth and reproduction when salinity exceeds oligohaline levels (Joanen 1969). When alligators occur in salt water it is usually to feed, and there is always a freshwater refugium in close proximity (Jacobsen 1983, Tamarack 1988). In a natural experiment in North Carolina, alligators that were exposed to diversion of freshwater flows due to construction of a power plant relocated to the diversion canal to maintain access to fresh water. Small alligators are especially vulnerable to exposure to salt water. In laboratory experiments, small alligators ceased feeding and exhibited signs of stress when exposed to salinities greater than 10 ppt (Lauren 1985). Alligators do feed and gain mass at 4 ppt (Mazzotti and Dunson 1984). For these reasons alligators are good indicators of restoring freshwater flows to estuarine systems and the subsequent reestablishment of an extensive freshwater/brackish water zone. The alligator is expected to repopulate and resume nesting in the freshwater reaches of tidal rivers upon the restoration of freshwater flow volume and duration to the Everglades mangrove estuaries.

The American crocodile dwells in the ponds and creeks of the mangrove estuaries of Florida Bay (Ogden 1976, Mazzotti 1983). American crocodiles are tolerant of a wide salinity range as adults because of their ability to osmoregulate (Mazzotti 1989). Juvenile crocodiles lack this ability, however, (Mazzotti 1989) and their growth and survival decline at salinities exceeding 20 ppt (Mazzotti et al. 1988, Mazzotti and Dunson 1984, Moler 1991). Juvenile crocodiles tend to seek freshwater pockets such as black mangrove stands when those choices are available. Diminished freshwater flow volume and duration has increased salinity in the shoreline and tidal creek habitats of juvenile crocodiles, thereby reducing their growth and survival in the mangrove estuary. Resumption of natural freshwater flow volume and duration to the mangrove estuaries will reestablish a salinity gradient with levels less than 20 ppt in shoreline and tidal creek habitats that will increase the growth and survival of juvenile crocodiles.

Level of certainty - high

A.3.6 Research Questions

The three interrelated causal relationships, estuarine productivity and subsequent effects on sediment accretion and food webs, of the Everglades mangrove estuaries have a low level of certainty. Supporting research is required to increase the level of certainity of these relationships.

Estuarine Productivity

How will estuarine productivity change in relationship to the restoration of freshwater flow, to sea level rise, and to the associated variables of nutrient mixing and salinity? How do the mangrove forests of Florida Bay and the Gulf of Mexico differ in this respect? Develop quantitative relationships and predictive models of estuarine productivity in relation to freshwater flow, sea level, salinity and nutrient mixing.

Estuarine Sediment Accretion

How will estuarine productivity affect the accretion of mangrove peat, and will predicted rates of peat accretion equal or exceed the predicted local, long-term rise in sea level? How will predicted rates of organic and inorganic sediment accretion, in combination with sea level rise, influence shoreline transgression and an inland shift in marine and estuarine environments? Develop quantitative relationships and predictive models of peat accretion resulting from productivity in gulf mangrove forests, as affected by sea level rise, freshwater flow and regional climate change. Similarly, develop quantitative relationships and predictive models of accretion of the coastal storm berm of Florida Bay as affected by sea level rise, freshwater flow and regional climate change.

Estuarine Food Webs

How will estuarine productivity interact with salinity and hydrology to affect populations of resident mangrove fishes, in food webs supporting nesting colonies of wood stork and roseate spoonbill? Develop quantitative relationships and predictive models of resident mangrove fish population density and size structure in relation to estuarine productivity, salinity and hydrology. Develop quantitative relationships and predictive models of the energetic requirements of wood stork and roseate spoonbill nesting colonies in relation to the population density, size structure and seasonal concentration of resident mangrove fishes.

A.3.7 Hydrologic Performance Measures

Ecological restoration of the Everglades mangrove estuaries requires a reduction in the frequency of high salinity events that have been identified as detrimental for each coastal basin through the conceptual ecological model process. Another restoration measure is to increase the frequency of low salinity events that have been identified as beneficial for each coastal basin. The high and low salinity levels represent the best professional judgement of those scientists working in the mangrove estuary, based on the existing information on the biological requirements and distributions of the estuarine organisms that are described above, available salinity data, and field observation.

Table A-1 displays the lower and upper salinity levels identified for coastal basins. It is desirable to decrease the frequency that salinity exceeds upper levels, and to increase the frequency that salinity drops below lower levels.

Table A-1: Salinity Values

Basin	Lower Level	Upper Level
Joe Bay	5 ppt	15 ppt
Little Madeira Bay	15 ppt	25 ppt
Terrapin Bay	25 ppt	35 ppt
Garfield Bight	25 ppt	35 ppt
North River Mouth	5 ppt	15 ppt

The strategy for ecological restoration of the Everglades mangrove estuaries is to maintain freshwater heads and flows in the Everglades at the upstream end of the salinity gradient in order to achieve desirable salinity regimes in the Florida Bay coastal basins at the downstream end of the salinity gradient. Regression analyses demonstrated inverse relationships of salinity in the coastal basins to water level upstream in the Everglades (Davis 1997). The regressions indicated that stages of 7.3 and 6.3 feet mean sea level at the P33 gage in mid-Shark River Slough produce the lower and upper salinity levels for Joe Bay, Little Madeira Bay, Terrapin Bay, Garfield Bight and North River Mouth. Four performance measures for the ecological restoration of the Florida Bay mangrove estuaries are derived from the simulated stages at the P33 gage and salinity levels in the coastal basins: frequency of stages of 6.3 feet or greater and 7.3 feet or greater at P33; and Natural Systems Model (NSM) high and low salinity levels.

The frequency of stages of 6.3 feet or greater at P33 is applied as a performance measure for the Florida Bay coastal basins. The performance measure is the number of months during the 31-year period of record when stages at P33 rose to, or above, 6.3 feet. The target is the number of months that NSM provided stages of 6.3 feet or above. A reduced frequency of high salinity events is given a high priority in the ecological restoration of the coastal basins.

The frequency of stages of 7.3 feet or greater at P33 is applied as a performance measure to the Florida Bay coastal basins. The performance measure is the number of months during the 31-year period of record when stages at P33 rose to, or above, 7.3 feet. The target is the number of months that NSM provided stages of 7.3 feet or above. An increased frequency of low salinity events is given a lower priority than a reduced frequency of high events.

The transition from the late dry season to the early wet season during March through June is a critical period to estuarine organisms in the Florida Bay coastal basins regarding the frequency and duration of high salinity events. Salinity is estimated based on relationships between mean monthly salinity in the coastal basins and water stage at the P33 gage in mid-Shark River Slough. The cumulative salinity difference (ppt) from the high salinity levels that have been identified for Florida Bay coastal basins is summed during the dry/wet season transition months of March-June. Differences are summed over five coastal basins (Joe Bay, Little Madeira Bay, Terrapin Bay, Garfield Bight and North River Mouth) and over the 31-year period of record. Differences above the specified high salinity levels are given a positive value, and differences below the high salinity levels are given a negative value. The target is to reduce the cumulative salinity difference to a value that does not exceed the cumulative difference produced by NSM.

