Summary of Findings

Purpose of this Report

This report serves two specific purposes. First and foremost, this is a report to the Science Oversight Panel about ecosystem research coordinated by the Florida Bay Science Program. A synthesis of results comprises the main body of this report, and this serves as the basis for a review of the Program by the Panel. Second, this report documents for the agencies cooperating in the Program the progress made toward the objectives established in the Strategic Plan revised in 1997. These objectives are expressed as five questions (see box below) that organize the research on the Florida Bay ecosystem. Each question examines different characteristics of the Florida Bay ecosystem and the relation of these to the geomorphic setting of the Bay and processes linking the Bay with adjacent systems and driving change. This report also examines the additional question of what changes have occurred in Florida Bay over the past 150 years.

Preparation of this report coincides with the reevaluation of the strategy of organizing ecosystem research in Florida Bay around these five central questions. This strategy originated in response to the need by resource managers for basic information about startling changes in the ecosystem that occurred in the late 1980s and early 1990s. Since 1994, the Program, focused by the central questions, has sought to identify the underlying mechanisms and causes of these decade-old events. Resource managers now ask a different set of questions. The inception of the Comprehensive Everglades Restoration Plan in 2000 signals a shift in resource management away from the reactive stance of protecting natural resources toward the proactive pursuit of restoring South Florida's ecosystems. In general, ecosystem restoration challenges us to look ahead.

Ecosystem History: What was the Florida Bay ecosystem like 50, 100, and 150 years ago?

Question 1 - Physical Processes: How and at what rates do storms, changing freshwater flows, sea level rise, and local evaporation/precipitation influence circulation and salinity patterns within Florida Bay and exchange between the Bay and adjacent waters?

Question 2 - Nutrient Dynamics: What is the relative importance of the influx of external nutrients and of internal nutrient cycling in determining the nutrient budget for Florida Bay? What mechanisms control the sources and sinks of the Bay's nutrients?

Question 3 - Plankton Blooms: What regulates the onset, persistence and fate of planktonic algal blooms in Florida Bay?

Question 4 - Seagrass Ecology: What are the causes and mechanisms for the observed changes in the seagrass community of Florida Bay? What is the effect of changing salinity, light and nutrient regimes on these communities?

Question 5 - Higher Trophic Levels: What is the relationship between environmental and habitat change and the recruitment, growth, and survivorship of animals in Florida Bay?

Can we predict future conditions in the Florida Bay ecosystem that will follow from resource management decisions made today? The 1997 Strategic Plan describes a set of interrelated predictive models for this purpose, i.e. for circulation, water quality, and ecological models. This activity has been pursued at several levels. Certainly, the most visible of these has been the ongoing effort to identify and implement an appropriate set of numerical simulation models to describe circulation and water quality within the Bay and the interaction of the Bay with the Everglades, the Florida Shelf, the reef tract and waters of the Florida Keys. Research has spawned the development of other types of predictive models, i.e. historical analogs, correlative models and mechanistically-based empirical models. Some of these models can be used now to peer into the future, albeit through somewhat narrow windows focused on specific elements of the Bay.

The concluding chapter examines progress toward answering the original central questions and explores some of the new challenges for research on Florida Bay. By maintaining focus on the central questions to serve the programmatic purposes described above, this report addresses most directly past concerns of resource managers. However, scientific information developed by the Florida Bay Science Program is also relevant to the present management goal of restoring the ecosystems of South Florida. For both the Program and for efforts to restore Florida Bay, knowledge of the past offers the best perspective for looking ahead.

Ecosystem History

The alarming ecological changes witnessed in Florida Bay during the late 1980s and early 1990s precipitated a shift in natural resource management in South Florida that culminated in the Comprehensive Everglades Restoration Plan. For many in the public-at-large, and among scientists as well, the restoration of Florida Bay will mean a return to conditions remembered from immediately prior to these changes – clear water, lush beds of seagrass, and good fishing. Resource managers must be concerned whether these conditions can be sustained by the ecosystem given the variety of processes driving change in the ecosystem. Perhaps viewed over a time span longer than only the last twenty years the natural state of Florida Bay will be revealed as something quite different than what is remembered.