During the August-October transition from the late wet season to the early dry season, it is important to achieve low salinity levels in the Florida Bay coastal basins to provide the seasonal environment for low-salinity estuarine organisms and to postpone the onset of high salinity events further into the dry season. Salinity is estimated based on relationships between mean monthly salinity in the coastal basins and water stage at the P33 gage in mid-Shark River Slough. The cumulative salinity difference (ppt) from the low salinity levels that have been identified for the Florida Bay coastal basins is summed during the wet/dry season transition months of August-October. Differences are summed over the five coastal basins and over the 31-year period of record. Differences above the specified low salinity levels are given a positive value, and differences below the low salinity levels are given a negative value. The target is to reduce the cumulative salinity difference to a value that does not exceed the cumulative difference produced by NSM.

Ecological attributes and indicators of restoration success in the Florida Bay mangrove estuaries that are linked to the above hydrology/salinity performance measures in the conceptual ecological model include 1) increased production of low-salinity mangrove fishes, 2) reestablishment of coastal nesting colonies of wood storks/great egrets and eastern Florida Bay colonies of roseate spoonbill, 3) earlier timing of coastal colony formation by wood storks/great egrets and of Florida Bay colony formation by roseate spoonbills, 4) increased growth and survival of juvenile American crocodiles, 5) return of American alligators to the tidal rivers, 6) increased cover of low-to-moderate salinity aquatic macrophyte communities in coastal lakes and basins, 7) return of seasonal waterfowl aggregations to coastal lakes and basins, 8) enhanced nursery ground value for spotted seatrout and pink shrimp in coastal basins, and 9) persistence and resilience of the mangrove, salt marsh and tidal creek vegetation mosaic.

A.3.8 Ecological Performance Measures

Table A-2 lists the ecological performance measures associated with the Everglades Mangrove Estuaries Conceptual Ecological Model.

Table A-2: Ecological Performance Measures for the Everglades Mangrove Estuaries Conceptual Ecological Model

Estuarine Geomorphology
Sea Level Rise
Shoreline Transgression
Coastal Storm Berm Accretion/Erosion
Mangrove Soil Accretion
Salinity Gradient/Mosaic

Mangrove Forests and Associated Plant Communities
    Mangrove Forest Functional Roles
        Mangrove Primary Productivity
        Mangrove Soil Accretion
        Nitrogen Accretion in Mangrove Soils
        Nutrient Flux Into and Out of Mangrove Estuary
    Plant Community Distribution and Taxonomic Composition
        Mangrove Forests
        Tidal Creeks and Adjacent Salt Marshes
        Coastal Lake and Basin SAV/Waterfowl
        White Zone
        Halophytic Prairie
        Tropical Forest Communities

- Estuarine Fish Communities and Fisheries
  - Resident Mangrove Fish Community
    - Population Density
    - Taxonomic Composition
    - Size Structure
    - Seasonal Concentration
  - Spotted Seatrout
    - Juvenile Density
    - Sport Catch Catch Per Unit Effort
  - Pink Shrimp
    - Juvenile Density
    - Commercial Catch, Tortugas Landings Catch Per Unit Effort

- Wood Stork and Roseate Spoonbill
  - Wood Stork/Great Egret Nesting Colonies: Southern Mainland and Tributary Headwaters
    - Colony Distribution
    - Timing of Colony Formation
    - Number of Nesting Pairs
    - Nesting Success
  - Roseate Spoonbill Nesting Colonies: Florida Bay and Gulf of Mexico
    - Colony Distribution
    - Number of Nesting Pairs

- Estuarine Crocodilian Populations
  - American Alligator
    - Distribution and Density
    - Size Class Relative Abundance
    - Nest Distribution and Density
    - Body Condition Index
  - American Crocodile: Juvenile Growth and Survival

A.3.9 Model

The diagram for the Everglades Mangrove Estuaries Conceptual Ecological Model is presented in Figure A-13. The key to the symbols used in the diagram is presented in Figure A-2.

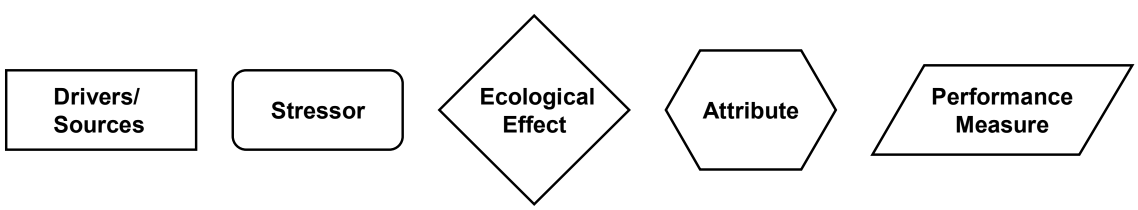

Figure A-12: Key to the Symbols Used in the Following Diagram

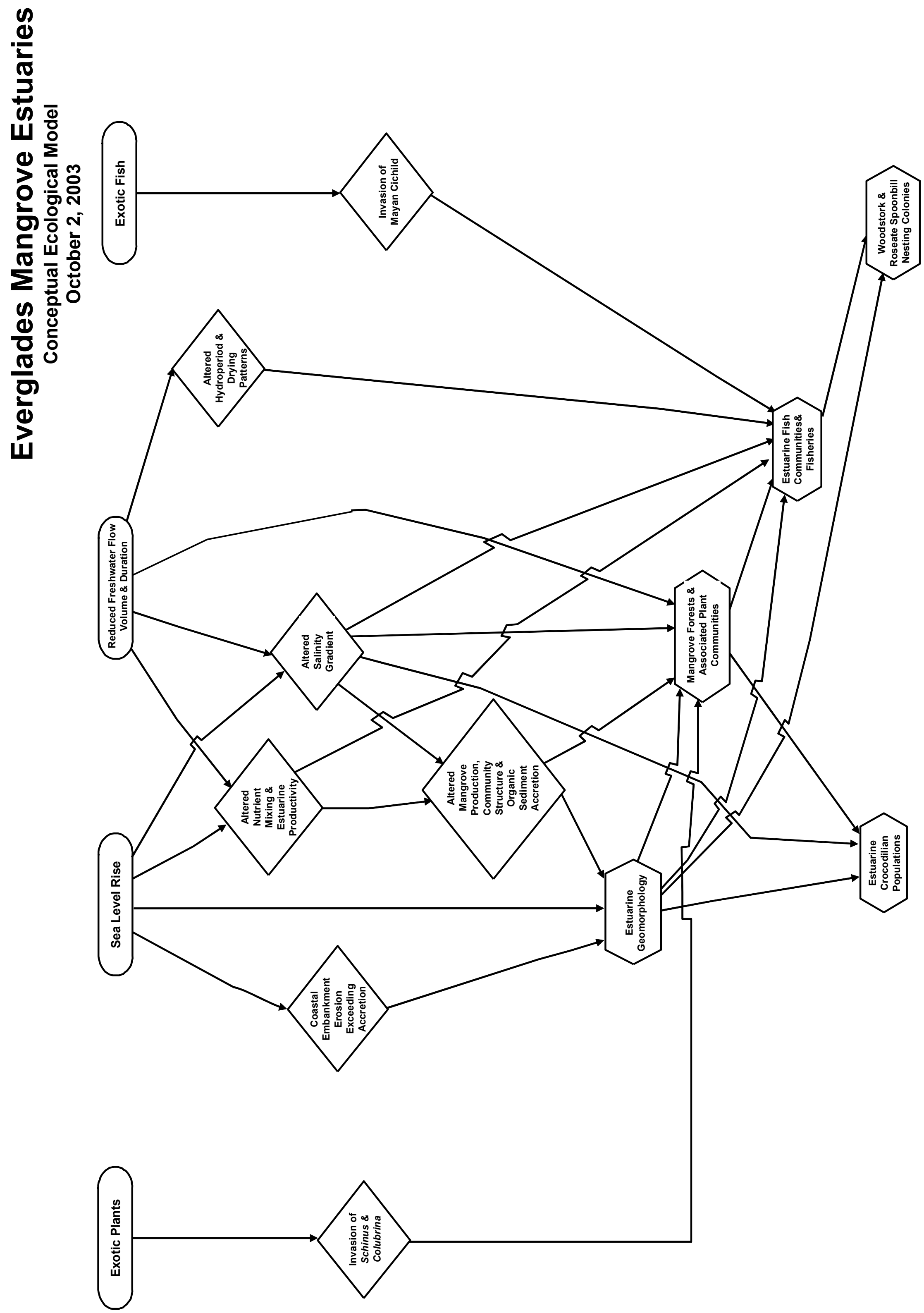

Figure A-13: Everglades Mangrove Estuaries Conceptual Ecological Model Diagram

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A.5 FLORIDA BAY CONCEPTUAL ECOLOGICAL MODEL

A.5.1 Model Lead

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A.5.2 Introduction

A simple conceptual ecological model of the Florida Bay ecosystem (Figure A-17) is presented here. This model is consistent with our effort to assess the current understanding of South Florida's ecosystems, identify the most important human effects on these ecosystems, identify restoration goals and success criteria, and identify the minimum measurements required to determine whether these criteria are being met. The structure of the model is largely based on the expert opinions of scientists who have focused their attention on Florida Bay during the past several years. During this time, detailed reviews of our understanding of the Florida Bay have been presented (Boesch et al. 1993, Boesch et al. 1995, Boesch et al. 1997, Fourqurean and Robblee 1999). Detailed plans that identify quantitative information needs for environmental management decision making, as well as strategies to provide this information have also been presented (Armentano et al. 1994, Armentano et al. 1997). While the conceptual ecological model presented here is largely consistent with the body of knowledge described in the reviews and plans noted above, some details or omissions of this model may not be consistent will the opinions of some contributors to the interagency Florida Bay Research Program.

Figure A-17: The Boundary of the Florida Bay Conceptual Ecological Model

A.5.2.1 Florida Bay Primer

Florida Bay is a triangularly shaped estuary, with an area of about 850 square miles that lies between the southern tip of the Florida mainland and the Florida Keys. About 80 percent of this estuary is within the boundaries of Everglades National Park. A defining feature of the bay is its shallow depth, with a mean depth of about 1 meter (Schomer and Drew 1981). This shallowness allows light to penetrate through the water to the sediment surface in almost all areas of the bay and results in the potential for the bay to sustain seagrass beds as a dominant habitat and source of productivity. The shallowness of the bay also affects the circulation and salinity regime of the bay; with a complex network of shallow mud banks, water exchange among the bay's basins and between these basins and the Gulf of Mexico is restricted (Smith 1994, Wang et al. 1994). With a long residence time and shallow depth, the salinity of Florida Bay water can rapidly rise during drought periods. Salinity levels as high as twice that of seawater have been measured (McIvor et al. 1994). Another defining feature of the bay is that the sediments are primarily composed of carbonate mud, which can scavenge inorganic phosphorus from bay waters (DeKanel and Morse 1978).

Until the 1980s, Florida Bay was perceived by the public and environmental managers as being a healthy estuary, with clear water, lush seagrass beds, and productive fish and shrimp populations. By the mid-1980s, however, catches of pink shrimp had declined dramatically (Browder et al. 1999) and in 1987, the mass mortality of turtle grass (*Thalassia*) beds began (Robblee et al. 1991). By 1992, the ecosystem appeared to shift from a clear water system, dominated by primary production on the sediment (benthic production) to a turbid water system, dominated by algae blooms in the water column and resuspended sediment. The conceptual ecological model focuses on these changes in seagrasses and water quality as the central issues to be considered by environmental managers.

A.5.2.2 Reality Check

The simple model presented below does not address the spatial complexity of Florida Bay. Florida Bay is, indeed, not so much a singular estuary, but a complex array of basins, banks, and islands that differ across a set of regions. The mosaic of seagrass habitat and mangrove habitat, as well as water quality and ecosystem processes vary distinctly with this spatial variation. Nevertheless, only a single, generic model is described and this model is intended to summarize the main characteristics and trends of the bay. While the structure of this model is appropriate for most areas of the bay, the relative importance of the model's components differ considerably among the bay's subregions. Any application of this model (for example, recommendations for a specific set of monitoring parameters and guidelines) must take the spatial variability of the bay into account.

A.5.3 External Drivers and Ecological Stressors

It has often been assumed that a direct cause of Florida Bay's ecological changes is a long-term increase in the bay's salinity that resulted from the diversion of fresh water away from Florida Bay via South Florida Water Management District canals. However, recent research has indicated that the bay's changes are not attributable to a single cause; while decreased freshwater inflow and resultant increased salinity have been part of the problem, it appears that other human activities, as well as natural forces, have also contributed to the problem (Armentano et al. 1997, Boesch et al. 1993, Boesch et al. 1995, Boesch et al. 1997, Fourqurean and Robblee 1999). This conceptual ecological model thus includes both natural and human derived sources of stress (Figure A-19, Section A.5.9). The discussion of external drivers and ecological stressors below is organized by stressor with the drivers in bold.

A.5.3.1 Altered Salinity Regime

The salinity regime of an estuary is a primary determinant of the species composition of communities, as well as strongly influencing functions of these communities (Sklar and Browder 1998). Salinity is a direct stress on biota; all estuarine biota have adapted to a given salinity range and a given degree of salinity variability. For a given organism, changing salinity beyond this range or too quickly within this range can result in poor health or death. Thus long-term changes in salinity *level* or *variability* are detrimental to some species, but favorable for other species.