An objective of the Program shared across the five central questions has been to construct a history of past conditions in the Bay based primarily on objective, quantitative data. Quantitative observations on the state of the Florida Bay ecosystem date back to the 1950s, when systematic surveys were conducted by Finucane, Dragovich and Tabb. Although invaluable, these observations provide an incomplete and biased representation of the Bay's natural state. Major changes had already occurred in the hydrology of the Everglades by the time that these studies took place. Fortunately, through analysis of coral and sediment cores we can read the history of the Florida Bay ecosystem recorded in the skeletons of organisms that resided here during the past 150 years or so. This work leads to the following conclusions:

- Salinity in Florida Bay is more strongly correlated to rainfall than any other single factor and a periodicity in salinity and rainfall data suggests linkages to El Niño-Southern Oscillation climatic patterns. Anthropogenic influences play a secondary role to rainfall in determining salinity for Florida Bay as a whole, but they may be a factor in the magnitude of salinity

variations seen in recent times. Additionally, anthropogenic factors may act on a local basis to influence salinity patterns.

- Seagrass has been more abundant in the last 50 years compared with the first half of the 20th century. Prior to mid-20th century epiphytal ostracodes were relatively rare at sites in Central and Northeast Florida Bay, suggesting a greater abundance and/or density of seagrass over the last 50 years, compared to the first half of the century. Epiphytal mollusks, while not rare, increased significantly in relative abundance from approximately 1940 on at most sites. These data suggest that dense and abundant seagrass beds may not have been the long-term normal state of the ecosystem, and they carry implications for restoration.

- Downcore profiles of dated cores from Central Florida Bay show that productivity events (i.e. blooms) have occurred historically in Florida Bay. A large multidecadal productivity event characterized by greatly elevated levels of organic carbon and nitrogen, dated to about the mid 1700s, was observed in two cores from Whipray Basin. Interestingly, total phosphorus was not elevated during this time span. This time period (the Little Ice Age) may correspond to a period of higher rainfall in the Everglades, and more extensive land runoff into Florida Bay, which may have triggered the productivity event.

- Sediments from Northeast Florida Bay (especially from sites near Pass and Russell Key banks) show indications of recent nutrient (carbon, nitrogen, and phosphorous) enrichment (1980 to present). This nutrient enrichment could be related to recent microalgal blooms and seagrass dieoff within Florida Bay.

- Northeast Florida Bay appears to be a source of nutrients to the mangrove zone at the southern end of Taylor Slough. Uranium isotope studies indicate that the phosphorus contamination at the northern end of Taylor Slough appears to be fertilizer-derived. However, phosphorus contamination in Taylor Slough diminishes to background by mid-slough; therefore Taylor Slough does not appear to be a source of nutrients to Northeast Florida Bay.

- Macroalgae has increased. Relative abundance of mollusks with a strong preference for *Thalassia* have declined since approximately 1970 in Northeast Florida Bay, and since 1910 in Whipray, while seagrass generalists have increased. This may indicate an increase in the amount of macro-benthic algae relative to *Thalassia*.

- At Bob Allen, seagrass abundance appears to have been increasing since a recent minimum around 1960. Downcore profiles of lignin phenols from Pass Key core shows large variations in lignin phenol distributions over short time intervals; reflecting the proximity of this site to the mangrove zone along the coast and the outlet of Taylor Creek.

- Changes also occurred in circulation and exchange with adjacent waters during the early part of the 20th century. Geochemical changes recorded in coral bands suggest that construction of the overseas railroad altered exchange by blocking passes between the Keys. Others changes appear to be the result of decreased freshwater inflow from the Everglades that resulted from “reclamation” activities on the mainland.

Physical Processes

Research on physical processes aims to identify the main external factors that control the movement of water and solutes within Florida Bay and their exchange with the Everglades and adjacent marine systems. The difficulty is in estimating the relative influence of the various physical driving processes; the identities of the physical processes themselves are known from the study of other estuaries. The two physical characteristics of Florida Bay that distinguish it from most other estuaries in the U.S. are the restricted exchange across the shallow but otherwise open boundary with the Florida Shelf and the relatively small amount of terrestrial freshwater discharge to the Bay.

- For the past several decades, Florida Bay has behaved as a marine lagoon with salinity reaching as high as 70 in the Central region on a few occasions, and typically exceeding 40 during drought years such as 1989-1990. Bay salinities have since declined under the influence of increased precipitation and runoff during the active hurricane and tropical storm seasons of 1994-1995 and 1999. However, more recent data from the dry seasons of 2000, 2001, and 2002 indicate that Florida Bay salinity may again be on the rise.