Florida Bay's salinity regime varies greatly over time and space. This variation ranges from coastal areas that can be nearly fresh during the wet season, to large areas of the central bay that can have salinity levels near 70 parts per thousand (ppt) during prolonged droughts, to nearly stable marine conditions (about 35 ppt) on the western boundary of the bay. The main forces that determine salinity regime in the bay are the inflow of fresh water from the Everglades, rainfall over the bay, evaporation from the bay, and exchange with seawater from the Gulf of Mexico and the Atlantic Ocean. Both freshwater inflow and seawater exchange have changed drastically in the past hundred years, resulting in an alteration of the bay's salinity regime.

Freshwater inflow to Florida Bay decreased in volume and changed in timing and distribution during this century because of **water management**. Hydrologic alteration began in the late 1800s, but accelerated with the construction of drainage canals by 1920, the Tamiami Trail by 1930, and the Central and South Florida (C&SF) Project and South Dade Conveyance System from the early 1950s through 1980 (Light and Dineen 1994). With the diversion of fresh water to the Atlantic coast and Gulf of Mexico coast, the bay's mean salinity inevitably increased. The extent of this increase and how the variability of salinity changed is not known, but is the subject of current research.

Results from this research indicate that another important development that altered the salinity regime of Florida Bay was construction of the **Flagler Railway** across the Florida Keys from 1905 to 1912 (Swart et al. 1996, Swart et al. 1999). It appears that in the last century, prior to railway construction and water management, Florida Bay had a lower mean salinity and more frequent periods of low (10 ppt - 20 ppt) salinity than during this century. The extent and frequency of high salinity events does not appear to have changed between centuries. The bay's salinity regime changed abruptly around 1910 because passes between the keys were filled to support the railway. Thus, water exchange between Florida Bay and the Atlantic Ocean was decreased and water circulation throughout the bay was probably altered.

Two important natural controls of salinity, **sea level rise** and the frequency of **major hurricanes** must also be considered. Florida Bay is a very young estuary, the product of sea level rising over the shallow slope of the Everglades during the past 4,000 years. With rising sea level, the bay not only became larger but also became deeper. With greater depth, exchange of water between the sea and the bay probably increased, resulting in a more stable salinity regime with salinity levels increasingly similar to the sea. However, a factor that has counteracted the rising sea is the accumulation of sediment, which makes the bay more shallow. Most sediment that accumulates in Florida Bay is carbonate that is precipitated from water by organisms that live in the bay. The extent to which these sediments accumulate is a function of the biology of these organisms (including skeletal carbonate production), the chemistry of the water, and the physical energy available to transport some of these sediments from the bay. **Major hurricanes** are thought to be important high energy events that can flush the bay of these sediments. However, since 1965, no major hurricane has directly affected Florida Bay. Florida Bay's ecological changes during the past decade may thus be indirectly influenced by changing circulation patterns and resultant changing salinity regimes because of changing water depth in the bay.

A.5.3.2 Nitrogen and Phosphorus Inputs

The productivity and food web structure of all ecosystems is strongly influenced by patterns of nutrient cycling and the import and export of these nutrients. Throughout the world, estuarine ecosystems have undergone dramatic ecological changes because they have been enriched by nutrients derived from human activity. These changes have often been catastrophic, with the loss of seagrasses and the occurrence of algal blooms and lethal low oxygen or anoxic events. The input of nitrogen and phosphorus to estuaries is thus a potentially important stressor of estuaries.

The importance of nitrogen and phosphorus as stressors in Florida Bay is unclear. In general, the bay is rich in nitrogen and poor in phosphorus, especially towards the eastern region of the bay (Boyer et al. 1997). There is little evidence that nutrient inputs to the bay have increased during this century, but with expanding **agriculture and residential development** in South Florida through this century, and particularly development of the Florida Keys, nutrient enrichment almost certainly has occurred (Lapointe and Clark 1992, Orem et al. 1999). Anthropogenic nutrients that enter Florida Bay are derived not only from such local sources (fertilizer and wastes from agriculture and residential areas), but also from remote sources. It is likely that remote contributions to the Gulf of Mexico, such as from the phosphate fertilizer industry of the Tampa-Port Charlotte area and residential development from Tampa to Naples, are the most important external sources of nutrients (Rudnick et al. 1999). This enrichment from external sources, however, may be less important to the bay's ecology than its own internal sources and cycling. It is, nevertheless, a reasonable hypothesis that a chronic increase in nutrient inputs has occurred in Florida Bay in this century and this increase has contributed to ecological changes. Ongoing research will provide information to test this hypothesis. Development of a water quality model will also help us understand the effects of past nutrient inputs and predict the effects of future management scenarios.

In this conceptual ecological model, **water management** is listed as a source of stress because the canal system can transport nutrients through the wetlands toward the bay, decreasing nutrient retention by the wetlands and possibly increasing nutrient inputs to the bay. Nutrient inputs from the Everglades and the Gulf of Mexico are affected not only by changes of fresh water flowing from Taylor Slough and Shark River Slough, but also by changes in bay circulation. Nutrient retention within the Bay is certainly sensitive to these changes in circulation, which have been caused by **Flagler Railway** construction and the balance of **sea level rise** and sedimentation or sediment removal by **major hurricanes**. The influence of hurricanes may be particularly important, as nutrients (particularly phosphorus) accumulate in the bay's carbonate sediment and the absence of major hurricanes may have resulted in an accumulation of nutrients during the past few decades.

A.5.3.3 Pesticides and Mercury

With the widespread **agriculture and residential development** of South Florida, the application and release of pesticides and other toxic materials has increased. Mercury is of particular concern because of high concentrations of methylmercury in upper trophic level species. However, it is unclear whether anthropogenic mercury inputs to the Everglades or Florida Bay have increased or whether, perhaps more importantly, mercury cycling and methylation rates have changed. Pesticides and mercury are of concern because they can affect human health after the consumption of fish or other biota with high concentrations of these toxins, and because other species may be adversely affected by these compounds. To date, there is no evidence the main ecological changes in Florida Bay are in any way linked to inputs of toxic compounds. **Water management** affects the distribution of these toxic materials and potentially their transport to Florida Bay. Controlling water levels in wetlands may also influence the decomposition of pesticides and mercury methylation rates because both of these processes are sensitive to the presence of oxygen in soils, which is affected by water levels.

A.5.3.4 Fishing Pressure

For any species that is the target of **recreational or commercial fisherman**, fishing pressure directly affects population dynamics and community structure. Within Everglades National Park, commercial fishing has been prohibited since 1985, but populations that live outside of Everglades National Park boundaries for at least part of their life cycle, which includes most of Florida Bay's sportfish species, are nevertheless affected by fisheries (Tilmant 1989).

A.5.4 Ecological Attributes

A set of Florida Bay's attributes that are either indicators of the health of the ecosystem or intrinsically important to society are given in this conceptual ecological model. These attributes in most cases are biological components of the ecosystem, including seagrass, mollusks, shrimp, fish and birds, but also an aggregated attribute (water quality condition) that includes phytoplankton blooms and aspects of the bay's chemical and physical condition. While the list of biological components is broad, it is clear from the links to stressors that are presented that these attributes are not equally weighted within the model; the central attribute of this conceptual ecological model of Florida Bay is the seagrass community. Details of each attribute and linkage are given below.

A.5.4.1 Seagrass Community

The keystone of the Florida Bay ecosystem is its seagrasses (Zieman et al. 1989, Fourqurean and Robblee 1999). These plants are not only a highly productive foundation of the food web, but are also the main habitat of higher trophic levels and a controller of the bay's water quality. Understanding how seagrasses affect water quality is essential for understanding the current status and fate of the bay.

Seagrasses affect water quality by three mechanisms: nutrient uptake and storage, binding of sediments by their roots, and trapping of particles within their leaf canopy. With the growth of lush seagrass beds, these mechanisms drive the bay towards a condition of clear water, with low nutrients for algae growth in the water and low concentrations of suspended sediment in the water. During the 1970s through the mid-1980s, lush *Thalassia* beds grew throughout central and western Florida Bay and the water was reported to be crystal clear. We hypothesize that with the onset of a *Thalassia* mass-mortality event in 1987 (Robblee et al. 1991), these mechanisms reversed, initiating a cycle that causes continued seagrass habitat loss and propagates persistent turbid water with algal blooms (Stumpf et al. 1999).

The cause of the 1987 mass-mortality event is not known, but thought to be related to earlier changes in two stressors, the salinity regime and nutrient availability. These changes caused *Thalassia* beds to grow to an unsustainable density by the mid-1980s. It is also likely that a decrease in shoal grass and widgeon grass (*Halodule and Ruppia*) occurred with the *Thalassia* increase. *Thalassia* "overgrowth" may have occurred because the species thrived when the salinity regime of the bay was stabilized, with few periods of low salinity. Nutrient enrichment also may have played a role, with a chronic accumulation of nutrients caused by increased inputs over decades or decreased outputs because of the absence of major hurricanes or closure of keys' passes. The factors that conspired to initiate the mass-mortality event in 1987 are also unknown, but thought to be related to the high respiratory demands of the dense grass beds and accumulated organic matter. During the summer of 1987, with high temperatures, sulfide levels may have risen to lethal concentrations. Low concentrations of dissolved oxygen in hypersaline bottom water may have been a critical component of this die-off scenario.

Regardless of the cause of the mass-mortality event, once this event was initiated, the ecology of Florida Bay changed. The cycle causing continued seagrass habitat loss, which characterizes the present Florida Bay, is illustrated in the model. Continued seagrass mortality results in increased sediment suspension (Prager and Halley 1999) and increased nutrient release from the sediments (increased nitrogen and phosphorus), stimulating the growth of phytoplankton (algae) in the water column. The presence of both phytoplankton and suspended sediment result in decreased light penetration to the seagrass bed. In this cycle, it is this decreased light that stresses the seagrasses and sustains the feedback loop. Light penetration is thus an essential aspect of the water quality condition attribute discussed in the next section.

The dynamics of this feedback loop are probably not independent of the salinity regime. A disease of seagrass, caused by a slime mold infection, seems to be more common at salinities near or greater than seawater (greater than or equal to 35 ppt) than at low (15 to 20 ppt) salinities (Landsberg et al. 1996). This may have played a role in either the initial seagrass mass mortality event, but more likely has served to continue seagrass mortality since that event. The incidence of this disease may be directly affected by water management actions.

If the state of the seagrass community is to be used as a criterion to decide the success of environmental restoration efforts, environmental managers must specify the desirability of alternative states. The consensus among scientists is that the Florida Bay of the 1970s and early 1980s, with lush *Thalassia* and clear water, was probably a temporary and atypical condition. From an ecological perspective, restoration should probably strive for a more diverse seagrass community, less dominated by *Thalassia* than during that period. Such diversity of seagrass habitat is generally expected to benefit upper trophic level species.

A.5.4.2 Water Quality Condition

Water quality condition reflects not only obvious characteristics, such as salinity, but also the light field, algal blooms in the water column, and the availability of nutrients in the ecosystem. All of these characteristics are closely related to the condition of seagrasses and the food web structure and dynamics of the bay. While these characteristics have been monitored and researched since the early 1990s, earlier information is scarce for salinity and even less available for other characteristics. Thus, at the present time, we do not know whether nutrient inputs to the bay have actually increased in recent decades or whether periods with sustained algal blooms and high turbidity occurred in the past.

Salinity has frequently been suggested as a primary restoration target. However, establishing salinity success criteria, such as those used in the C&SF Comprehensive Review Study's (Restudy's) evaluation of the effects of hydrological alternatives on coastal salinity (USACE and SFWMD 1999), depends on the development of a model of the "natural" salinity distribution of Florida Bay in time and space. This requires a both a water budget for the bay (monitoring rainfall, evaporation, and freshwater flow, ground water flow, water level, and salinity) and a hydrodynamic model, which is now under development. With modeled salinity variability for a wide variety of target sites in the bay, the fit of observed salinity fields to modeled fields could serve as the basis of deciding levels of success.

The magnitude of nutrient inputs to the bay and their relationship to freshwater inputs is under investigation. Success criteria based on water column nutrient concentrations are probably less meaningful than criteria based on nutrient loading. Results show that phosphorus loads to the bay do not greatly increase with increased freshwater inputs (Rudnick et al. 1999), but Florida Bay is probably very sensitive to any increase in phosphorus availability. Unlike phosphorus, nitrogen loads probably do increase with more freshwater flow and algal blooms in western and central Florida Bay appear to be stimulated by increased nitrogen (Tomas 1996). The potential thus exists for hydrological restoration to increase nitrogen loading and stimulate phytoplankton blooms (Brand 2000). Because most of the nitrogen that is exported from the Everglades to the bay is in the form of organic compounds (Rudnick et al. 1999), the fate of these compounds within the bay is a critical unknown; if these compounds are easily decomposed and their nitrogen is available to algae, then increased freshwater flow could stimulate algal growth. However, internal losses (denitrification) of this nitrogen may compensate for any increased nitrogen supply.

Finally, as emphasized earlier, the penetration of light through Florida Bay waters is a key to the health of seagrasses. An important success criterion should be light penetration, which is largely a function of turbidity from algae and suspended sediment. Light penetration should be sufficient to support a viable seagrass habitat. Such light-based criteria have been used successfully in other estuaries.