- The South Florida coastal region is surrounded by an intense, large-scale oceanic boundary current (the Loop Current/Florida Current system) and its evolving eddies that link local coastal waters to remote river sources upstream in the Gulf of Mexico.

- Seasonal cycles in local wind forcing produce seasonal patterns in circulation pathways, connecting South Florida coastal waters through West Florida Bay and transporting Everglades fresh water discharges. Southward flows through the Keys passages predominate in winter and spring, north-northwest flows in summer, and southwest flow toward the Tortugas in the fall. Large volume wind-forced flows through the Keys passages provide linkage for Gulf to Atlantic exchange through the southwest shelf region adjacent to West Florida Bay.

- Seasonal cycles in South Florida coastal current systems provide seasonal pathways for local larval recruitment and opportunities for recruitment from remote sources.

- Shallow bank configurations that restrict water exchange tend to separate the Bay's interior into three distinct regions with differing salinity regimes. The Northeast region is the most isolated from oceanic influences, receives most of the surface runoff and has the largest seasonal cycle of salinity; the Central region receives little runoff and has the maximum salinity; and the basins in the Western region have the greatest oceanic exchange and the smallest seasonal change in salinity.

- Variability of Florida Bay average salinity is directly related to the net flux of fresh water from the combined influence of evaporation, precipitation, and runoff. For the Bay as a whole on seasonal or annual time scales, evaporation is approximately equal to precipitation, while runoff is roughly ten percent of either. Historical salinity data and salinity proxy data show that Florida Bay salinity has commonly undergone large salinity changes on time scales of seasonal, interannual (ENSO), decadal (NAO) and even longer periods that are not understood.

- Stable isotopic markers indicate that runoff from the Everglades is the dominant source of fresh water to the Northeast region of Florida Bay; whereas for the West region precipitation shows a strong signal. In the Central region a mixture of runoff and precipitation provides the fresh water.

- Since 1985, freshwater discharge from Taylor Slough and C-111 canal have increased as a consequence of changes in water management. Trout Creek conveys the largest volume of fresh water to northeast Florida Bay, varying from -6 to 32 m^3/s. By contrast, the flow from each of another eight creeks where discharge is metered ranges from -1.4 to 6 m^3/s. Negative flows can occur during the dry season and during storm events.

- Low salinity Shark River plume waters are advected southward around Cape Sable to West Florida Bay and the Keys reef tract by seasonal wind-driven coastal flows. For the Ten Thousand Island region of the western Everglades, the mean annual river discharge is estimated at 13.3 m^3/s for Harney River, 11 m^3/s for Broad River, and 12.4 m^3/s for Shark River.

- Ground water inflows are believed to be most influential along the northern boundary of the Bay. However, estimates for the rate of groundwater discharge are higly uncertain, ranging over four orders of magnitude.

Nutrient Dynamics

In contrast to water movement and salinity, which reflect the influence of outside processes, both external and internal processes combine to determine characteristics of water quality. Research on this question has focused on quantifying external sources and sinks of nitrogen and phosphorus and, more recently, internal exchanges between the sediment and the water column. The major external sources of nutrients have proven difficult to quantify. This has made it difficult to resolve the question of whether the seagrass die-off and subsequent plankton blooms were triggered by the onset of eutrophication of Florida Bay.

- Temporal trends over a 13-year period of record show bay-wide declines in total phosphorus, total nitrogen, and chlorophyll *a* with an overall increase in turbidity.

- Objective analysis shows that there are three zones in Florida Bay that exhibit significant differences in water quality characteristics due to nutrient inputs, tidal advection, and water residence time. These zones correspond generally to the Northeast, Central, and West regions expressed in patterns of variation in other characteristics of the ecosystem. In general, dissolved phosphorus concentrations increase and nitrogen decreases from east to west resulting in a shift from phosphorous limitation to nitrogen limitation. Central Bay waters have high ammonium concentrations, which may indicate a bottleneck in the process of nitrification.

- Atmospheric input of nutrients is large relative to other sources.