A.5.4.3 Mollusks and Other Benthic Grazers

Consumption of phytoplankton cells by mollusks and other benthic filter feeders and suspension feeders may have a significant impact on the distribution, magnitude, and duration of algal blooms. The long-term abundance and biomass of these grazers may increase such that blooms decrease. However, some grazers may be negatively affected by the blue-green algae (*Synechococcus* sp., the dominant species in central Florida Bay's algal blooms [Phlips and Badylak 1996]) and loss of seagrass habitat loss. Benthic grazers' abundance, biomass, and distribution should be monitored because of their functional link with phytoplankton blooms and also because their shells provide information on historical community structure. The composition and activity of the mollusk community is a function of salinity, seagrass and other habitat availability, and food supply. Studies of long-term changes in the composition of this community (by analyzing shells in the sediment) have indeed found changes that reflect the large-scale changes of the bay's salinity regime. Furthermore, because mollusks can be important as grazers of phytoplankton, the trophic status of the bay is reflected by mollusk community composition. It is also important to monitor other major invertebrate groups that could control phytoplankton blooms, such as sponges and tunicates. With increased phytoplankton blooms, benthic filter feeders and other grazers may increase such that they decrease these blooms.

A.5.4.4 Pink Shrimp

Pink shrimp are intrinsically important to society as an economic asset. They are also ecologically important, serving as a major component of the diet of game fish and wading birds; pink shrimp are an indicator of the bay's productivity. Florida Bay and nearby coastal areas are a primary nursery ground for pink shrimp. This nursery supports the shrimp fishery of the Tortugas grounds (Ehrhardt and Legault 1999). Hydrological and ecological changes in the Everglades and Florida Bay may have impacted this fishery, which experienced a decline in annual harvest from about 10 million pounds per year in the 1960s and 1970s to only about 2 million pounds per year in the late 1980s (Ehrhardt and Legault 1999). This decline may have been associated with seagrass habitat loss or high salinity (50 to 70 ppt) during the 1989-1990 drought; experiments have shown that pink shrimp mortality rates increase with salinities above 40 ppt (Browder et al. 1999). Shrimp harvest statistics indicate that shrimp productivity increases with increasing freshwater flow from the Everglades (Browder et al. 1999).

A.5.4.5 Fish Populations

The health of Florida Bay's fish populations is of great importance to the public; sport fishing is a major economic asset to the region. Recruitment, growth and survivorship of these fish populations are affected by many factors, including salinity conditions, habitat quality and availability, food web dynamics and fishing. Changes in mangrove and seagrass habitats are likely to influence the structure and function of the fish community. However, seagrass mass mortality appears to have had a greater influence on fish community structure than on the absolute abundance of fish; no dramatic baywide decreases in fish abundance have been observed along with seagrass mass mortality (Thayer et al. 1999). Rather, a shift in the species composition of this upper trophic level has occurred as a result of the cycle of seagrass habitat loss and sustained algal blooms. While some fish species have declined, fish that eat algae in the water, such as the bay anchovy, are thriving. Thus the stressors, such as altered salinity, not only affect upper trophic level animals directly, but also affect them indirectly through food web changes.

Another important stressor that needs to be considered with regard to fish populations is the impact of pesticides and mercury. As concentrations of mercury and some pesticides greatly increase in upper trophic level animals, such as sport fish, (via the process of bioaccumulation), and people eat such fish, a human health issue potentially exists. Pesticides and mercury can also have ecological impacts by physiologically stressing organisms (particularly reproductive functions). The extent of any existing problem with these toxic compounds in Florida Bay is being investigated, but they currently do not appear to significantly impact human health or ecological health in the bay. The possible impact of future restoration efforts on these issues, however, must still be considered.

Among the many fish species that could be used as indicators of the health of the ecosystem's upper trophic level, there is consensus among scientists that spotted sea trout is a key species. This is the only major sport fish species that spends its entire life-span in the bay. Population changes and toxic residues in this species thus reflect the specific problems of the bay and should also reflect the restoration actions that we take. For northeastern Florida Bay, the abundance of snook, red drum, crevalle jack, and mullet should also be considered.

A.5.4.6 Fish-Eating Birds

Florida Bay and its mangrove coastline are important feeding and breeding grounds for water fowl and wading birds. Conceptual ecological models for other regions of the Everglades, particularly the Everglades Mangrove Estuaries Conceptual Ecological Model, present more detailed descriptions of the use of bird populations as ecological indicators and consider a wide variety of birds. For the Florida Bay Conceptual Ecological Model, we consider only fish-eating birds, such as osprey, brown pelicans and cormorants. These birds are important predators of fish in the bay and are potentially impacted by any stressors that affect their prey base, including salinity changes, nutrient inputs, toxic compounds, and fishing pressure. As with other top predators, these bird species are the most vulnerable members of the ecosystem with regard to pesticide and mercury effects.

A.5.5 Ecological Effects
Critical Linkages Between Stressors and Attributes/Working Hypotheses

Described below are major hypotheses regarding the structure and function of Florida Bay. The level of certainty associated with each hypothesis was estimated. More detailed descriptions and reviews of many of the ideas presented below, as well as this narrative as a whole, can be found on the web page of the Florida Bay and Adjacent Marine Systems Science Program (www.aoml.noaa.gov/flbay/; see "Science Program" and then "Important Documents").

A.5.5.1 Estuarine Geomorphology and Water Circulation

Relationship of Mud Bank Dynamics and Accretion to Sea Level Rise

The mud banks and associated seagrass beds of Florida Bay will accrete sediments at rates comparable to predicted rates of sea level rise, which are estimated to be roughly two feet during the next 100 years. Persistence of the mud banks will sustain patterns of banks and basins, and related circulation patterns much as they are today, even with the occurrence of future major hurricanes.

Level of certainty - moderate

Relationship of the Exchange and Circulation of Gulf and Atlantic Water

Predicted rates of sea level rise during the next century will increase the exchange and circulation of Gulf of Mexico and Atlantic water in Florida Bay, shifting the bay from an estuarine to a more marine system. Construction of the Flagler Railway and Keys Highway decreased water exchange between the bay and Atlantic, increasing water residence time in the Bay and changing circulation and salinity patterns.

Level of certainty – moderate

A.5.5.2 Hydrologic Restoration and Water Quality Condition

Linkage of Everglades Hydrology to Freshwater Inflow, Circulation and Water Quality in Florida Bay

Water quality and circulation of coastal systems are linked to inland, freshwater wetlands through a combination of diffuse overland flow, creek and river flow, and ground water seepage. The salinity regime of Florida Bay, as well as many other aspects of the Florida Bay ecosystem (water residence time, stratification, nutrient loading, etc.) depend upon the quantity, timing, and distribution of freshwater inputs to the bay. Planning and implementation of ecosystem restoration requires the capability to link, through a predictive model, changes in hydrology of Everglades wetlands and consequent changes in Florida Bay and adjacent coastal ecosystems. These linkages have yet to be modeled and this is perhaps the highest priority need for Florida Bay restoration.

Level of certainty- low

Relationship of Phytoplankton Blooms to Nutrient Sources, Seagrass Die-off, Sediment Resuspension and Circulation Pattern

The spatial extent, duration, density and prevalence of *Synechococcus* in phytoplankton blooms in central Florida Bay are controlled by the combined and inter-related effects of external nitrogen loading, internal phosphorus cycling, seagrass die-off, sediment resuspension and water residence time. Seagrass die-off results in increased phytoplankton growth because of increased sedimentary nutrient mobilization, reduction in competition for water column nutrients, and decreased grazing pressure because of the loss of habitat for benthic filter feeders. Sediment resuspension due to seagrass die-off supplies additional water column nutrients via both porewater advection and desorption of surface-bound nutrients from resuspended particles, which is salinity dependent. The latter process may be an important phosphorus source for phytoplankton.

Level of certainty – low

Relationship of Phytoplankton Blooms to Dissolved Organic Nutrients

Dissolved organic nutrients are available to phytoplankton and support phytoplankton blooms in Florida Bay. Increased inputs of dissolved organic nitrogen from the restoration of natural water inflows from the Everglades will thus increase the prevalence of phytoplankton blooms in Florida Bay.

Level of certainty – low

Relationship of Salinity to Nutrient Cycling and Availability

Reduced incidence of hypersalinity will yield greater phosphorus retention within the bay sediments. With this greater retention, the extent of phosphorus limitation in the bay will increase and algal growth will decrease.

Level of certainty- moderate

Functional Importance of Florida Bay as Source and Sink for Nitrogen

A net loss of nitrogen occurs in Florida Bay because of rapid denitrification. Both nitrogen fixation and denitrification occur within bay sediments and seagrass beds and the rates of these processes are likely to greatly exceed the rate of nitrogen input from the Everglades watershed. The impact of any change of nitrogen loading to the bay that is associated with hydrologic restoration will depend upon the relative magnitude of these rates. Internal nitrogen cycling rates (and the balance of nitrogen fixation and denitrification) will also change with restoration, because of changing salinity and seagrass community structure. Internal nitrogen cycling rates (and the balance of nitrogen fixation and denitrification) will also change with restoration, because of changing salinity and seagrass community structure.

Level of certainty - low

A.5.5.3 Seagrass Community

Relationship of Seagrass Community to Light Penetration, Nutrient Availability, Salinity Sulfide Toxicity, Epiphyte Load, and Disease

The spatial coverage, biomass, production and taxonomic composition of seagrass beds in Florida Bay are controlled by the combined and inter-related effects of light penetration, epiphyte load, nutrient availability, salinity, sulfide toxicity, and disease. Decreased salinity caused by increasing freshwater flow will have a direct effect on seagrass communities through physiological mechanisms, resulting in greater spatial heterogeneity of seagrass beds, a decrease in the dominance of *Thalassia testudinum*, and an increase in coverage by other seagrass species. Decreased salinity will also decrease the importance of slime mold infection of *Thalassia*. Light availability will depend upon phytoplankton growth and sediment resuspension, which depend both on nutrient availability, grazing, and seagrass bed binding of sediments.

Level of certainty - moderate

A.5.5.4 Estuarine Fish Communities and Fisheries

Seagrass Habitat and Salinity as Determinants of Fish Community Structure

Seagrass habitat loss and sustained algal blooms have resulted in a community shift from demersal to pelagic fish species, including increased abundance of fish that eat algae in the water, such as the bay anchovy. Decreased freshwater flow has resulted in a community shift from euryhaline to marine fish species.

Level of certainty - moderate

Relationship of Spotted Seatrout Populations to Salinity

Juvenile density and sport catch of spotted seatrout in Florida Bay reflect the suitability of estuarine habitat and nursery grounds as influenced by salinity. Density of post-larvae is highest at an intermediate salinity range of 20-40 ppt (Alsuth and Gilmore 1994). Juvenile density is expected to increase due to the resumption of natural volumes and timing of freshwater flow into the bay, in response to a reduction in the frequency and duration of hyper-salinity events. Adult abundance and distribution based on sport catch per unit effort should reflect juvenile growth and survival, although that relationship is not presently known.

Level of certainty - moderate

Relationship of Pink Shrimp Juvenile Density and Adult Catch Per Unit Effort to Salinity and Freshwater Flow

Juvenile density of pink shrimp in Florida Bay reflects the suitability of estuarine nursery grounds as influenced by salinity. Optimal salinity conditions for survival appear to be somewhat below that of seawater (35 ppt). Pink shrimp juvenile density is expected to increase in Florida Bay in response to the restoration of estuarine salinity ranges and the reduction of the frequency and duration of hypersalinity events. Beneficial conditions in Florida Bay will contribute to an increase in annual catch per unit effort in the Tortugas fishing grounds.

Level of certainty – moderate

A.5.6 Research Questions

Although Florida Bay is one of the most intensively studied ecosystems in South Florida, three key areas of uncertainty hamper our ability to predict ecological responses to the restoration of freshwater flows to Florida Bay. They pertain to 1) the hydrologic linkage between the Everglades and the bay, including the relationship of changing upland hydrologic conditions to freshwater flow to the bay and water circulation and salinity within the bay; 2) the fate and ecological consequences of increased nutrient inputs that may accompany restored in flows to the bay; and 3) the relationship of phytoplankton blooms to nutrient sources, seagrass die-off, sediment resuspension and circulation pattern.

Linkage of Everglades Hydrology to Freshwater Inflow

How does Everglades' hydrology relate to the inflow and circulation of fresh water in Florida Bay? Develop a validated, predictive model to link changes in Everglades' hydrology to consequent changes in the freshwater inflow and circulation of surface and ground water in the bay. Develop validated hydrodynamic and water quality models of the bay that can accurately predict water residence times and salinity in the bay.

Fate and Ecological Consequences of Increased Nutrient Inputs That May Accompany Restored Freshwater Inflows to the Bay

What is the functional importance of Florida Bay as a source and sink of nitrogen? Is there a net loss of nitrogen in Florida Bay via denitrification? Measure quantitative relationships of nitrogen inputs from the Everglades and dentrification and nitrogen fixation rates within the bay, their relationships to salinity patterns, and model how they will change with restoration of natural freshwater inflows and salinity patterns. Will increased inputs of dissolved organic nitrogen from the restoration of natural water inflows of the Everglades result in an increase in the prevalence of phytoplankton blooms in Florida Bay? Determine the extent to which dissolved organic nutrients in different sources of water, particularly Everglades' runoff, are mineralized. Determine the availability of dissolved organic nutrients directly to phytoplankton in different water sources.

Relationship of Phytoplankton Blooms to Nutrient Sources, Seagrass Die-off, Sediment Resuspension and Circulation Pattern

Phytoplankton blooms may be strongly influenced by factors other than nitrogen availability. Rates of phosphorus supply and grazing (particularly benthic grazing) need to be measured, and relationships with seagrass cover and sediment resuspension determined. These dynamics need to be included in a water quality model.