- There is a measurable effect of water management on nutrient loading in the Taylor Slough system. Terrestrial nutrient loading fluctuates in phase with freshwater flow; however, flow-weighted concentrations decrease with increasing flow. A serious disconnect exists between upland/canal loading estimates and actual input to the Bay because of unmeasured nutrient processing in the intervening wetland/mangrove areas.

- High rates of organic carbon and nitrogen fluxes occur, both into and out of sediments, over diel cycles. Benthic denitrification is higher than predicted from nitrogen-loading rates. There are times when benthic N_2 fixation in Florida Bay balances denitrification but the system overall shows a net loss of nitrogen.

- Sediment flux of ammonium decreases with increase in sediment chlorophyll *a* concentration indicating that the microphytobenthos is important in regulating water column nitrogen concentrations.

- There is very little, if any, inorganic phosphorous flux out of the sediments with the exception of the Western Bay/Shelf area.

Plankton Blooms

For Florida Bay as a whole, plankton blooms can be viewed as a distinct mode of variation in the ecosystem that arises from a consequence of external drivers and internal processes. On a mechanistic level, plankton blooms form whenever plankton growth exceeds the combined effect of grazing and dispersion, the processes that reduce plankton concentrations. Studies of a number of other estuaries link plankton blooms to increased nutrient loads in runoff. Research on plankton blooms in Florida Bay has been directed at describing the combination of internal and external conditions associated with the onset, persistence and fate of blooms in this ecosystem. Research to date indicates that there are three ecologically distinct regions within the Bay from the standpoint of algal blooms; the Northeast region, Central region and West region. The nature and causes of blooms can be most appropriately summarized within the context of these three regions.

Northeast Region

- Algal blooms are largely absent from the Northeast region of Florida Bay. The phytoplankton community of the Northeast region is a diverse mixture of cyanobacteria, dinoflagellates, diatoms and microflagellates, none of which form blooms.

- The lack of algal blooms in the Northeast region of Florida Bay is largely attributable to the severe phosphorus limitation characteristic of the region. Despite significant water inflows to the region from the Everglades, the very low phosphorus levels in these inputs combined with the calcium carbonate rich waters of the region result in nutrient-limited conditions.

Central Region

- Large algal blooms have been a common feature of the Central region since at least 1992. The focal point for blooms in the Central region is in the north Central region from Rankin and extending into Whipray basin. The greatest bloom activity is generally in the summer

and early fall, although blooms have been observed in other seasons. In the fall and early summer blooms originating in the north Central region are pushed southward by prevailing wind-driven circulation into the south Central region, where they can spread out into the Atlantic reef tract through cuts in the Florida Keys. The dominant bloom-forming alga in the Central region is the picoplanktonic cyanobacterium *Synechococcus elongatus*, although several species of diatom and dinoflagellate do occasionally occur in bloom proportions.

- Nutrient limitation of phytoplankton growth in the Central region appears to switch back and forth from phosphorus to nitrogen. The nature of the sources of nutrients for blooms in the Central region has been a subject of considerable debate, yielding several hypotheses: (1) A significant supply of nutrients for algal production is available from the flocculent muddy sediments within the region, (2) A groundwater source of phosphorus is present within the region that, in combination with nitrogen from the Northeast region, feeds algal blooms, (3) Nutrients from the shelf region west of the Bay are available to blooms in the Central region via tidal water exchange and (4) Atmospheric deposition is a significant source of nutrients (particularly N) for algal primary production. These hypotheses are not mutually exclusive and several mechanisms may be operational at the same time.

- The domination of blooms in the Central region by *Synechococcus elongatus* is attributable to the unique ecophysiological characteristics of this species of cyanobacterium. These characteristics include: (1) Wide tolerance to salinity, (2) Superior ability to compete for phosphorus at low concentrations, (3) Ability to regulate buoyancy and thereby take advantage of nutrients available in the sediments and (4) Lower susceptibility to grazing losses.

West Region

- Algal blooms are also a common feature of the West region of Florida Bay. These are dominated by diatoms, in contrast to the cyanobacterial blooms in the north Central region. The diatom-dominated blooms in the West region are mainly *Rhizosolenia* spp. *Chaetoceros* spp. and pennates are major genera in term of cellular biomass. Diatom blooms in the West region begin in late summer and are advected into the bay from shallow coastal waters off Cape Sable.