A.5.7 Hydrologic Performance Measures

A.5.7.1 Salinity Pattern

Salinity patterns will be altered as a result of the modification of the volume, timing and distribution of freshwater inflow. The desired alterations include less abrupt and less extreme decreases in salinity in northeastern Florida Bay; a reduction in the frequency, extremity and extent of hypersaline conditions in the central and western bay; an increase in the frequency and extent of low salinity conditions in the central bay; and an increase the frequency and extent of salinities less than that of seawater in the western bay, extending westward along the Gulf of Mexico coastal shelf to Lostman's River.

A.5.8 Ecological Performance Measures

A list of fundamental measures associated with each of the model's ecosystem attributes is given in Table A-3. This list should be considered minimal; interpretation of many of these measures requires a set of associated measures. The list includes not only "structural" variables (e.g., pink shrimp abundance), but also dynamic, process variables (e.g., nutrient fluxes). Note that this list does not reflect the temporal or spatial time scale at which measurements are necessary, but temporal patterns, such as seasonality and interannual variability, and spatial patterns are a central aspect of ecological dynamics. Also note that the power to predict the fate of any ecosystem requires more than monitoring; research and modeling are also essential, with these three interdependent approaches providing the scientific basis for environmental management.

Table A-3: Ecological Performance Measures for the Florida Bay Conceptual Ecological Model Listed by Attribute

Water Quality Condition	
Salinity	Phytoplankton
Dissolved Oxygen	Nutrient Concentrations
Freshwater Inflow	Nutrient Fluxes
Water Budget	Sediment Nutrients and Toxics
Light Extinction and Turbidity	
Seagrass Community	
Spatial Heterogen	Coverage
Biomass	Pure Water Sulfide
Productivity	Disease Frequency
Mollusks and Filter Feeders	
Grazing Rates on Phytoplankton	Mollusk Abundance and Diversity
Zooplankton and Benthic Grazer Biomass	
Pink Shrimp	
Abundance	Mortality
Productivity	
Fish Community	
Diversity	Mortality
Abundance	Toxic Residues
Productivity	
Fisheating Birds	
Abundance	Mortality
Reproduction	Toxic Residues

A.5.9 Model

The diagram for the Florida Bay Conceptual Ecological Model is presented in Figure A-19. The key to the symbols used in the diagram is presented in Figure A-18.

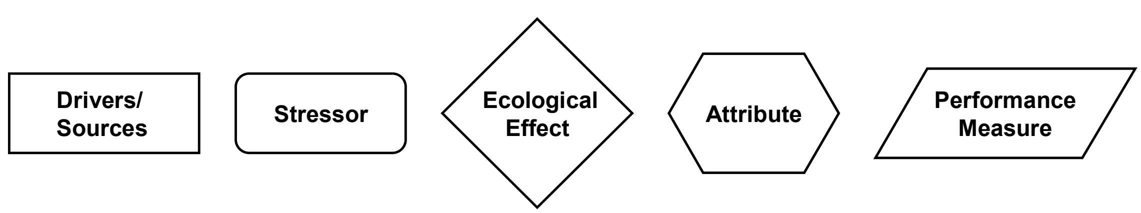

Figure A-18: Key to the Symbols Used in the Following Diagram

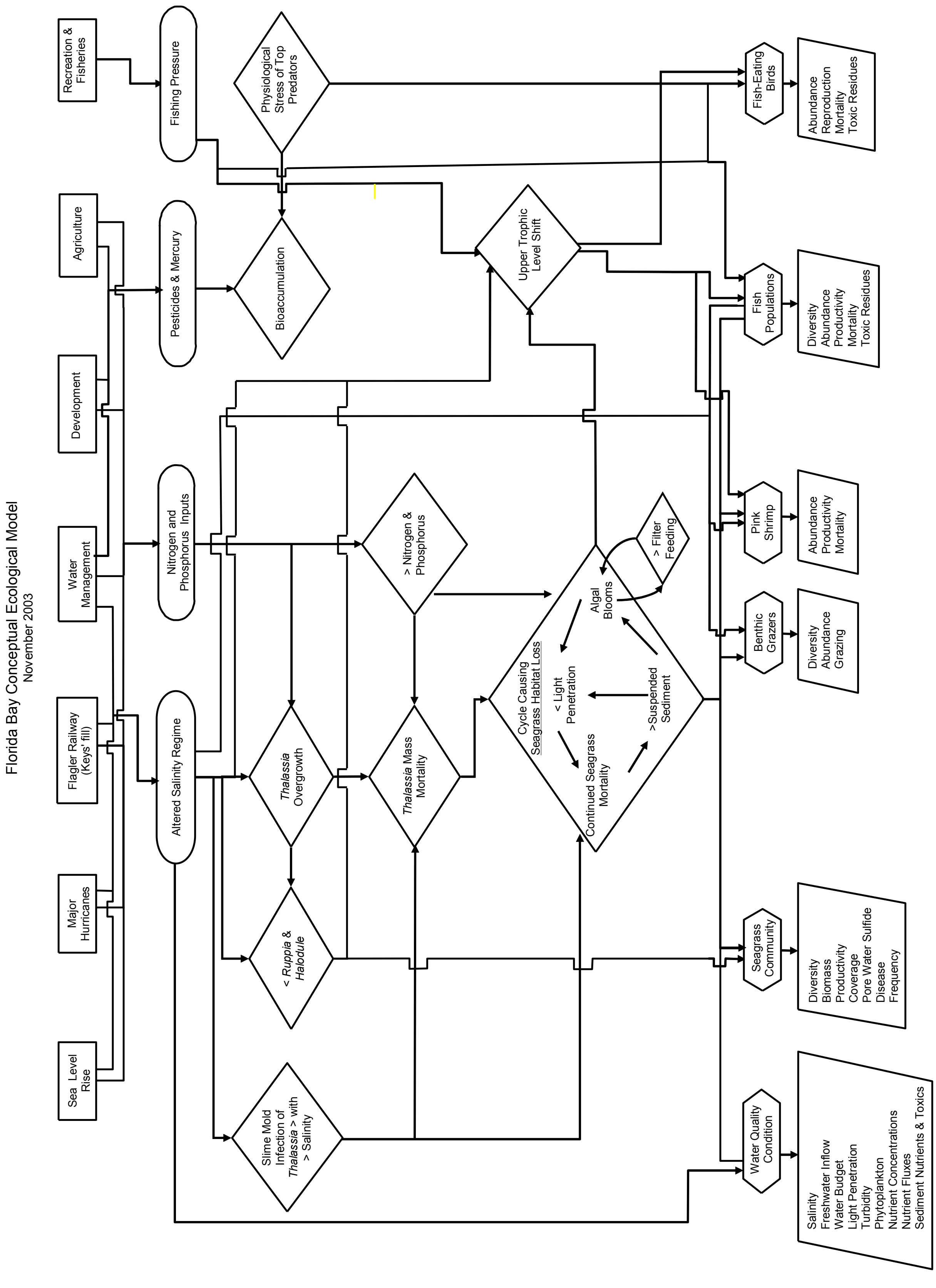

Figure A-19: Florida Bay Conceptual Ecological Model Diagram

A.5.10 Literature Cited

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