- The diatom-dominated blooms in West Florida Bay are mainly limited in their growth by nitrogen, either singly or in combination with phosphorus and/or silicon supply. Temperature, salinity and light do not appear to be important factors in the initiation or maintenance of diatom blooms. Maximum growth rates of the diatom community during bloom initiation in the West region range from 1 to 2 day^{-1} (first-order rate constant), based on increases in netplankton (> 5μm size fraction) chlorophyll a or biogenic silica. The onset of diatom blooms on the western Florida Shelf appears to be associated with enhanced riverine outflow, predominantly from the Shark River. The onset of increased diatom biomass occurs within the riverine, low-salinity plume near Cape Sable.

Seagrass Ecology

Seagrasses account for a major portion of the primary production in the Florida Bay ecosystem. Therefore, it is particularly important to understand the mechanism for the die-off observed in the late 1980s and the relation of this event to the algal blooms that occurred subsequently. The loss of seagrass observed in other estuaries has been explained as a consequence of eutrophication increasing algal growth and reducing the amount of light available to the seagrasses. The seagrass die-off in Florida Bay did not follow this pattern, and its cause may be unique to Florida Bay. Research on this topic has focused on the influence of both internal conditions and external driving factors on plant growth and metabolism and on documenting the sequence and patterns of seagrass die-off and recovery in Florida Bay.

- Geographic variation in patterns of seagrass loss suggests multiple causes and a distinction between primary die-off and secondary mortality. There is a high spatial coincidence among the distribution of *Thalassia* loss, *Labyrinthula* abundance, high sediment sulfide levels, and turbidity, but determining the relative contributions of these factors to die-off versus secondary mortality has been problematic.

- Primary die-off is associated with high-density *Thalassia* beds. High-density beds result in conditions that increase stress on *Thalassia*: high sediment sulfide levels (>2-4 mM); self-shading of shoots; night-time/early morning anoxia/hypoxia in meristems; and increased susceptibility for leaf-to-leaf transmission of the *Labyrinthula* disease organism. Recent die-off in the Barnes Key area occurred where *Thalassia* densities and standing crop are among the highest in Florida Bay.

- Recent bay-scale changes in seagrass distribution and abundance following the region-scale primary seagrass die-off (1987-1991) are largely due to secondary mortality of *Thalassia* associated with areas of chronic turbidity (since 1994) in the West region. These changes are most likely due to light limitation as indicated by stand thinning in *Thalassia* beds with concommitant increases in low light adapted species such as *Halodule wrightii* and *Halophila engelmanii*. There has also been a loss of *Thalassia* in northern Little Madiera Bay, near the mouth of the Taylor River, followed by recolonization by *Halodule* and *Ruppia*. The cause of this loss is unknown. Primary acute die-off (rapidly developing dead patches within dense beds) is only known to be currently occurring (initiated in 1999) in the high-density *Thalassia* beds of the Barnes Key area. A chronic die-off is occurring in dense beds in Sunset Cove. However, the etiologies of these two sites are different.

- There has been little net change in seagrass distribution and abundance since 1995 in Central basins that are periodically subjected to low salinities or have shallow sediments and lower overall densities of *Thalassia*. These conditions may reduce density-related stresses and allow for development of robust species communities; low-salinity may also provide refugia from disease since *Labyrinthula* has never been observed in Florida Bay in salinities below 15 psu.

- Unique characteristics of the Florida Bay ecosystem make it susceptible to conditions that contribute to primary die-off. Other marine areas with high *Thalassia* densities and

carbonate sediments, such as the Lakes Region of the Lower Keys, did not experience extensive die-off in the late 1980s. Relative to these other areas, the Central basins in Florida Bay are isolated from tidal influences and are subject to relatively high terrestrial influence.

- A statistical, disciminant-function model of seagrass species occurrence has been developed. The model predicts that an increase in freshwater delivery to Florida Bay will result in an expansion of *Ruppia maritima* and *Halodule wrightii* distribution into the Northeast region with a concomitant loss of *Thalassia* in this region.

Higher Trophic Level Species

The value placed on Florida Bay derives largely from its role supporting ecologically and commercially important animal species. These species and the communities they create depend on and integrate the net ecosystem metabolism at lower trophic levels. As well, the structure of the ecosystem at higher trophic levels can feed back to influence the structure and function at lower levels, i.e. top-down control. Research in this area focuses on the influence of internal conditions of water quality and benthic habitat on both the growth and survival of individual organisms and on whole populations and communities. A key objective in this work has been to formulate models that can predict how valued species can be expected to respond to changes in the supply of freshwater and water quality.

- Salinity patterns and variability directly affect recruitment, survival and growth of many animals that live in Florida Bay and that use Florida Bay as a nursery ground. We have sufficient information on about a dozen key species to predict how they will respond to future salinity conditions that might arise from altered freshwater inflow into Florida Bay.

- Habitat, tidal amplitude, freshwater inflow to Florida Bay, and salinity were the most widely influential variables explaining density in 11 forage species in a meta-analysis of data from historical surveys. Seagrass density and tidal amplitude each were significant for 10 species; seagrass type and freshwater inflow each were significant for nine species; and salinity was significant for seven species.

- Analysis of historical data indicates that water management affects the productive capacity of Florida Bay. This information has been used to predict the annual catch of pink shrimp in the Dry Tortugas fishery based on upstream hydrologic conditions in the Everglades.

- Recent findings discount earlier concerns that seagrass die-off and subsequent plankton blooms signaled a fundamental change in the food web. The abundance of bay anchovy in the West region, one signal of a possible shift, has fluctuated since it reached a maximum in 1995. The diversity and overall abundance of canopy-dwelling fauna has increased since 1995 without a return to the original *Thalassia*-dominated seagrass canopy.

- Seagrass diversity may determine faunal density. A Principal Components analysis suggested that faunal species have affinities to certain seagrass types, *Thalassia*, *Halodule*, *Syringodium*, or macroalgae. Seagrass type was a significant explaining variable in a

metanalysis of faunal density in Florida Bay, and faunal density in relation to seagrass type varied differently depending on faunal species. No species was favored by pure *Thalassia*.

- Characteristics of the bottom and shoreline habitats affect abundance and community composition. Mangrove prop root habitat in Northeast Florida Bay have significantly more fish larvae than nearby open water sites or nearshore areas without mangroves.

- Fishing affects fish populations. Recreational fishing in Everglades National Park affects the size structure of gray snapper, according to a comparison of the length frequency distribution inside and outside of an area in the park protected from fishing. Evidence of overfishing is seen in gray snapper and other species on the reef tract.

- Spatial variation in influencing factors (e.g., freshwater inflow, tidal mixing) is reflected in distinct regional patterns of species distributions and community and trophic composition. Postlarval shrimp enter the Bay preferentially where tidal flows are greatest. Peak concentrations of postlarval pink shrimp are roughly an order of magnitude greater in passes leading into the West region from the Gulf of Mexico than in channels to Florida Bay through the Florida Keys.

- The food web exhibits the same regional structure as seen in the variation of circulation, salinity, and water quality. Based on stable isotope analyses, the Central region has a strongly seagrass-based trophic structure; whereas the northwestern Bay has a more plankton dominated trophic structure. The Northeast region has a non-seagrass-based diet base (likely more water-column based). The trophic structure of the southwestern Bay is based on macroalgae.

- Temporal variation in recruitment strength of spiny lobster, snapper, and pink shrimp is related to regional oceanographic processes, especially the Tortugas gyres.

- High methylmercury in Florida Bay and its biota may have a local source in the Bay. Sources of elevated mercury concentrations in fish from Northeast Florida Bay include (1) methylmercury in runoff from the Everglades and (2) *in situ* mercury methylation in sediments from both the mangrove transition zone and the open Bay itself. Mercury concentrations seem to be higher along a Taylor River/Little Madeira Bay sampling transect than along a C-111 canal/Joe Bay transect, suggesting that the urban and agricultural runoff that more strongly influences the C111 canal/Joe Bay transect is not the most important source of mercury to the Bay and its biota.

- Loss of sponges may have reduced water clarity and affected seagrass recovery. Recovery of the largest and most abundant species has been extremely slow following a dieoff in the early 1990s. Sponges are efficient filters of small (< 5 µm) planktonic particles. At pre-dieoff (pre 1992) densities, sponges in Florida Bay may have been capable of filtering the entire water column in one day. At present densities, filtering takes an estimated four days.